Designing Optical-Circuit-Switched Networks in Data Centers

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「入室後、詳細→名前の変更で、以下の通り名前を変更してください。 学生番号（半角）＋姓名 例：12345678山田太郎 上記形式になっていない場合、欠席とみなす場合があります。 退室までそのままにしておいてください。 間違って退室し、再入室した際も、名前の変更を忘れないようにお願いします。」

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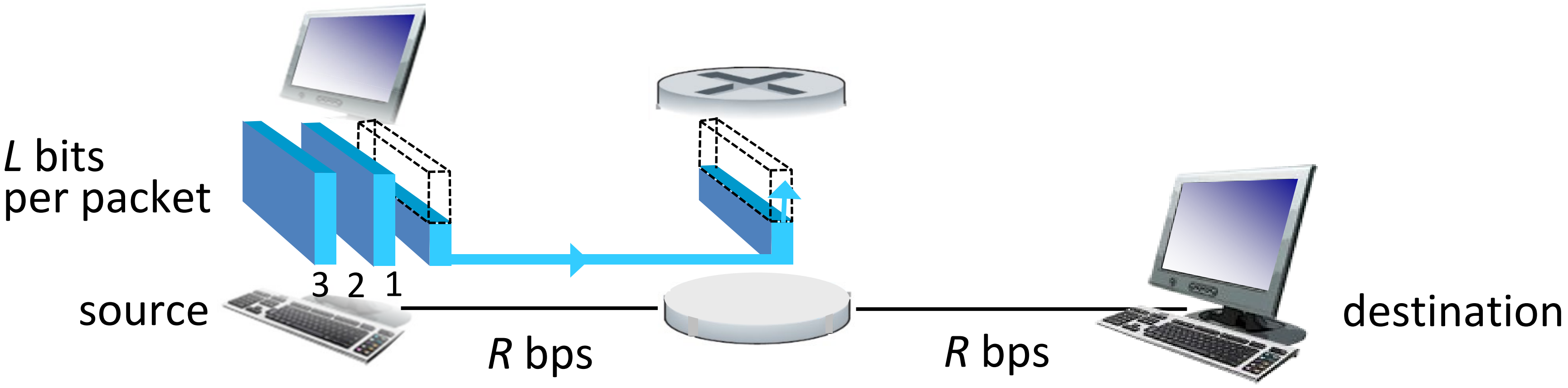
KYOTO UNIVERSITY

Outlines

- Packet switching versus circuit switching
- Optical circuit switching in data center
- Optical switches
- Basics of switching networks
- Clos network
    - Blocking
    - Strict non-blocking (SNB) condition
- Twisted-folded Clos network (TF-Clos)
    - TF-Clos design with SNB to maximize switching capacity
- Increasing switching network size
    - Allowing admissible blocking probability
    - TF-Clos design models with guaranteeing admissible blocking probability
- Further increasing switching network size
- Summary
- Report assignment

Packet-switching: store-and-forward



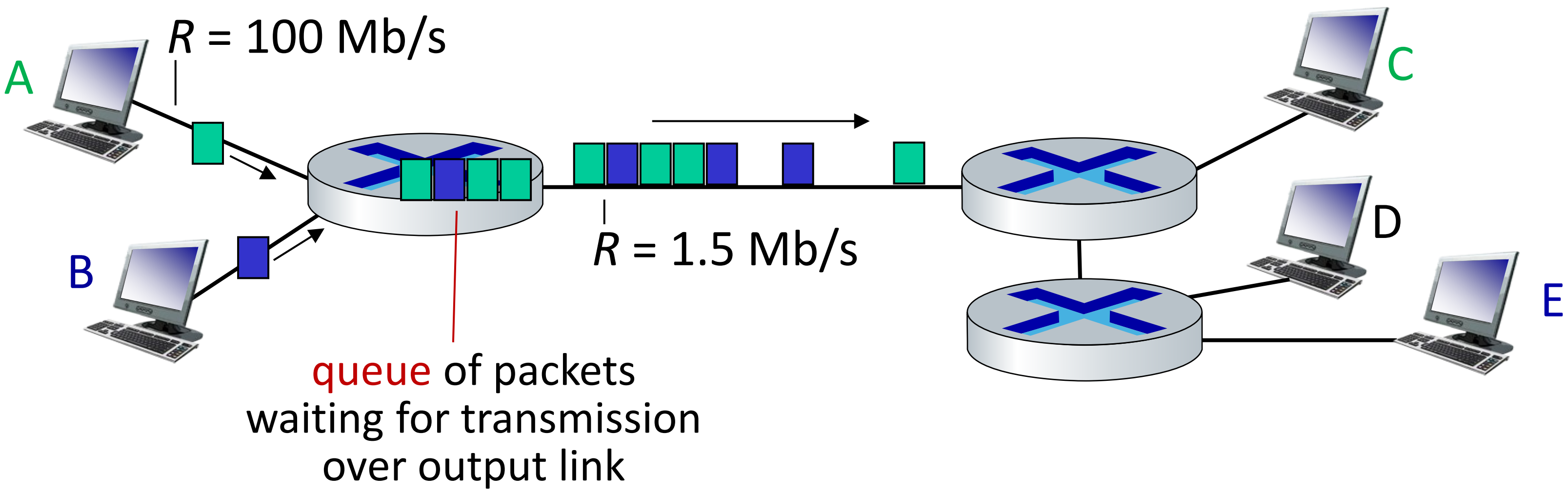
- packet transmission delay: takes *L*/*R* seconds to transmit (push out) *L*-bit packet into link at *R* bps
- *store and forward:* *entire* packet must arrive at router before it can be transmitted on next link

One-hop numerical example:

- *L* = 10 Kbits
- *R* = 100 Mbps
- one-hop transmission delay = 0.1 msec

Source:
Computer Networking: A Top-Down Approach
8th edition, Jim Kurose, Keith Ross, Pearson, 2020

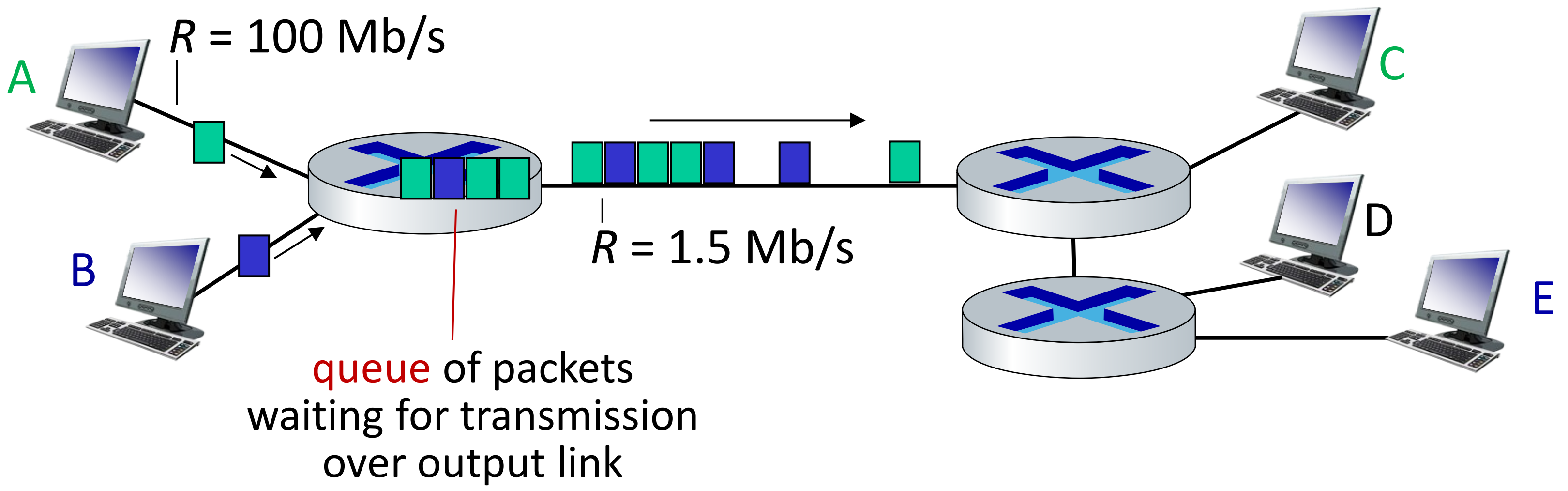
Packet-switching: queueing



Queueing occurs when work arrives faster than it can be serviced:

Source:
Computer Networking: A Top-Down Approach
8th edition, Jim Kurose, Keith Ross, Pearson, 2020

Packet-switching: queueing



Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

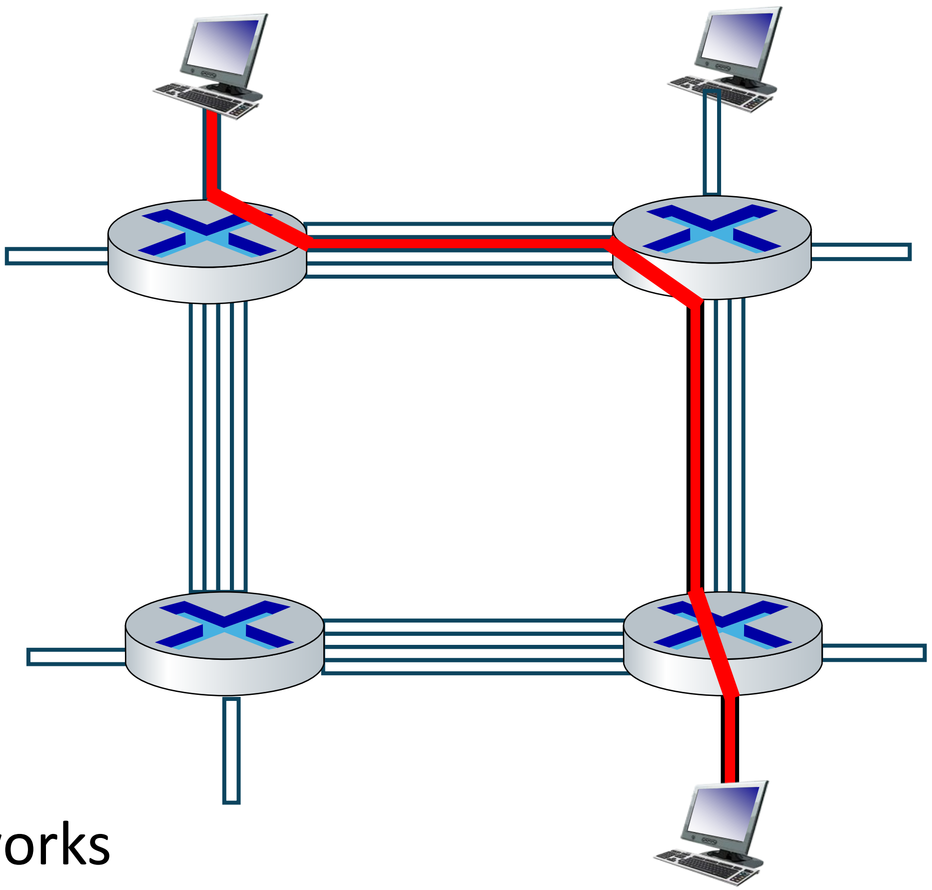
- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up

Source:
Computer Networking: A Top-Down Approach
8th edition, Jim Kurose, Keith Ross, Pearson, 2020

Alternative to packet switching: circuit switching

end-end resources allocated to, reserved for “call” between source and destination

- in diagram, each link has four circuits.
    - call gets 2^{nd} circuit in top link and 1^{st} circuit in right link.
- dedicated resources: no sharing
    - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)



- commonly used in traditional telephone networks

Source:
Computer Networking: A Top-Down Approach
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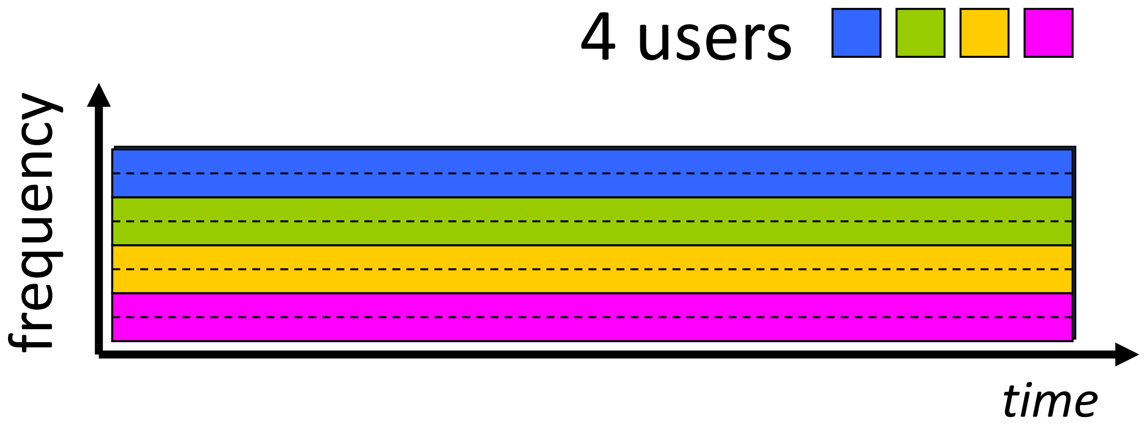
Circuit switching: FDM and TDM

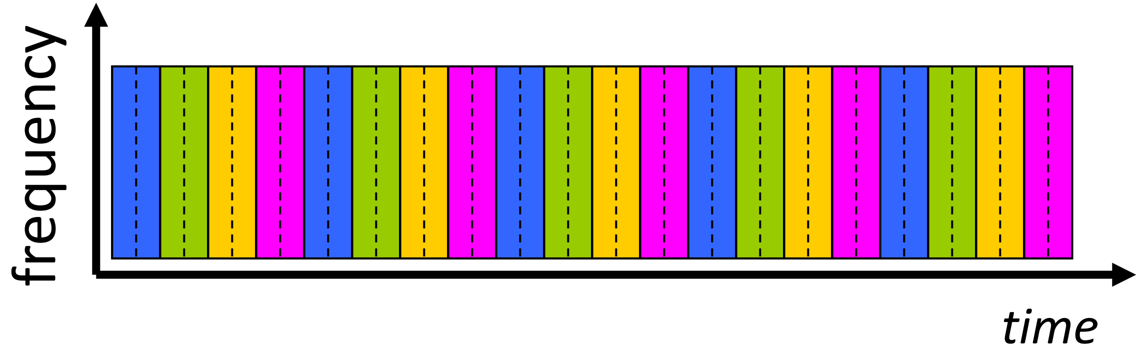
Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
  - each call allocated its own band, can transmit at max rate of that narrow band



Time Division Multiplexing (TDM)

- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



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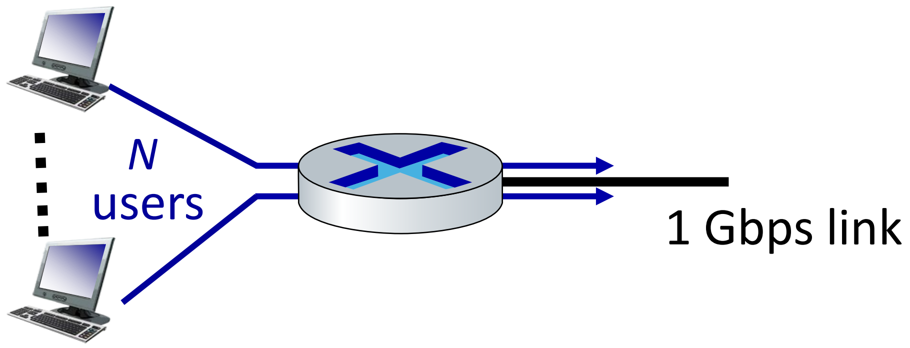
Packet switching versus circuit switching

example:

- 1 Gb/s link
- each user:
  - 100 Mb/s when "active"
  - active 10% of time



Q: how many users can use this network under circuit-switching and packet switching?

- *circuit-switching:* 10 users
- *packet switching:* with 35 users, probability > 10 active at same time is less than .0004 *

Q: how did we get value 0.0004?

Answer: …

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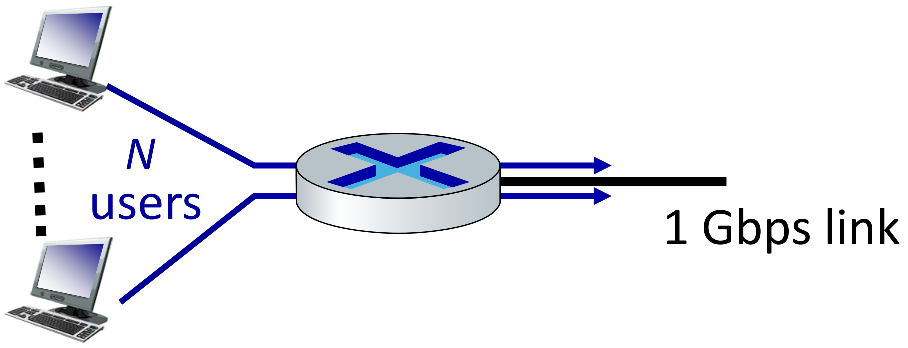

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- *circuit-switching:* 10 users
- *packet switching:* with 35 users, probability > 10 active at same time is less than .0004 *

Q: how did we get value 0.0004?

Answer:

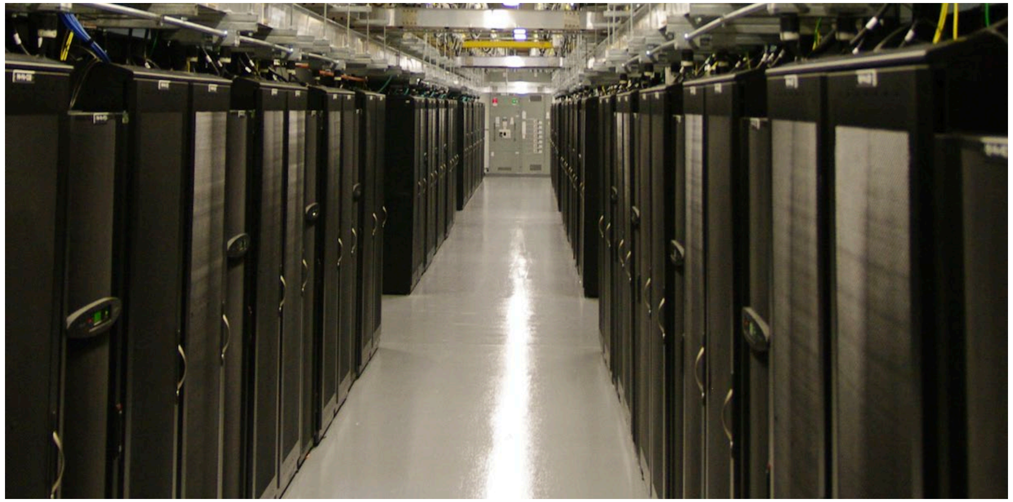
Active probability, *p*=0.1

$$\sum_{x>10}^{35} \binom{35}{x} p^x (1-p)^{35-x} < 0.004$$

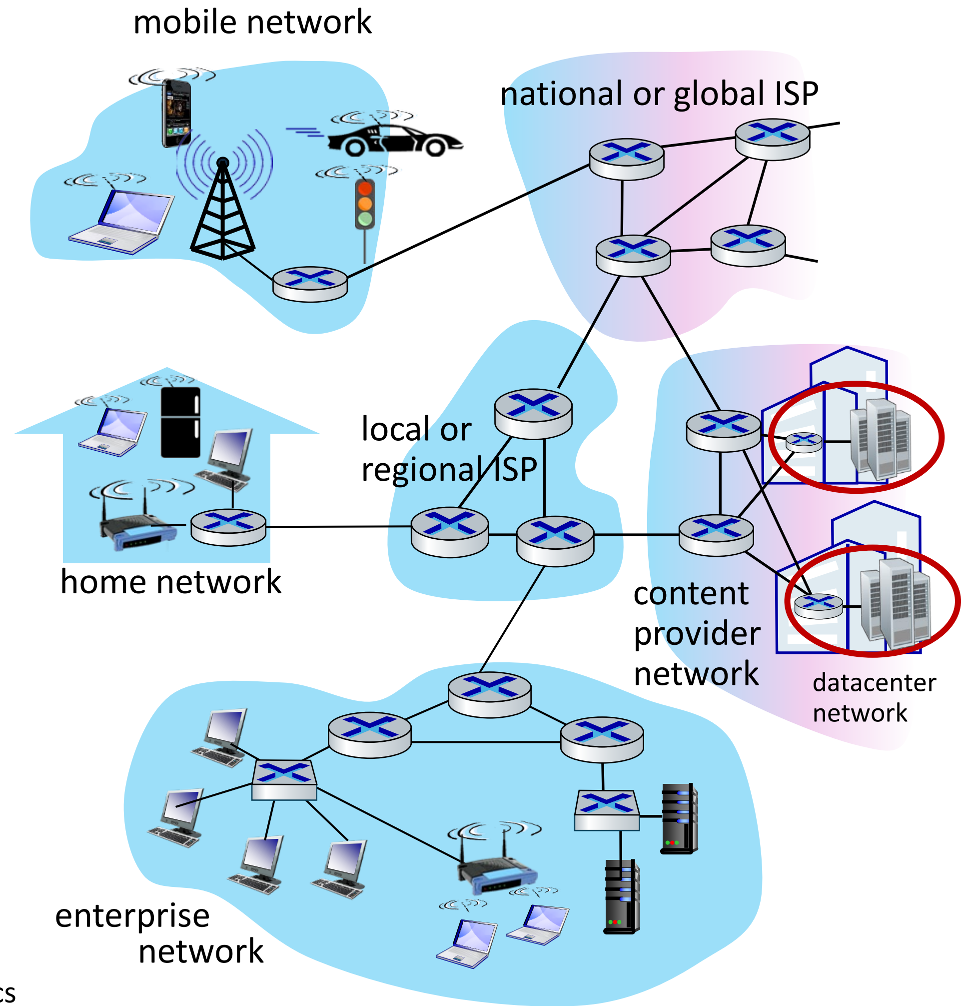
Source:
Computer Networking: A Top-Down Approach
8th edition, Jim Kurose, Keith Ross, Pearson, 2020

Data center networks

- high-bandwidth links (10s to 100s Gbps) connect hundreds to thousands of servers together, and to Internet



Courtesy: Massachusetts Green High Performance Computing Center (mghpcc.org)



Source:
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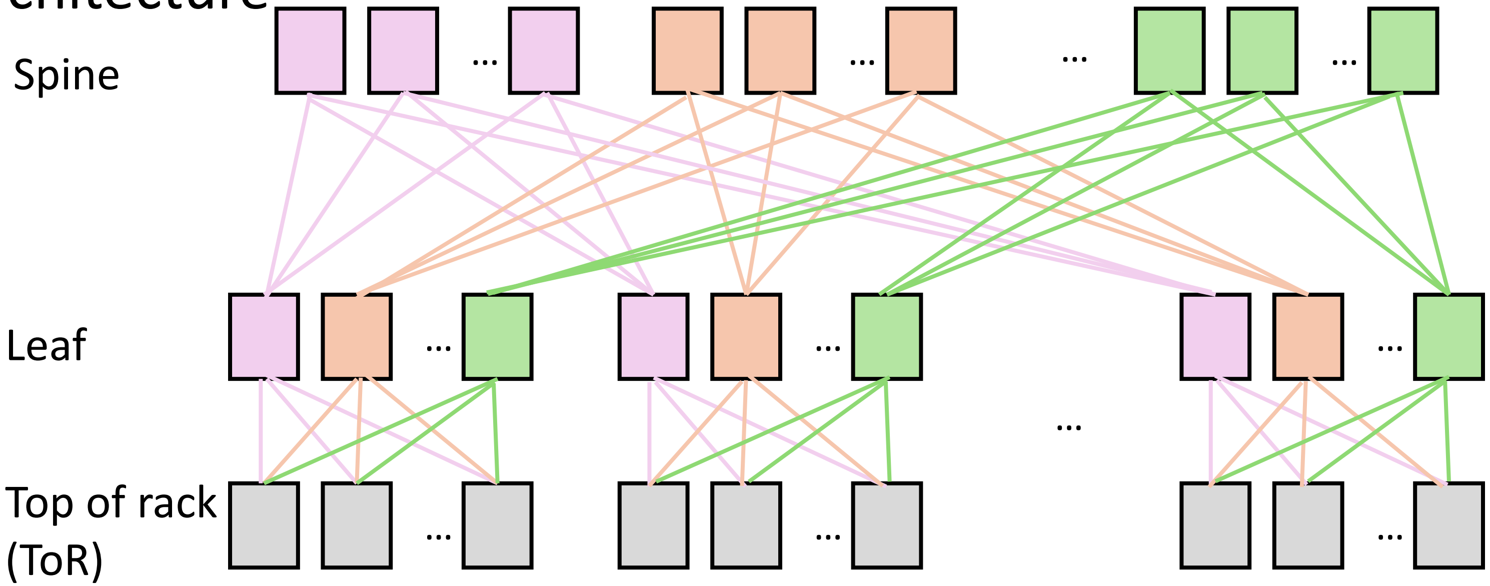
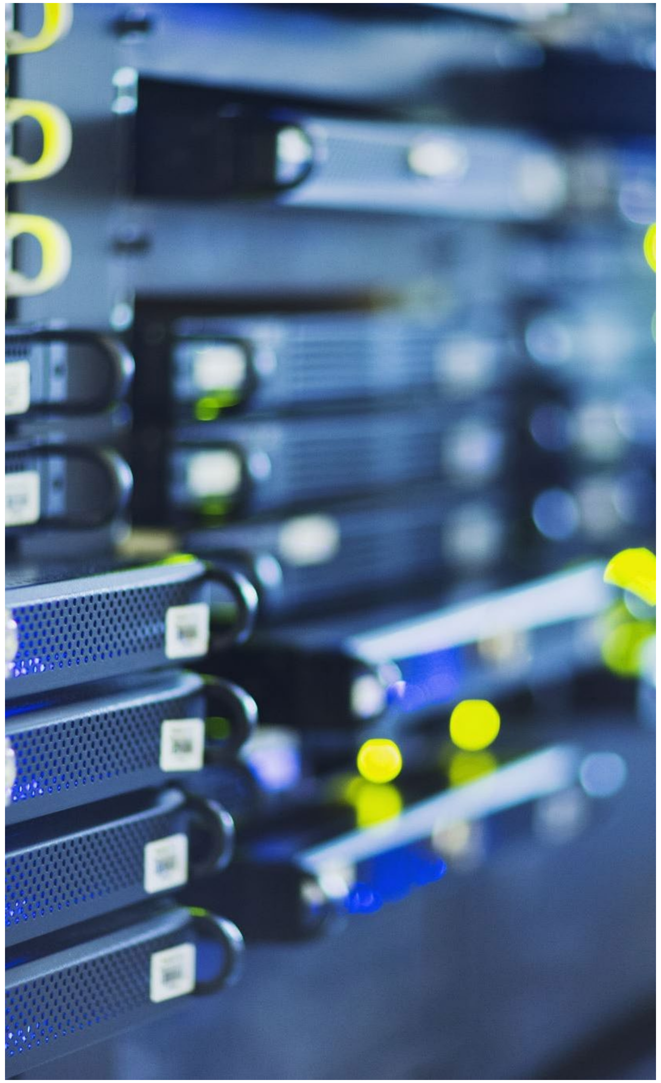
Data center networks (cont'd)

- A current data center network, comprising switches and routers, handles extensive data processing
  - Electrical packet switching
- Clos network
  - Multi-stage switching architecture featuring hierarchically combined switches [Clos, BellJ 1953][Jajszczyk, Commag 2003][Kabacinski, Springer 2005]
  - Folded Clos network architecture



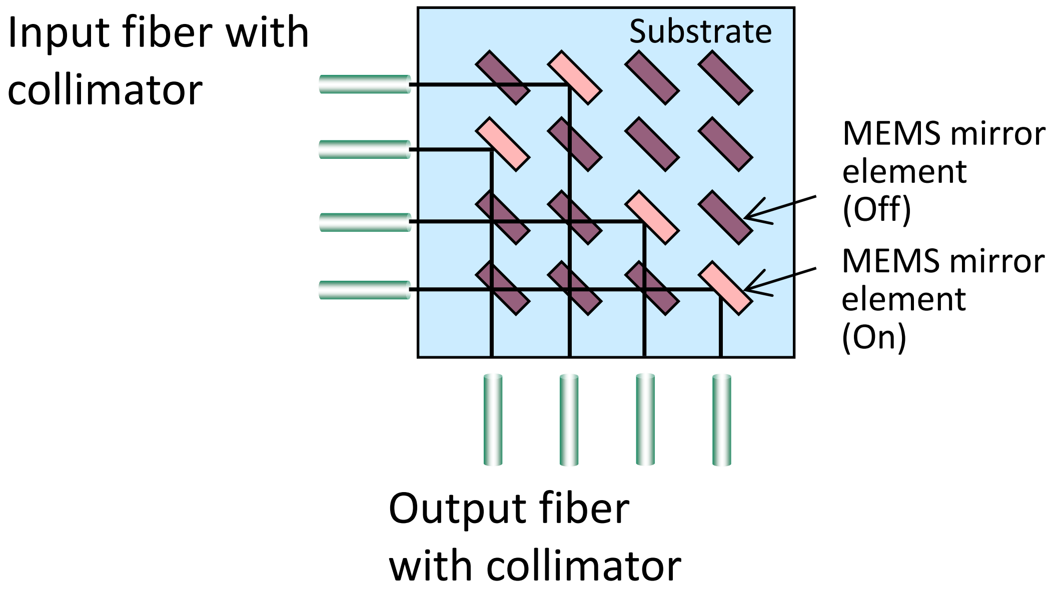
Optical circuit switching in data center

- The slowdown in Moore's law has worsened the energy efficiency and performance of data center networks
- Data centers are adopting advanced optical circuit switching technologies for enhanced transmission capacity and power efficiency [Sato, JOCN 2024][Poutievski, SIGCOMM 2022].
- Optical circuit switching technology ensures stable communication quality by:
  - establishing a connection exclusively for data transmission and
  - maintaining it throughout the process.



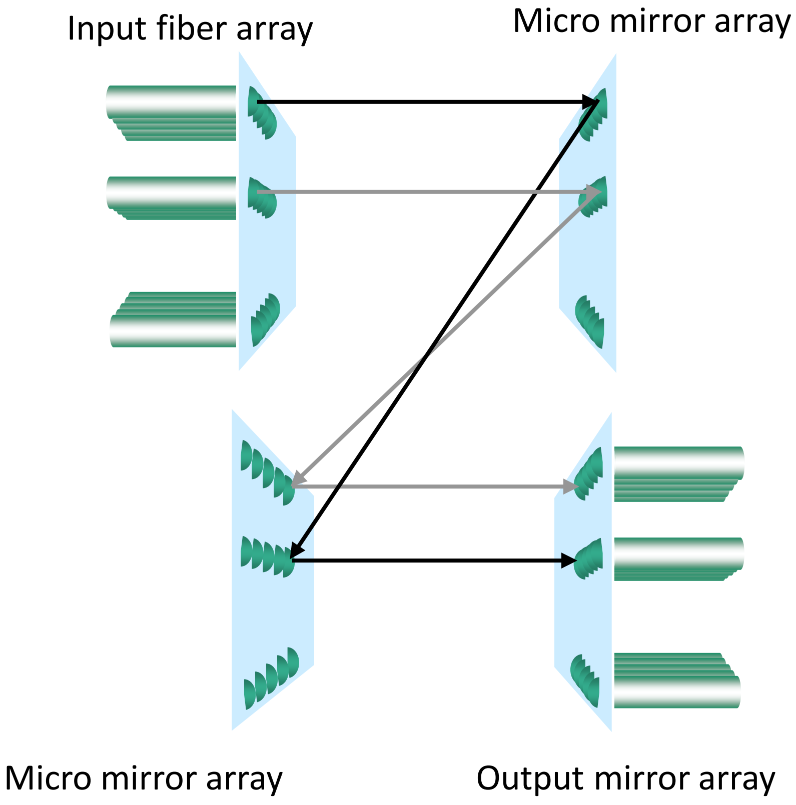
Examples of optical switches

- MEMS (micro-electro-mechanical system)
  - To increase optical switch size, the switching system complexity increases.



4 x 4 optical switch

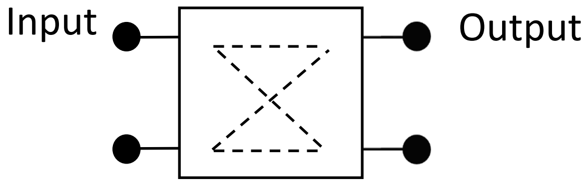
Two-dimensional (2D) MEMS



Three-dimensional (3D) MEMS

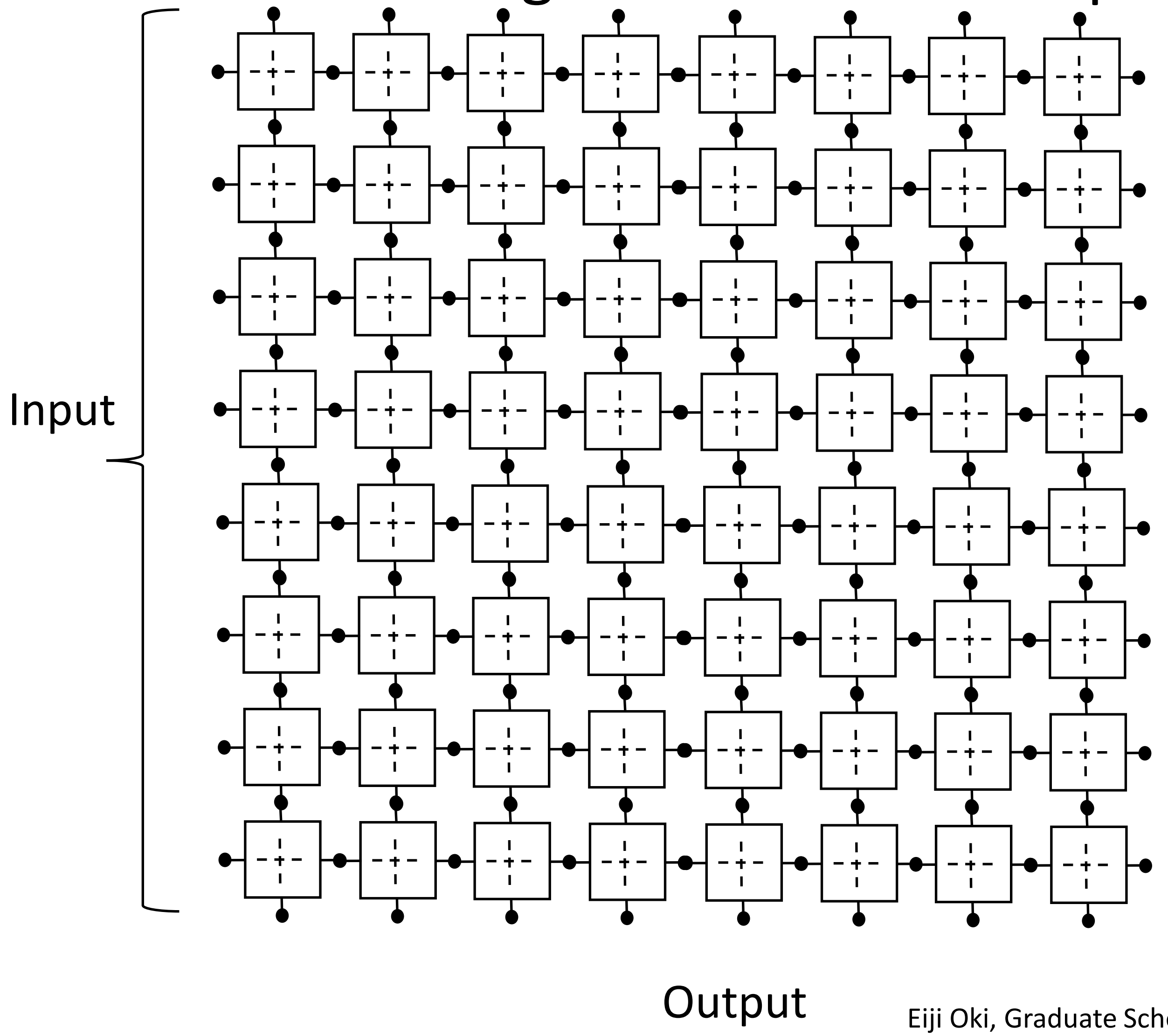
How to increase switching size?

- We want to increase the switching network size by using small-sized optical switches.
- Exercise
  - By using the following 2 x 2 optical switches, design 8 x 8 optical switching network. Find the network structure and the required number of optical switches.



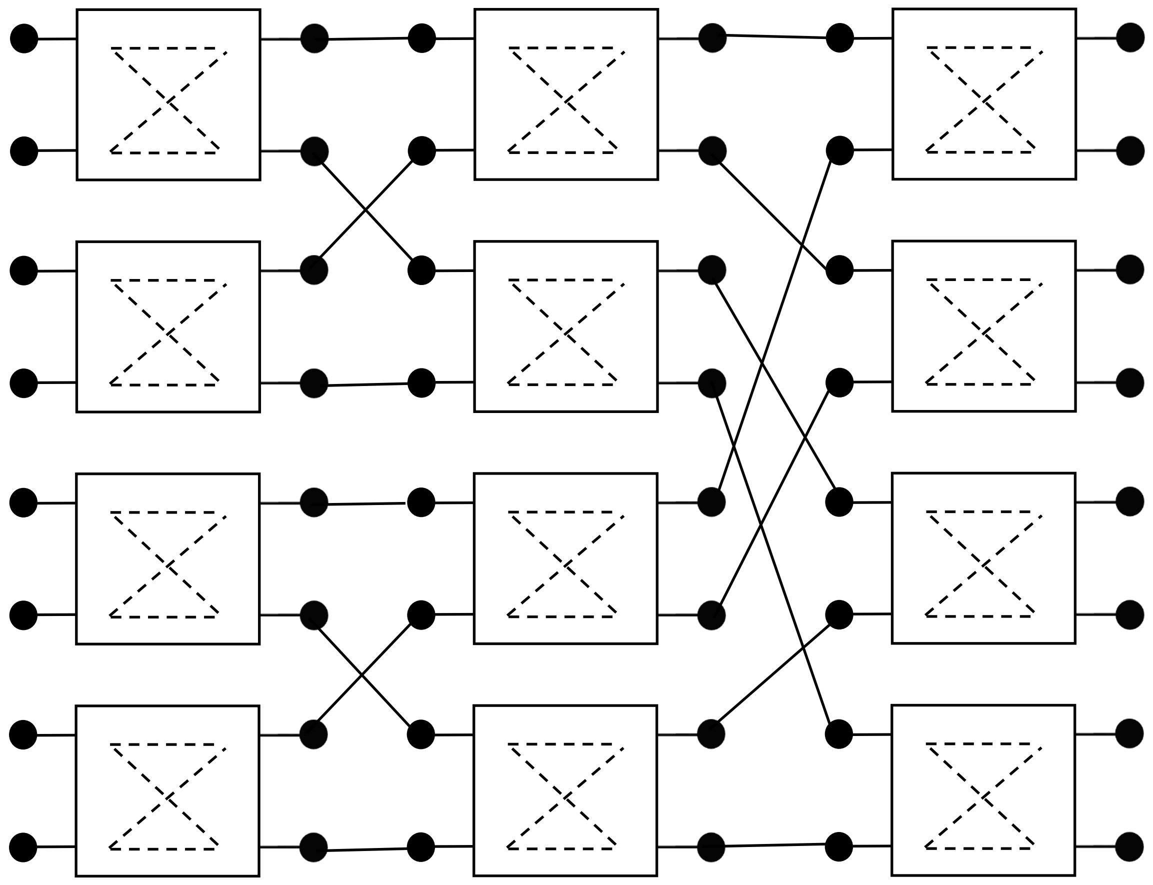
Example 1

- 8x8 switching network with 64 optical switches (non-blocking)



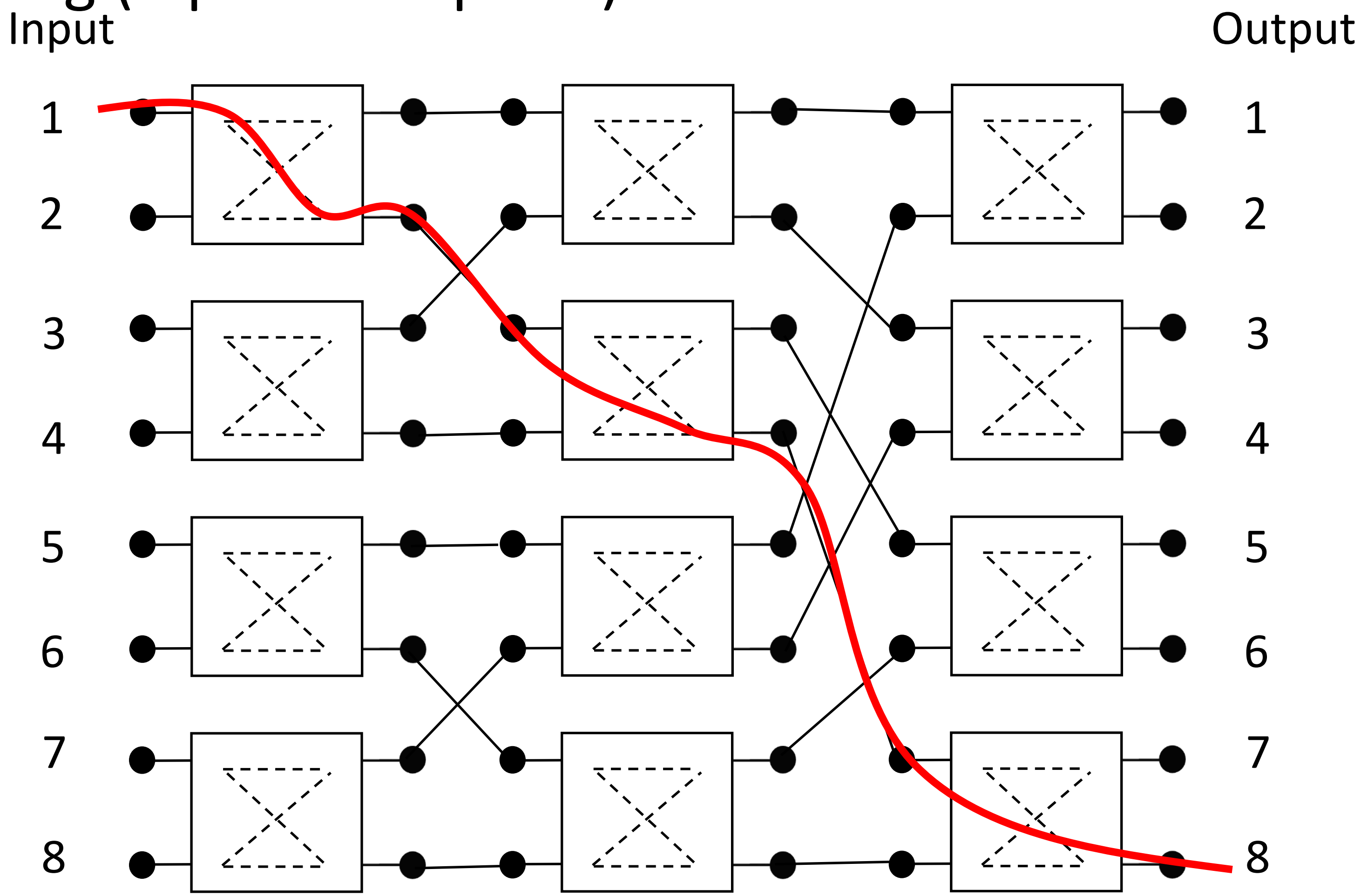
Example 2

- 8x8 switching network with 12 switches (blocking)



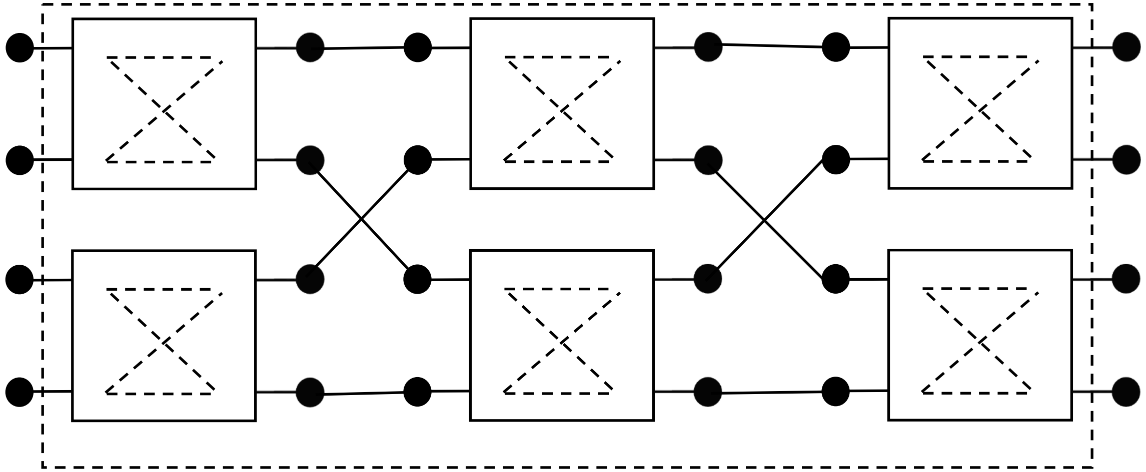
Example 2 (cont'd)

- Suppose that the connection of (input 1-output 8) exists.
- Connecting (input 2-output 7) cannot be achieved.



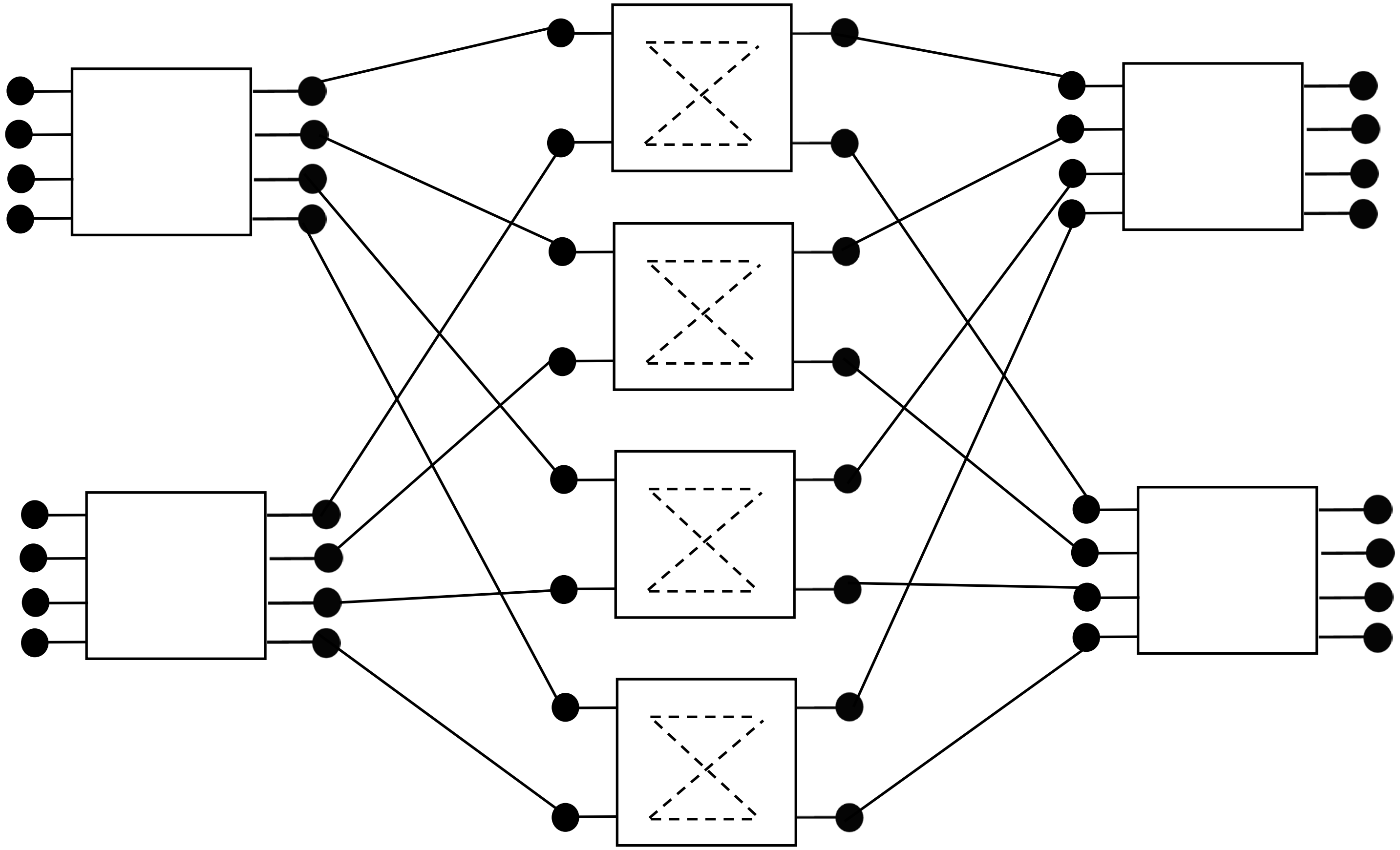
Example 3

- 4x4 switching network with 12 switches (rearrangeable non-blocking)



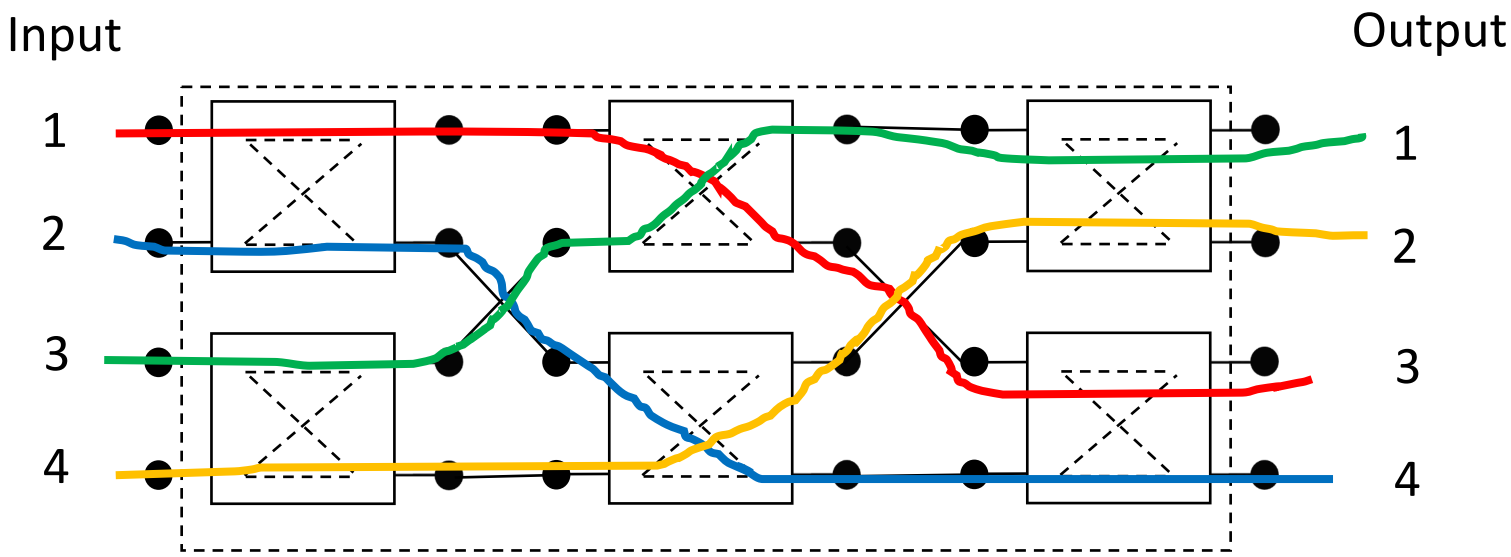
Example 3 (cont'd)

- Four 4x4 switches, and four 2x2 switches (rearrangeable non-blocking)
  - 12x4+4 = 28 2x2 switches



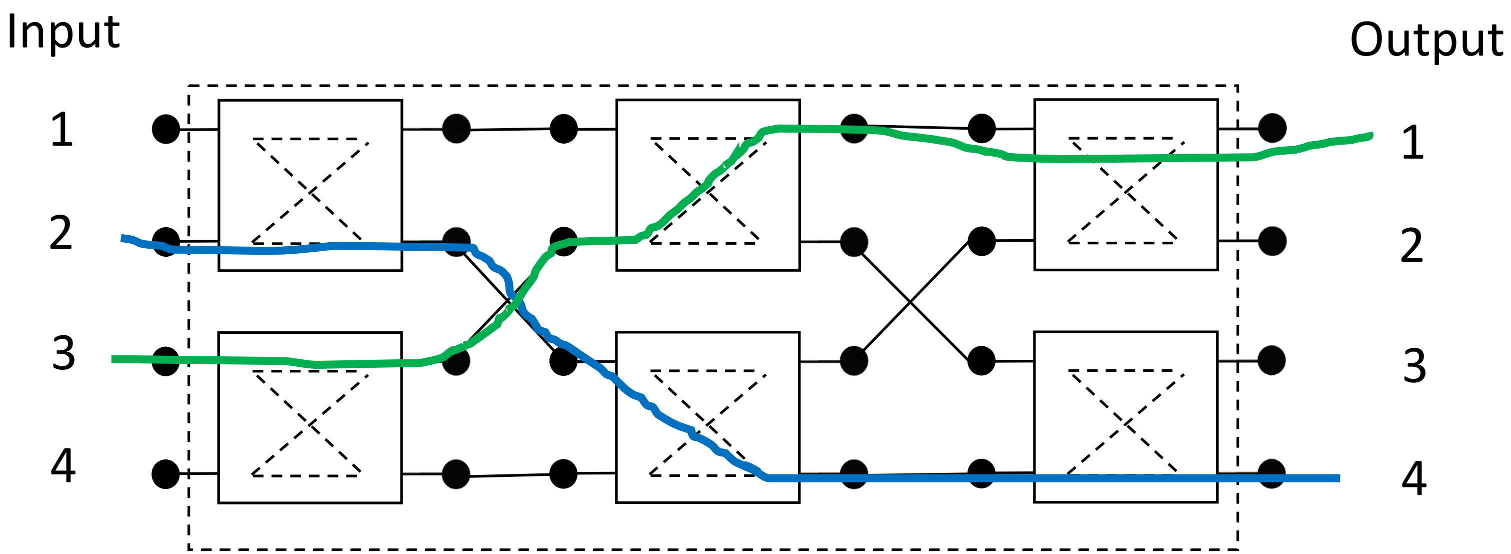
Example 3 (observation)

- What does “rearrangeable non-blocking”?
  - 4x4 switching network with 12 switches (rearrangeable non-blocking)



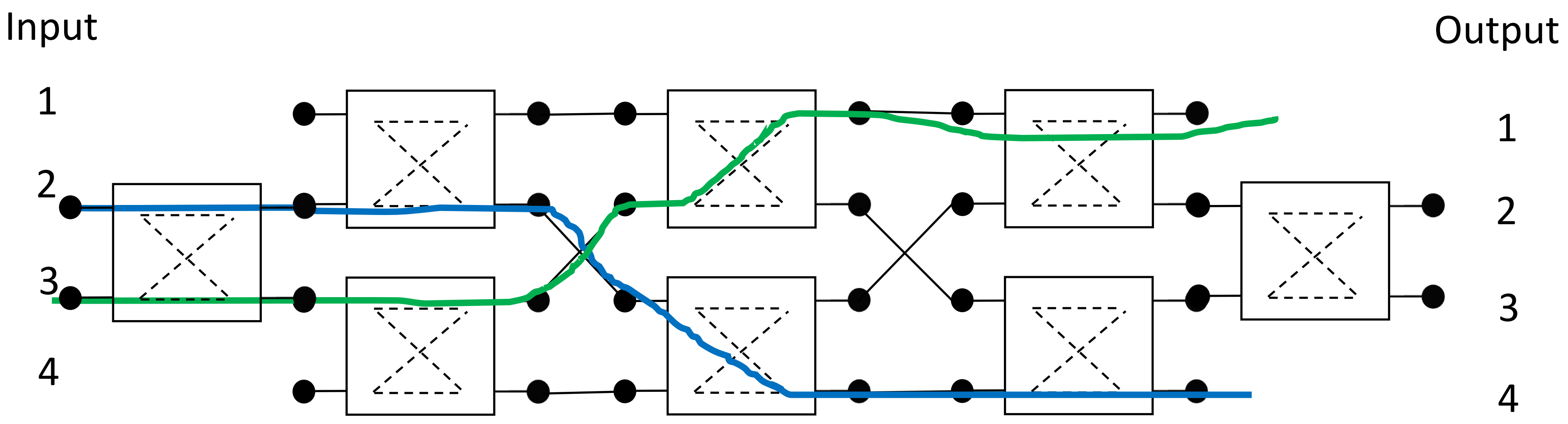
Example 3 (observation, cont’d)

- Suppose that (input 1-output 3) and (input 4-output 2) are disconnected.
- Then, (input 1-output 2) and (input 4-output 3) cannot be connected.



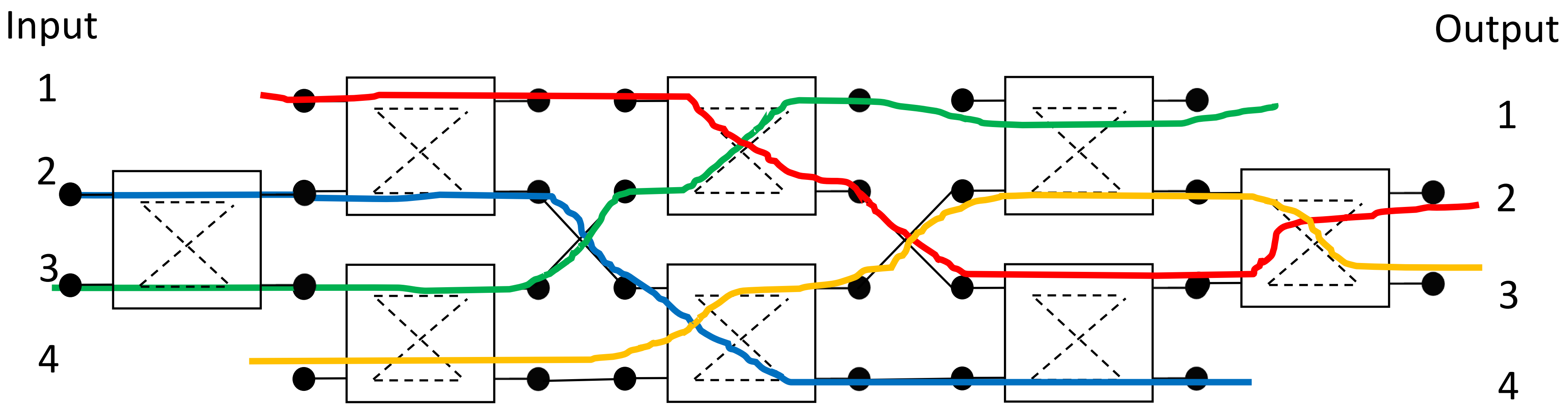
Example 3 (observation, cont'd)

- 4x4 switching network with 12 switches (strict-sense non-blocking)
- Solution:
  - Add two stages (first and fifth stages)



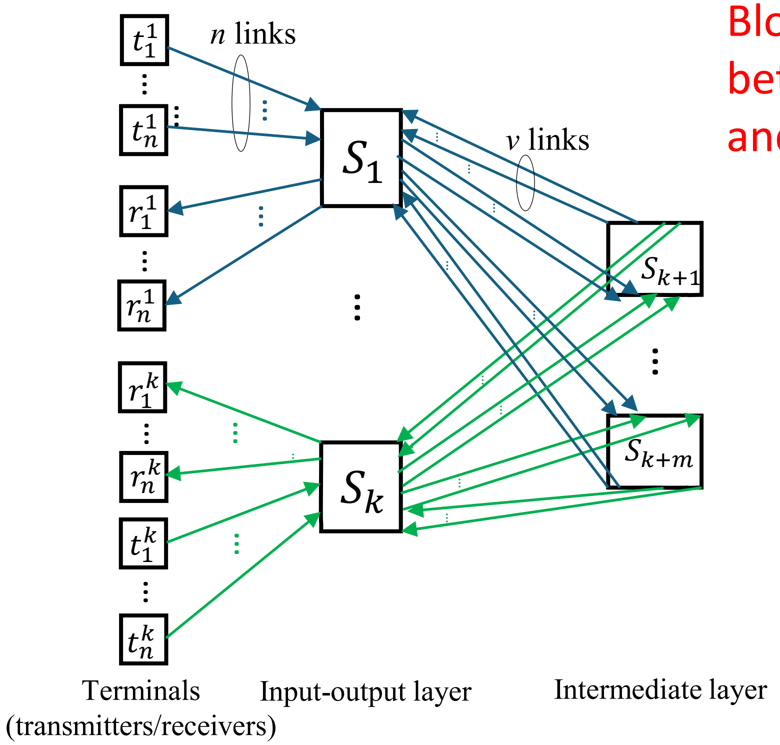
Example 3 (observation, cont'd)

- After (input 1-output 3) and (input 4-output 2) are disconnected, (input 1-output 2) and (input 4-output 3) can be connected.



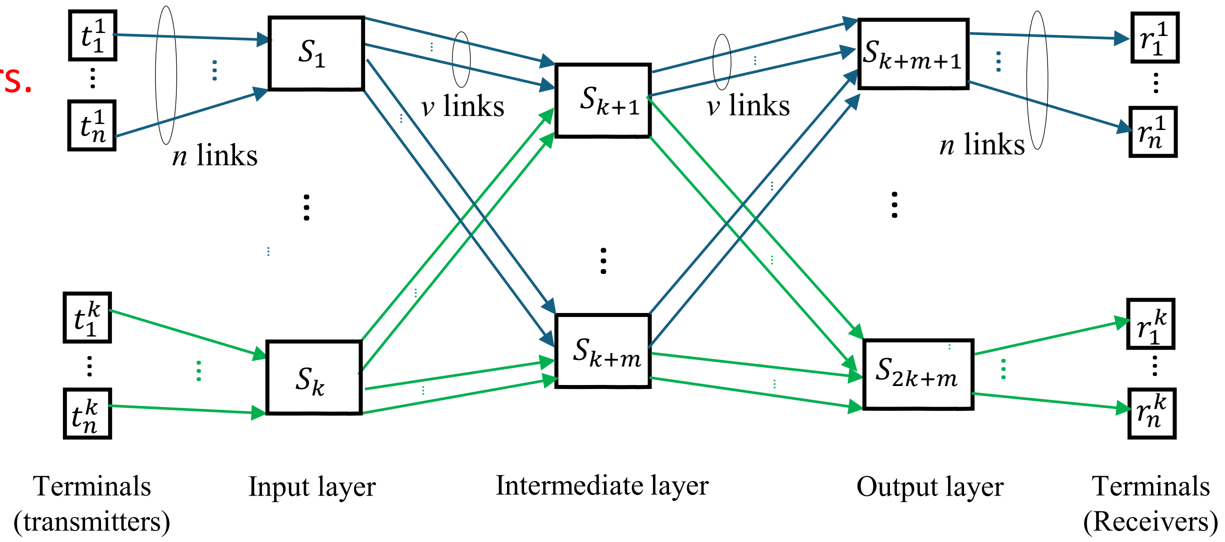
Folded-Clos network (F-Clos) used in datacenter

- F-Clos consists of input-output and intermediate layers.
- A transmitter and receiver pair to be accommodated in a common switch in the input-output layer.
- Datacenters are likely to adopt F-Clos rather than unfolded-Clos (UF-Clos).



Folded-Clos (F-Clos)

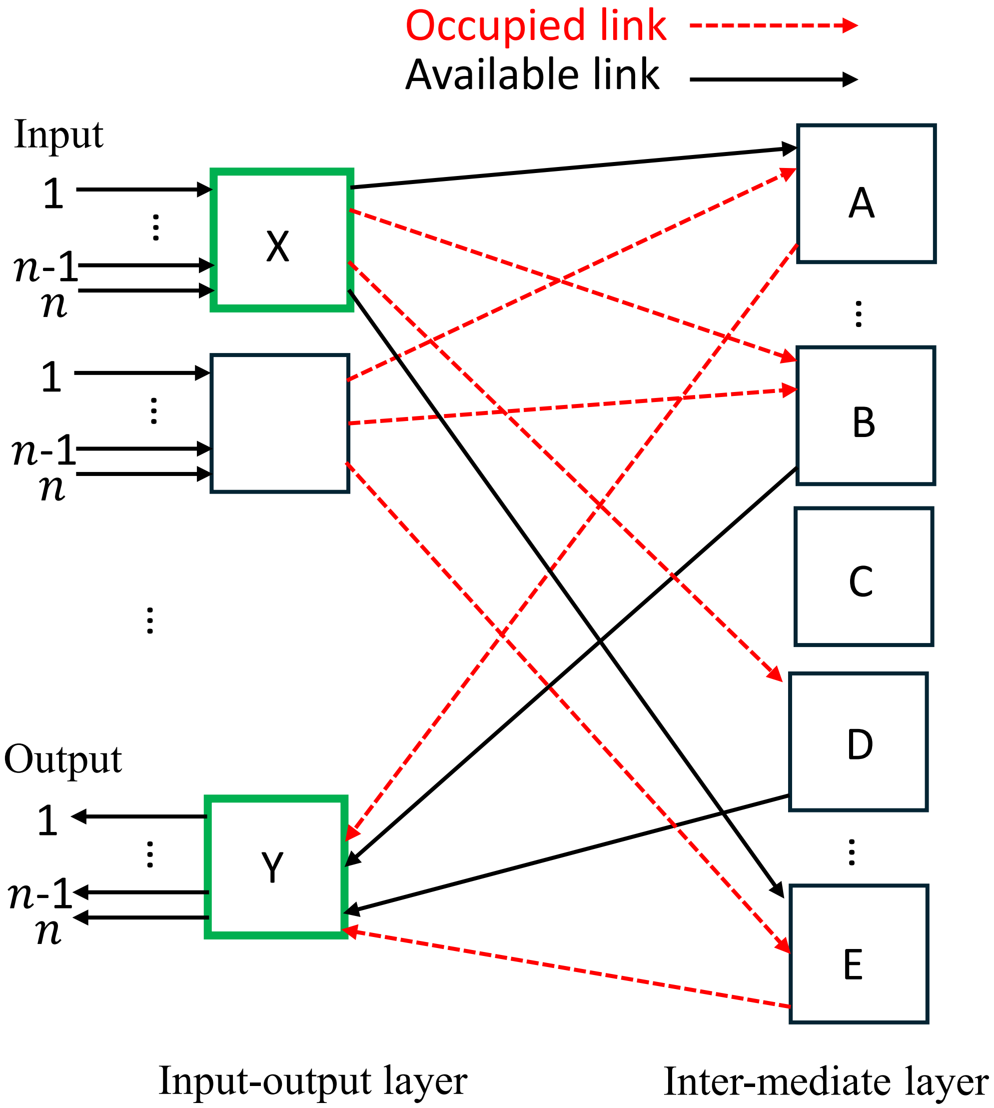
Blocking can occur between input-output and intermediate layers.



Unfolded-Clos (UF-Clos)

Blocking in switching network

- Blocking in switching network
  - A request cannot reach its destination due to switching network usage.
  - Example
    - Consider a request from switch *X* to switch *Y* in the input-output layer.
    - No available route from switch *X* to switch *Y*.



Non-blocking types in switching fabric

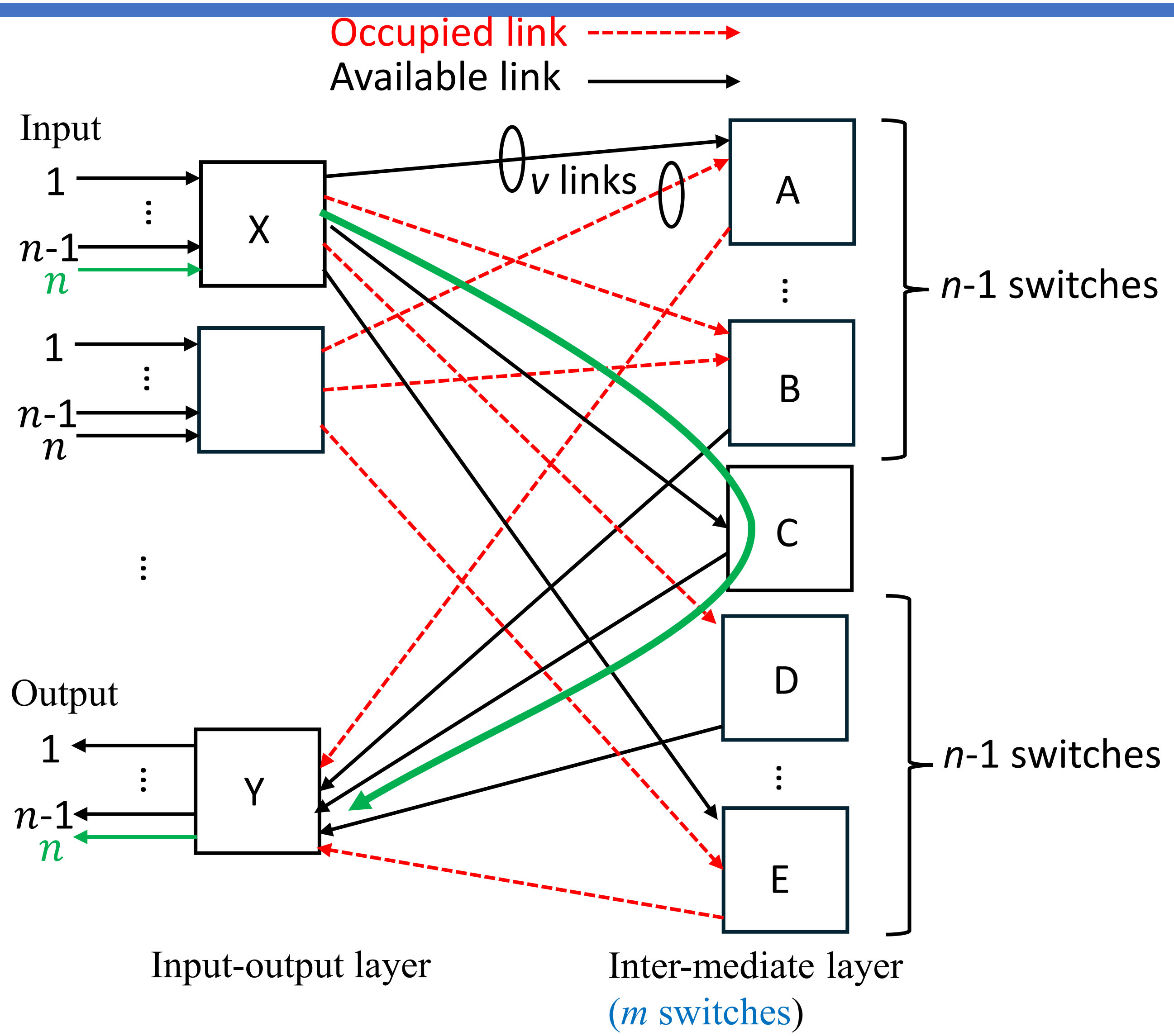
- Strict-sense non-blocking
  - A switching fabric can always connect each idle input port to an arbitrary idle output port independent of its current state and no matter how connecting paths were selected for the existing connections.
- Wise-sense non-blocking
  - A switching fabric can always connect each idle input port to an arbitrary idle output port independent of its current state provided that some given path selection algorithm was used for setting up connections.
- Rearrangeable non-blocking
  - A switching fabric can also always connect each idle input port to an arbitrary idle output port; however, it may be necessary to move existing connections to alternate connecting paths.

Strict non-blocking (SNB) condition

- Strict non-blocking (SNB) condition
  - …
- When $v = 1$
  - $(n-1) + (n-1) + 1 \leq m$

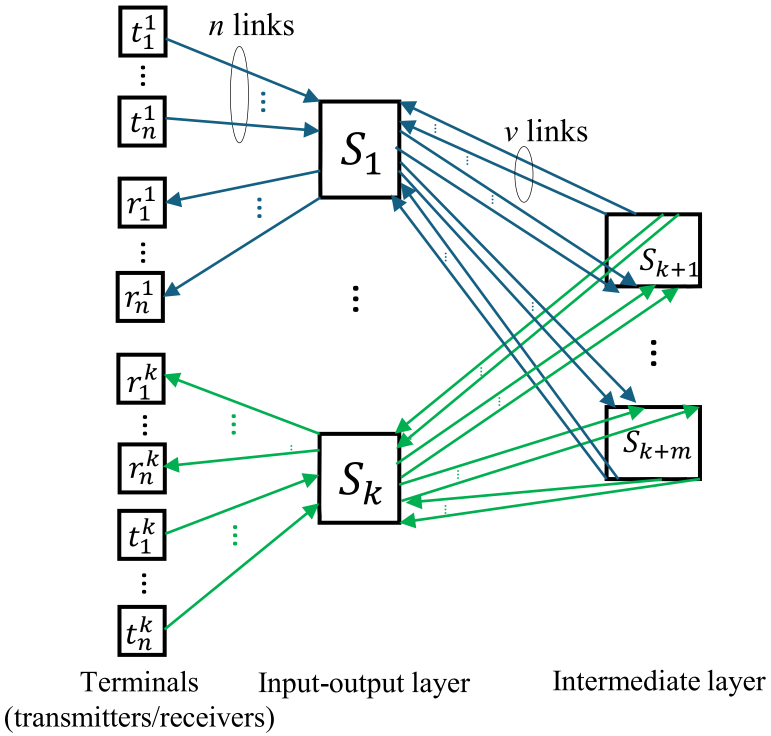
  i.e.,
  - $2n - 1 \leq m$
- When $v \geq 1$
  - $\left\lfloor \frac{n-1}{v} \right\rfloor + \left\lfloor \frac{n-1}{v} \right\rfloor + 1 \leq m$

  i.e.,
  - $2\left\lfloor \frac{n-1}{v} \right\rfloor + 1 \leq m$



[Kabacinski, Springer 2005] W. Kabaciński, *Nonblocking Electronic and Photonic Switching Fabrics*. Springer, 2005.

Design of Folded-Clos (F-Clos) with strict non-blocking (SNB)



Folded-Clos (F-Clos)

$$
\begin{aligned}
\max \quad & nk & \text{(1a)} \\
\text{s.t.} \quad & 2n \le N & \text{(1b)} \\
& 2vm \le N & \text{(1c)} \\
& vk \le N & \text{(1d)} \\
& 2\left\lfloor \frac{n-1}{v} \right\rfloor + 1 \le m & \text{(1e)} \\
& k + m \le a & \text{(1f)} \\
& n, k, m, v \in \mathbb{N}, & \text{(1g)}
\end{aligned}
$$

(1a) Maximize switching network size

(1b)–(1d) Constraint of number of used ports in an $N \times N$ switch

(1e) Strict non-blocking (SNB) condition

(1f) Limitation of number of usable $N \times N$ switches

Given conditions
- Use identical $N \times N$ switches.
- The number of usable $N \times N$ switches, a, is given.

Objective:
Maximize the switching network size, nk.

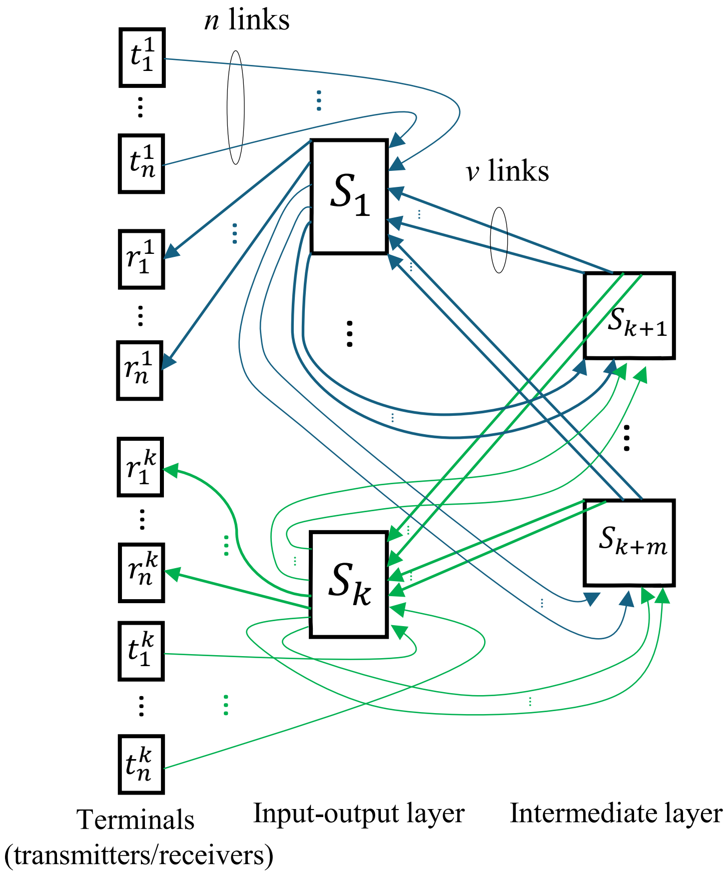
Parameters	Descriptions
N	Number of ports in a switch.
a	Number of usable switches.

Variables	Descriptions
n	Natural. It is the number of ports used in an input-output switch*.
k	Natural. It is the number of input-output switches.
m	Integer. It is the number of intermediate switches.
v	Integer. It is the number of links between an input-output switch and an intermediate switch.

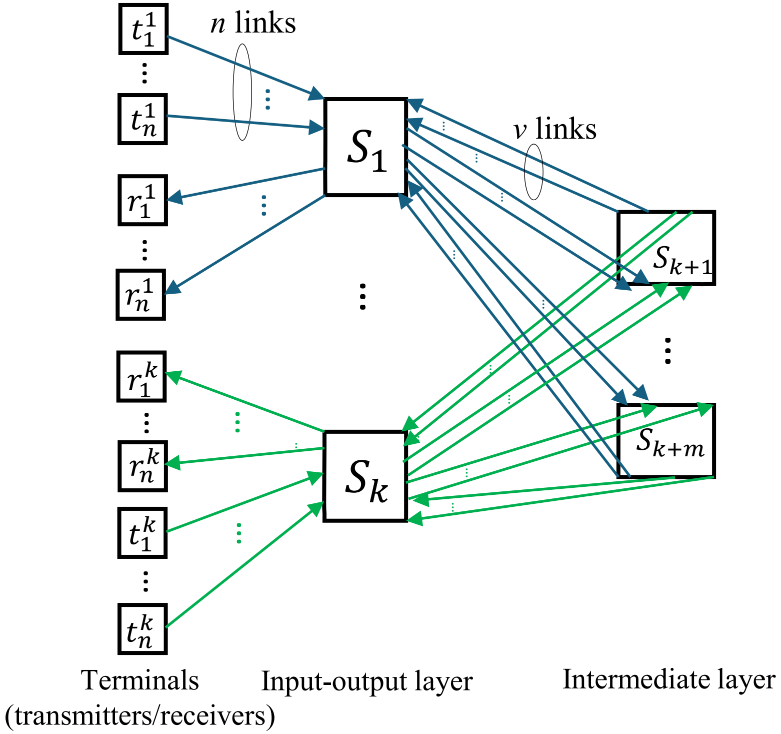
Twisted-folded Clos network (TF-Clos) [T. Mano, GLOBECOM 2019, TNSM 2023]

- F-Clos has a limitation regarding the number of ports in an input-output switch to maximize the switching network size.
- TF-Clos relaxes the limitation by introducing the idea of *twisting*.

[Mano, TNSM 2023] T. Mano, T. Inoue, K. Mizutani, and O. Akashi, “Redesigning the nonblocking Clos network to increase its capacity,” *IEEE Trans. Netw. Service Manag.*, vol. 20, no. 3, pp. 2558–2574, Sep. 2023.



Twisted-folded-Clos (F-Clos)



Folded-Clos (F-Clos)

Checking differences between TF-Clos and F-Clos with strict non-blocking (SNB)

- Twisted-folded-Clos (TF-Clos)

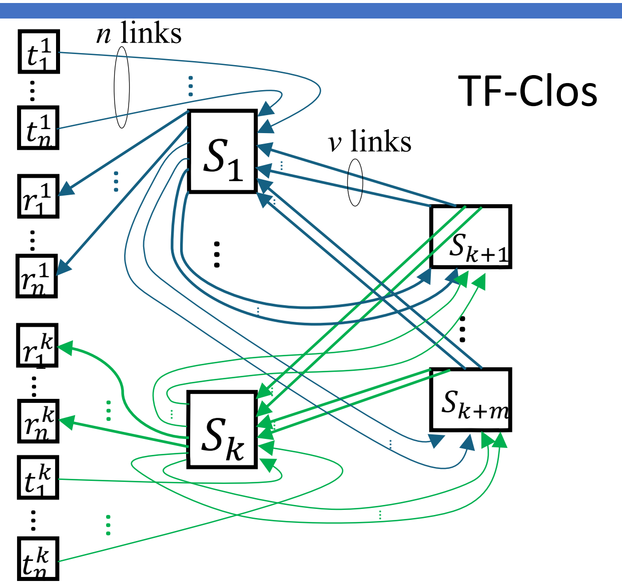
$$
\begin{aligned}
\max \quad & nk && \text{(2a)} \\
\text{s.t.} \quad & n + vm \leq N && \text{(2b)} \\
& vk \leq N && \text{(2c)} \\
& 2\left\lfloor \tfrac{n-1}{v} \right\rfloor + 1 \leq m && \text{(2d)} \\
& k + m \leq a && \text{(2e)} \\
& n, k, m, v \in \mathbb{N}. && \text{(2f)}
\end{aligned}
$$

(2a) Maximize switching network size

(2b)–(2c) Constraint of number of used ports in an $N \times N$ switch -> Relaxed by twisting

(2d) Strict non-blocking (SNB) condition

(2e) Limitation of number of usable $N \times N$ switches



- Folded-Clos (F-Clos)

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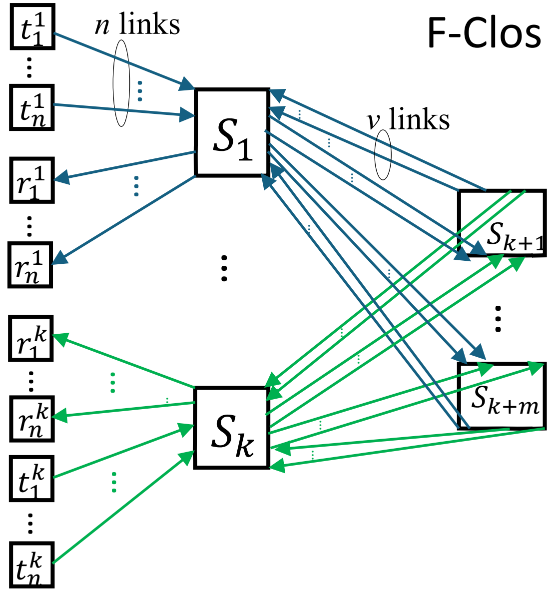
$$

(1a) Maximize switching network size

(1b)–(1d) Constraint of number of used ports in an $N \times N$ switch

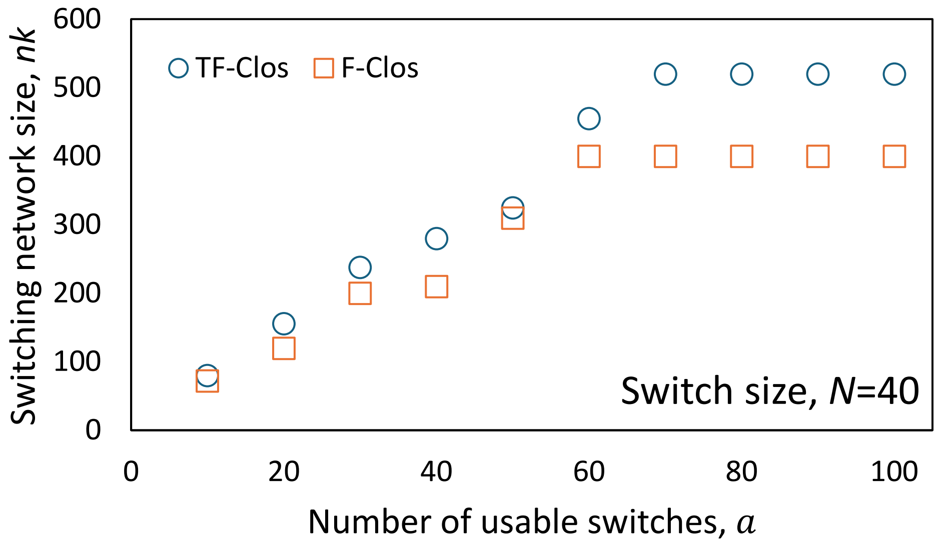
(1e) Strict non-blocking (SNB) condition

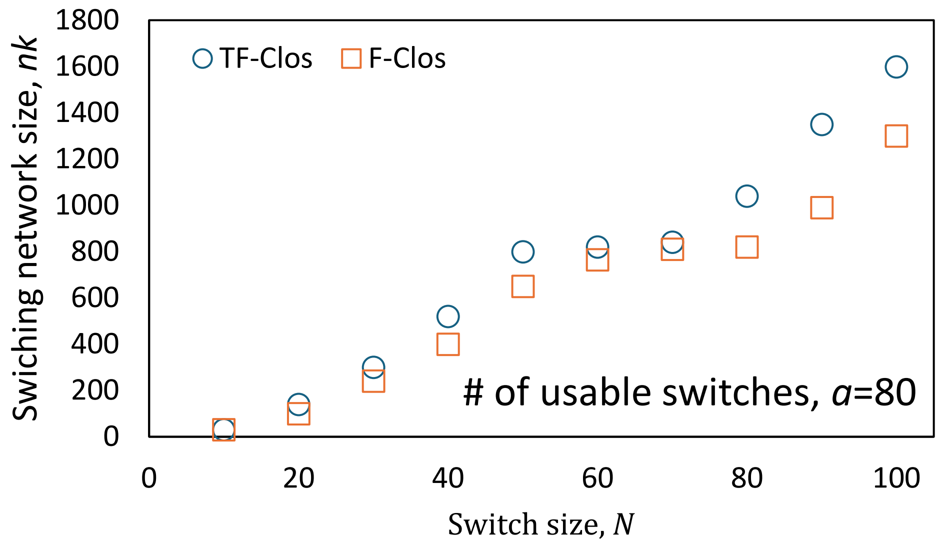
(1f) Limitation of number of usable $N \times N$ switches



Switching network size of TF-Clos and F-Clos with SNB

- Twisted-folded-Clos (TF-Clos) has a larger switching network size than folded-Clos (F-Clos).
  - TF-Clos relaxes the port restriction by *twisting*.





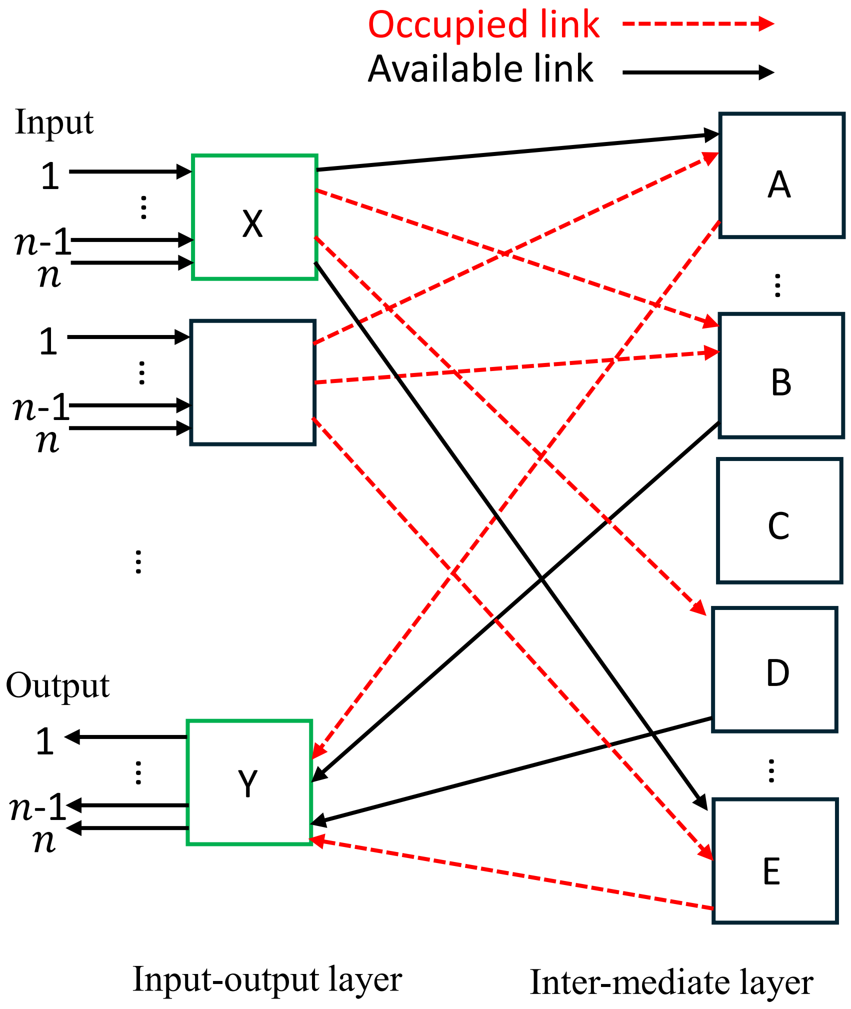
SNB: strict non-blocking

Tolerates blocking to some extent

- While guaranteeing non blocking in TF-Clos has the advantage that any blocking does not occur, the available switching network size tends to be small.
  - Strict non-blocking (SNB) condition is too strict.
    - SNB condition still limits increasing switching network size
- A network structure that tolerates blocking to some extent is expected to allow for a more flexible design.
- We want to analyze the blocking probability for a switching network while keeping the network quality.

Difficulty in analyzing blocking probability

- Analyzing exact blocking probability has not been achieved so far.
  - Both links are not available from an input to an output.
    - Two blocking points
  - Occupation behavior of both links are not independent.
- Previous studies approximately analyzed blocking probability [Lee, Bell 1995][Yang, 1998]
  - Introducing the assumption of independent behavior.
  - However, no guarantee the conservativeness.
    - No theoretical upper bound of blocking probability was given.



[Lee, Bell 1995] C. Y. Lee, “Analysis of switching networks,” Bell Syst. Tech. J., vol. 34, no. 6, pp. 1287–1315, Nov. 1955.
[Yang, 1998] Y. Yang and N. H. Kessler, “Modelling the blocking behaviour of Clos networks,” in Proc. DIMACS Ser. Discrete Math. Theor. Comput. Sci., vol. 42, 1998, pp. 85–102.

Problem statement

- Can we design TF-Clos that guarantees an admissible blocking probability to maximize the switching network size?
  - Key parameters given in advance by a network designer
    - An admissible blocking probability, ε
      - Maximum allowable blocking probability
    - Number of available switches, a
      - Each switch size: $N \times N$
  - A blocking probability is defined as:
    - the probability that a connection request generated at a terminal connected to an input port is blocked due to internal blocking in the switching network.

TF Clos design models to guarantee admissible blocking probability

- One-step design model (basic model) [Taka, NL 2023]
  - This model firstly provided the design model that theoretically guarantees admissible blocking probability.
- Two-step design model [Taka, NL 2024]
  - Extended version of the one-step model.
  - This model ensures an admissible blocking probability in a two-step manner
- *S*-step design model [Taka, JOCN 2024] [Oki, ICTON 2024]
  - Generalizing the number of steps

[Taka, NL 2023] H. Taka, T. Inoue, and E. Oki, "Design of twisted and folded Clos network with guaranteeing admissible blocking probability,"
IEEE Netw. Lett., vol. 5, no. 4, pp. 265–269, Dec. 2023.
[Taka, NL 2024] H. Taka, T. Inoue, and E. Oki, "Twisted and folded Clos-network design model with twostep blocking probability guarantee," *IEEE Netw. Lett.*, vol. 6, no. 1, pp. 60–64, Mar. 2024.
[Taka, NL 2024] H. Taka, T. Inoue, and E. Oki, "Design model of twisted and folded Clos network with multi-step grouped intermediate switches guaranteeing admissible blocking probability," *J. Opt. Commun. Netw.*, vol. 16, no. 3, pp. 328–341, Mar. 2024.

Admissible blocking probability (ABP) guarantee

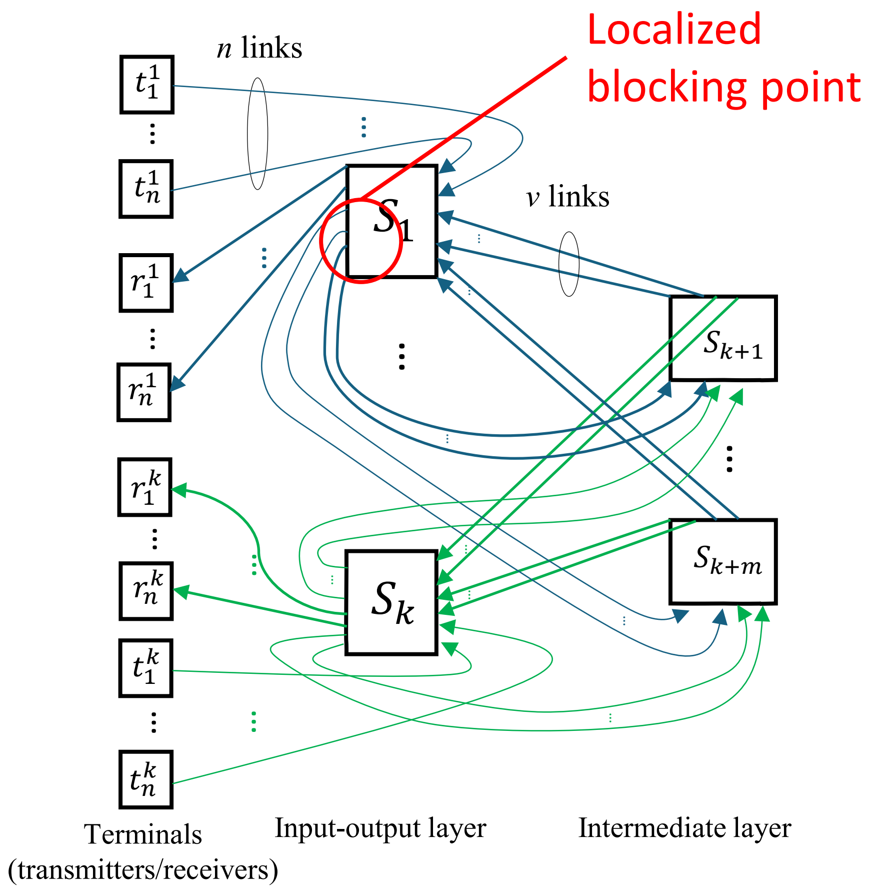
- Given parameters
  - Admissible blocking probability: ϵ
  - Request arrival rate at each port: p
- Strict non-blocking (SNB) condition

$$2\left\lfloor \frac{n-1}{v} \right\rfloor + 1 \leq m$$

- Introducing condition for admissible blocking probability guarantee

$$\sum_{w=n^{\mathrm{snb}}+1}^{n} \binom{n}{w} p^{w}(1-p)^{n-w} \leq \epsilon$$

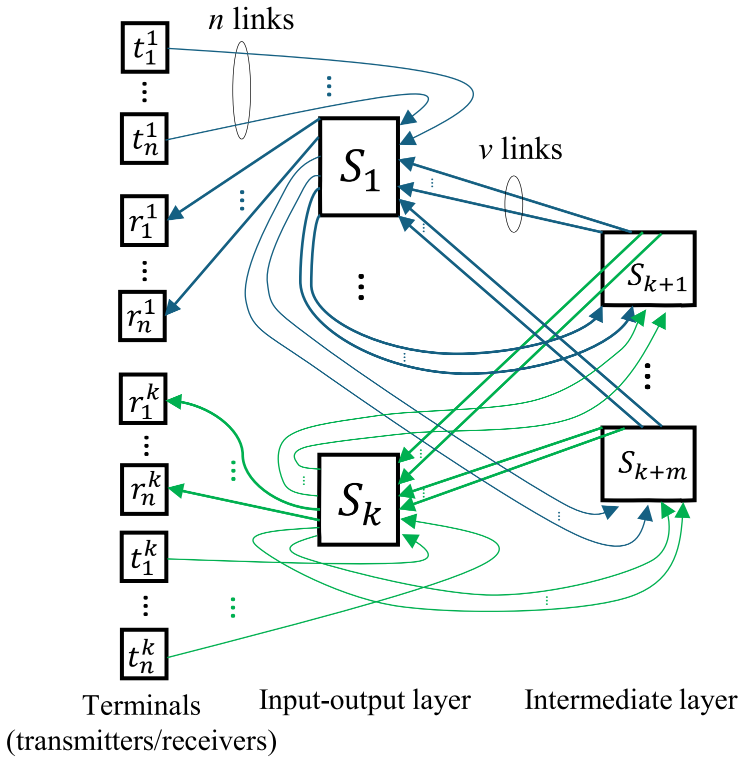
$$2\left\lfloor \frac{n^{\mathrm{snb}}-1}{v} \right\rfloor + 1 \leq m$$



n^{SNB} is a newly introduced decision variable.

n^{SNB} decreases as ϵ increases and p decreases. This relaxes the constraint of TF-Clos design.

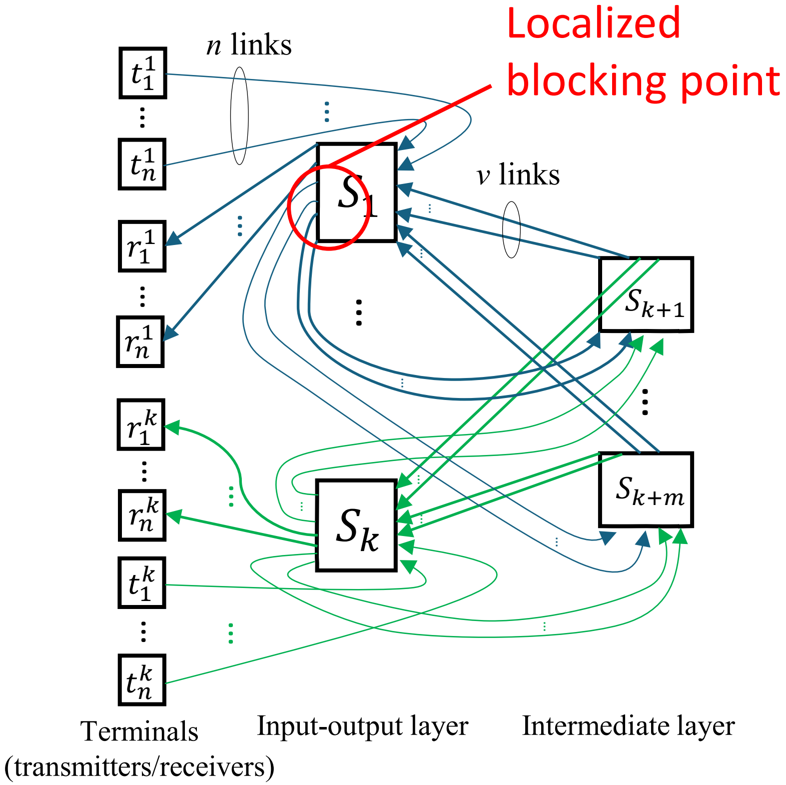
Given parameters and decision variables for TF Clos design to guarantee admissible blocking probability



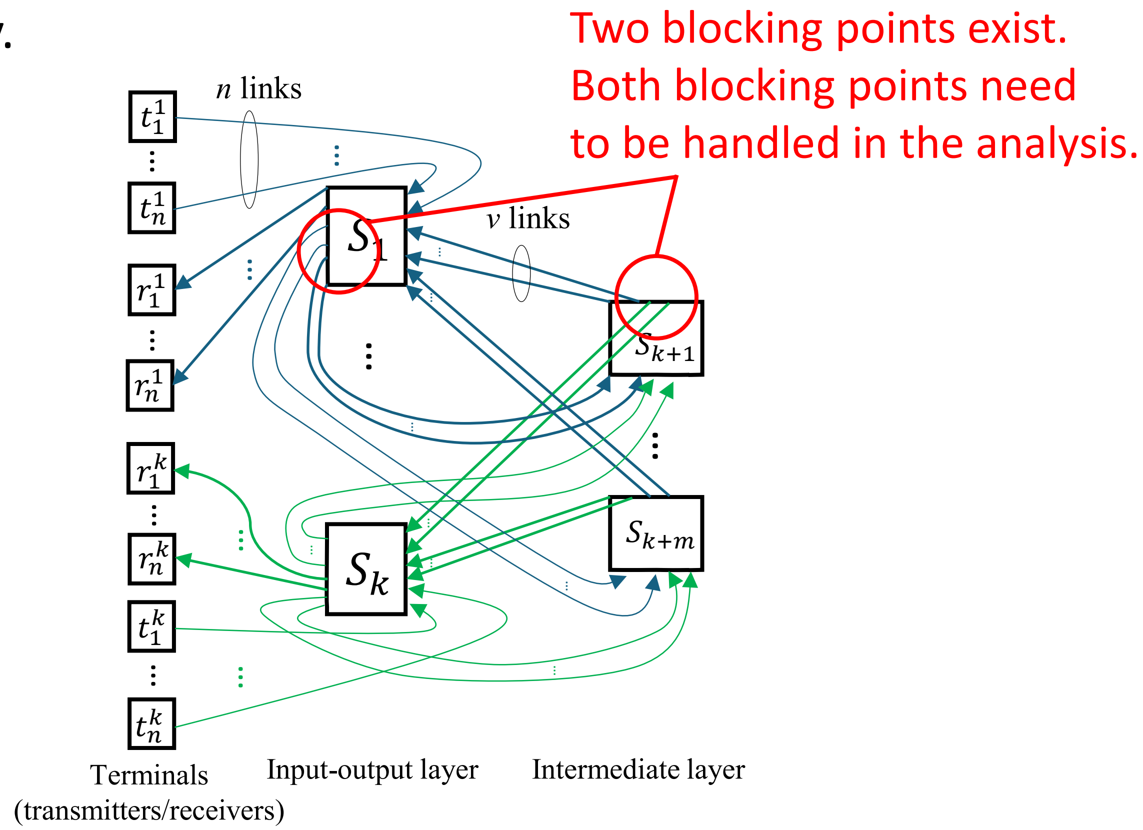
Parameters	Descriptions
N	Number of ports in a switch.
a	Number of usable switches.
p	Probability of request arrival rate.
ϵ	Admissible blocking probability (ABP).
Variables	**Descriptions**
n	Natural. It is the number of ports used in an input-output switch*.
n^{snb}	Integer. It is the number of ports that satisfy the strict-sense non-blocking (SNB) condition.
k	Natural. It is the number of input-output switches.
m	Integer. It is the number of intermediate switches.
v	Integer. It is the number of links between an input-output switch and an intermediate switch.

Comparison between our blocking-localized design model and conventional blocking analytical strategy

- Our design model localizes one blocking points.
  - Achieving blocking probability guarantee strictly.
- The conventional blocking analytical strategy needs to handle two blocking points.
  - Not achieving blocking probability guarantee strictly.



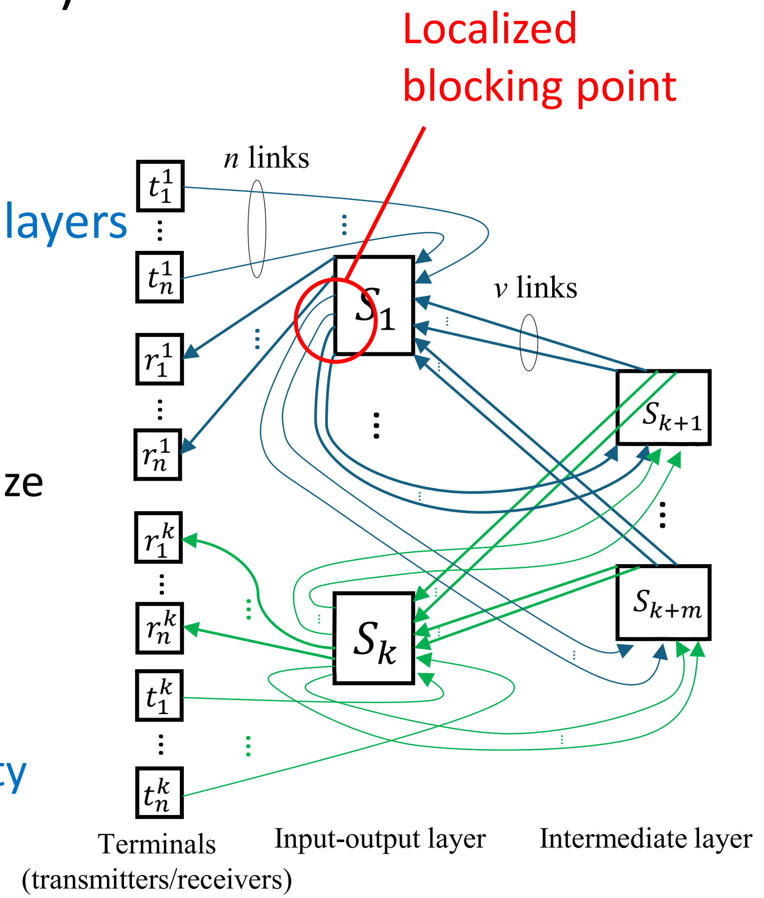
Our blocking-localized design model [Taka, NL 2023]



Conventional blocking analytical strategy

One-step TF-Clos design model guaranteeing admissible blocking probability (ABP)

- The APB guarantee condition replaces the strict non-blocking (SNB) condition.
- If an arriving request violate the APB condition, it is blocked.
  - Blocking point is localized at each input-output switch.
  - SNB condition remains for links between input-output and intermediate layers
  - The admission process is one step.
- This local blocking management guarantees APB.



$$
\begin{aligned}
\max \quad & nk && \text{(5a)} \\
\text{s.t.} \quad & n + vm \le N && \text{(5b)} \\
& vk \le N && \text{(5c)} \\
& \sum_{w=n^{\text{snb}}+1}^{n} \binom{n}{w} p^{w}(1-p)^{n-w} \le \epsilon && \text{(5d)} \\
& 2\left\lfloor \frac{n^{\text{snb}}-1}{v} \right\rfloor + 1 \le m && \text{(5e)} \\
& k + m \le a && \text{(5f)} \\
& n, n^{\text{snb}}, k, m, v \in \mathbb{N}. && \text{(5g)}
\end{aligned}
$$

(5a): Maximize switching network size

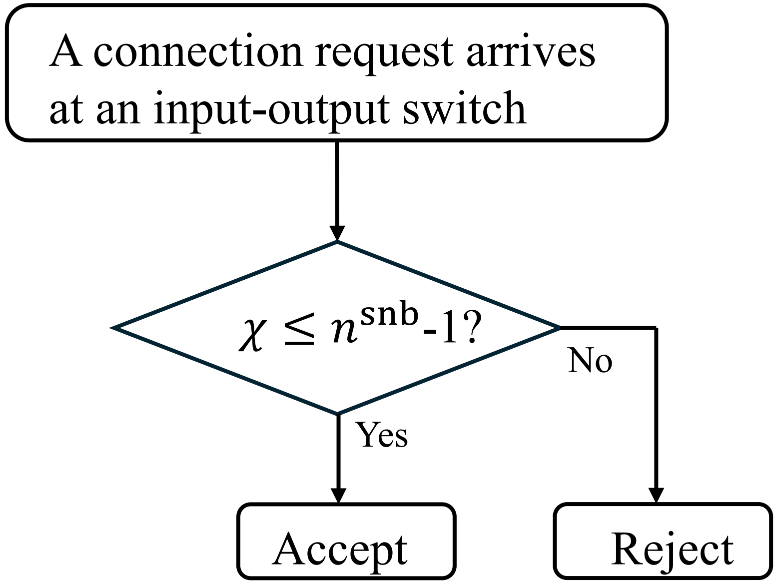
(5b)–(5c): Constraint of number of used ports in an $N \times N$ switch
-> Relaxed by twisting

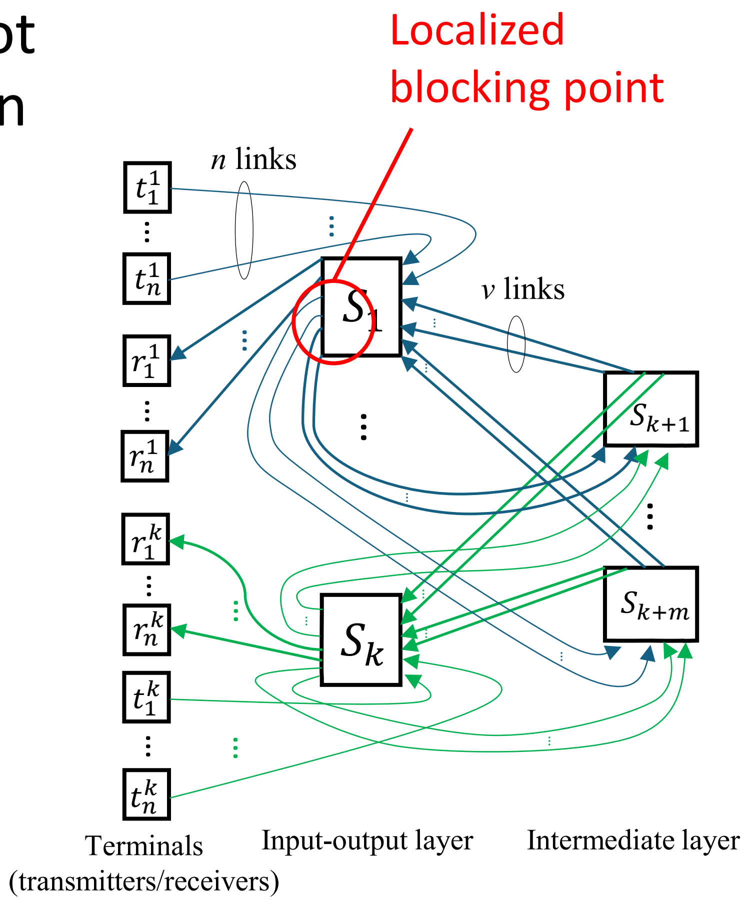
(5d)–(5e): Admissible blocking probability guarantee

(5f): Limitation of number of available $N \times N$ switches

Request admission in one-step design model

- If the number of occupied links from the input-output switch to all intermediate switches, denoted by χ, does not exceed n^{snb}-1, the request is accepted, and the connection is established, and otherwise rejected.

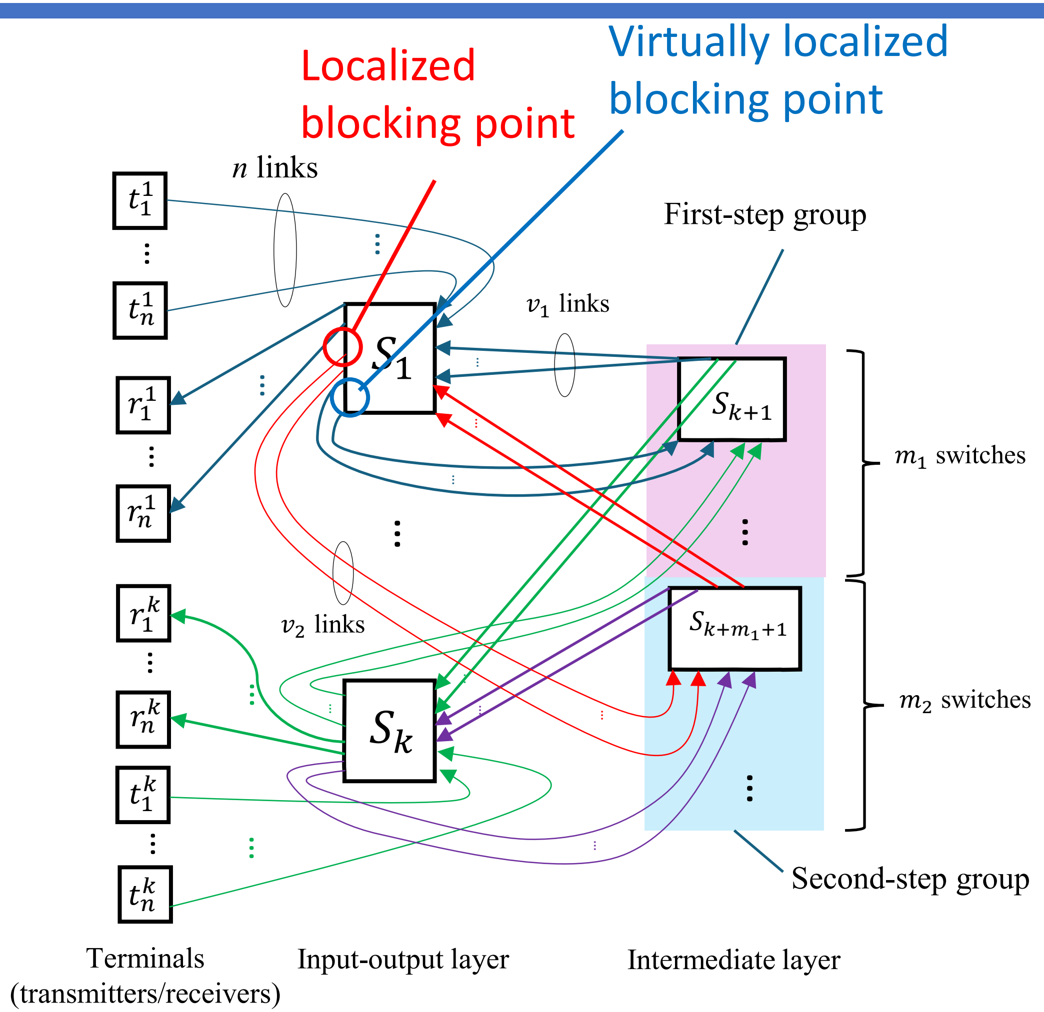




χ: Number of occupied links from the input-output switch to all intermediate switches.

Two-step design model [Taka, NL 2024]

- The admission process is performed by two steps to ensure an admissible blocking probability.
- Categorizes intermediate switches into two groups to alleviate the constraints of the optimization problem.
  - The first group requests are routed first. The second-step group to which requests are routed after they are blocked in the first-step group.
  - In this way, the admissible blocking probability is guaranteed.

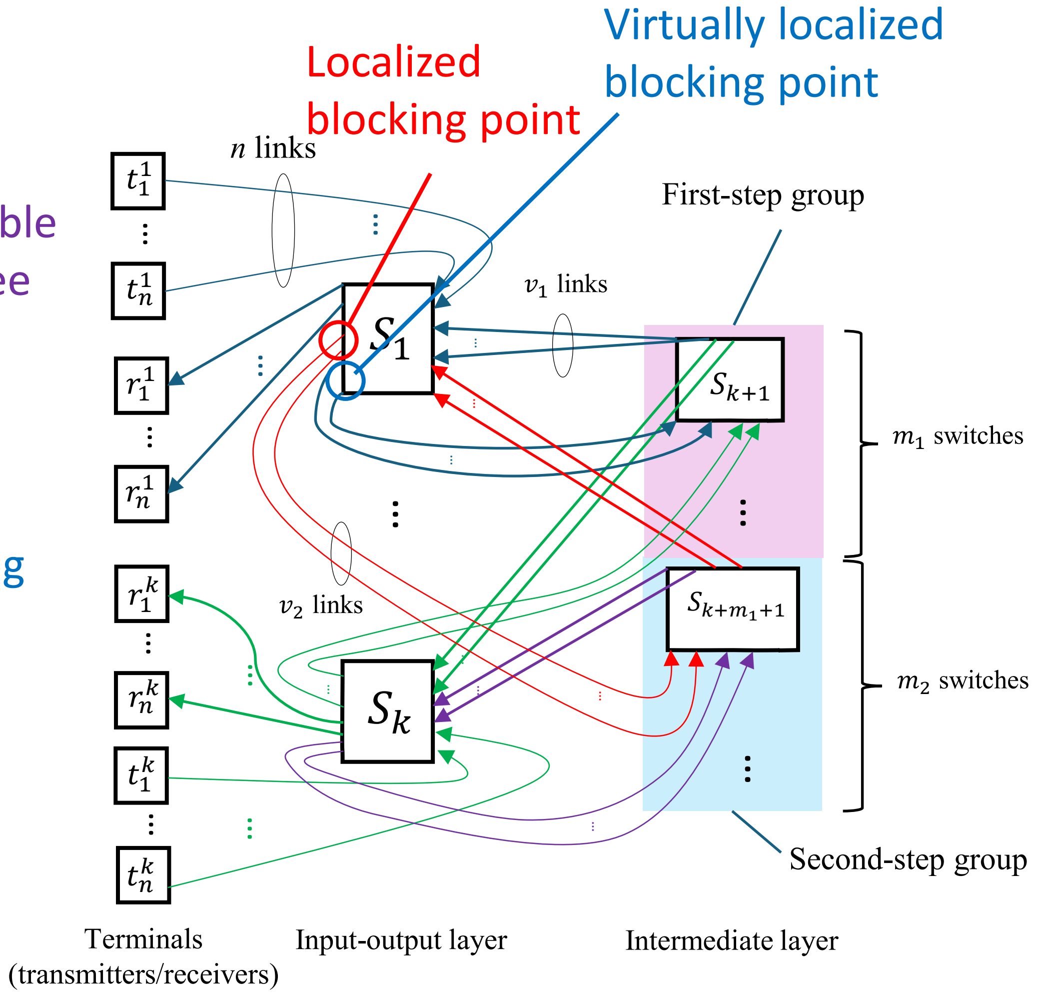


Formulation of two-step design model

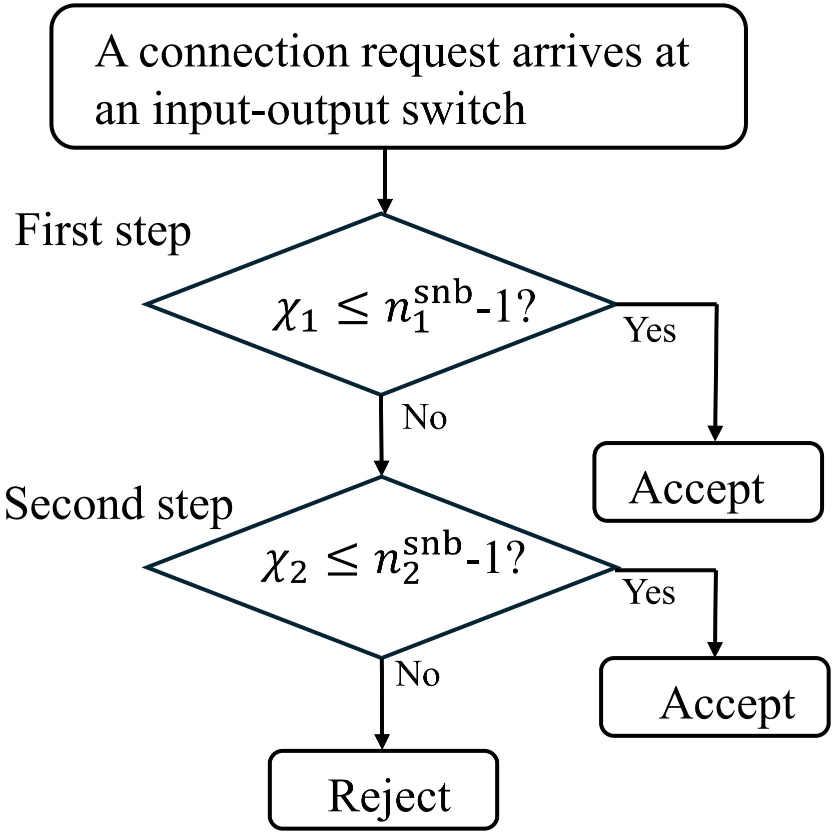
$$
\begin{aligned}
\max\quad & nk && \text{(5a)}\\
\text{s.t.}\quad & n + v_1 m_1 + v_2 m_2 \leq N && \text{(5b)}\\
& v_1 k \leq N && \text{(5c)}\\
& v_2 k \leq N && \text{(5d)}\\
& \sum_{w=n_1^{\mathrm{snb}}+1}^{n} \binom{n}{w} p^w (1-p)^{n-w} \leq \begin{cases} \epsilon_1, & \text{if } m_2 > 0 \\ \epsilon, & \text{if } m_2 = 0 \end{cases} && \text{(5e)}\\
& 2\left\lfloor \frac{n_1^{\mathrm{snb}}-1}{v_1} \right\rfloor + 1 \leq m_1 && \text{(5f)}\\
& \sum_{w=n_2^{\mathrm{snb}}+1}^{n-n_1^{\mathrm{snb}}} \binom{n-n_1^{\mathrm{snb}}}{w} (\epsilon_1 p)^w \\
& \quad \times (1-\epsilon_1 p)^{n-n_1^{\mathrm{snb}}-w} \leq \epsilon, \text{ if } m_2 > 0 && \text{(5g)}\\
& 2\left\lfloor \frac{n_2^{\mathrm{snb}}-1}{v_2} \right\rfloor + 1 \leq m_2 && \text{(5h)}\\
& k + m_1 + m_2 \leq a && \text{(5i)}\\
& \epsilon \leq \epsilon_1 \leq 1 && \text{(5j)}\\
& n, n_1^{\mathrm{snb}}, k, v_1, v_2, m_1 \in \mathbb{N} && \text{(5k)}\\
& n_2^{\mathrm{snb}}, m_2 \in \mathbb{N} \cup \{0\} && \text{(5l)}\\
& \epsilon_1 \in \mathbb{R}, && \text{(5m)}
\end{aligned}
$$

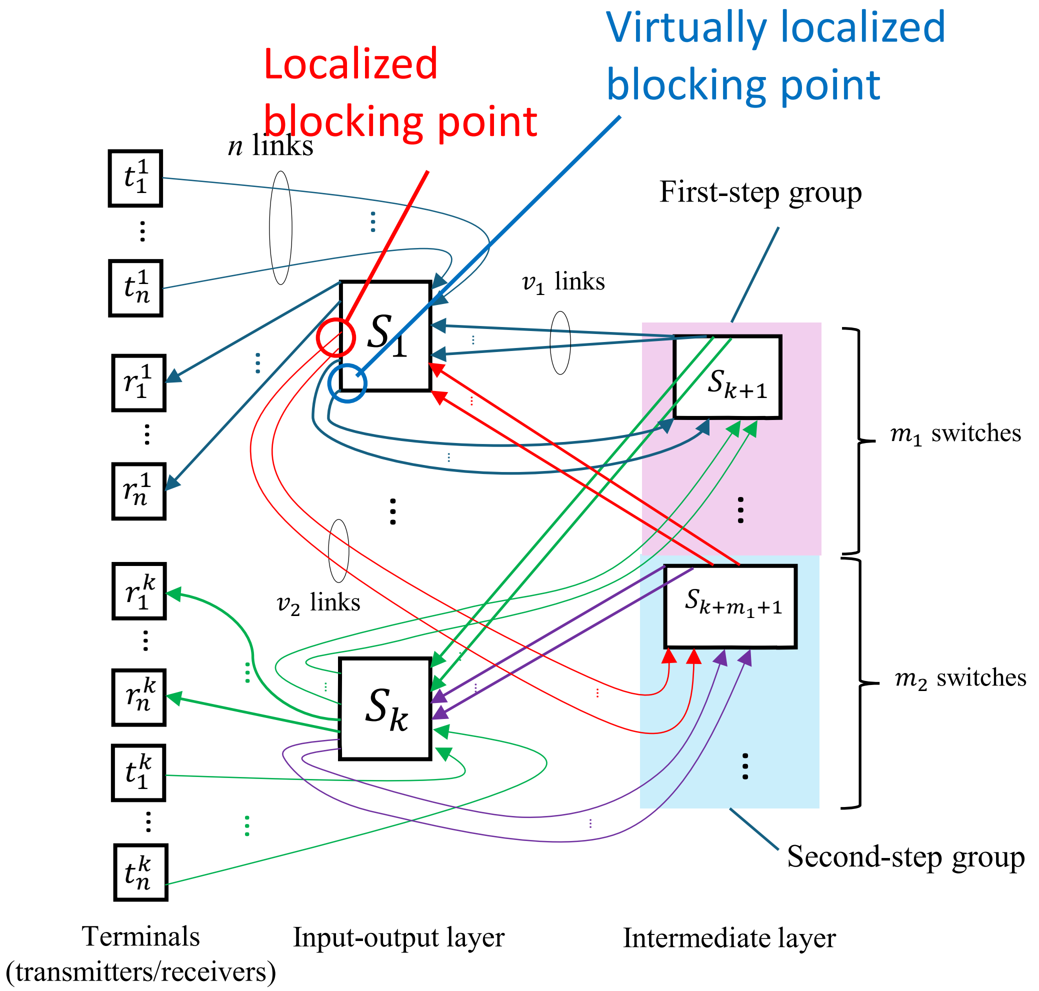
First-step admissible blocking guarantee

Second-step admissible blocking guarantee



Request admission in two-step design model

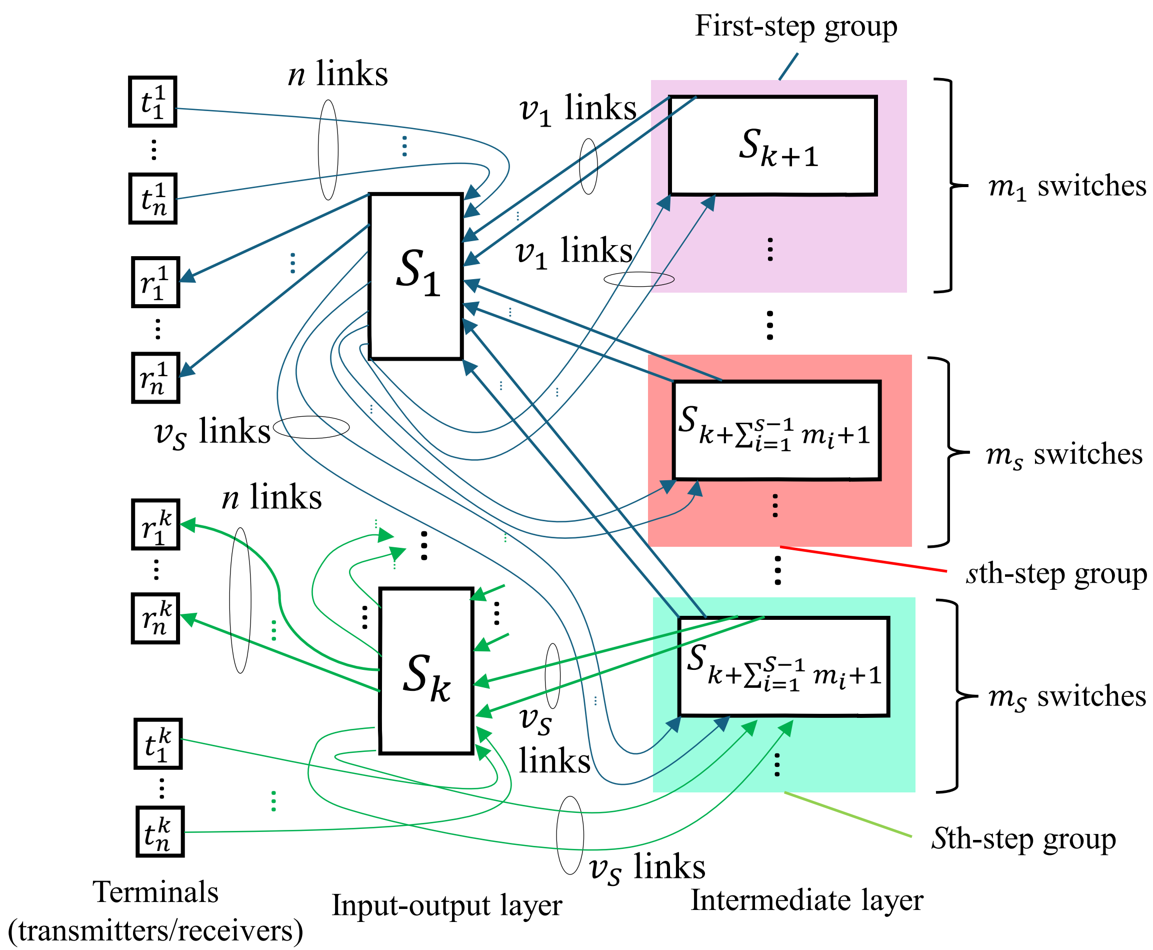




χ_s: Number of occupied links from the input-output switch in the sth step to all intermediate switches.

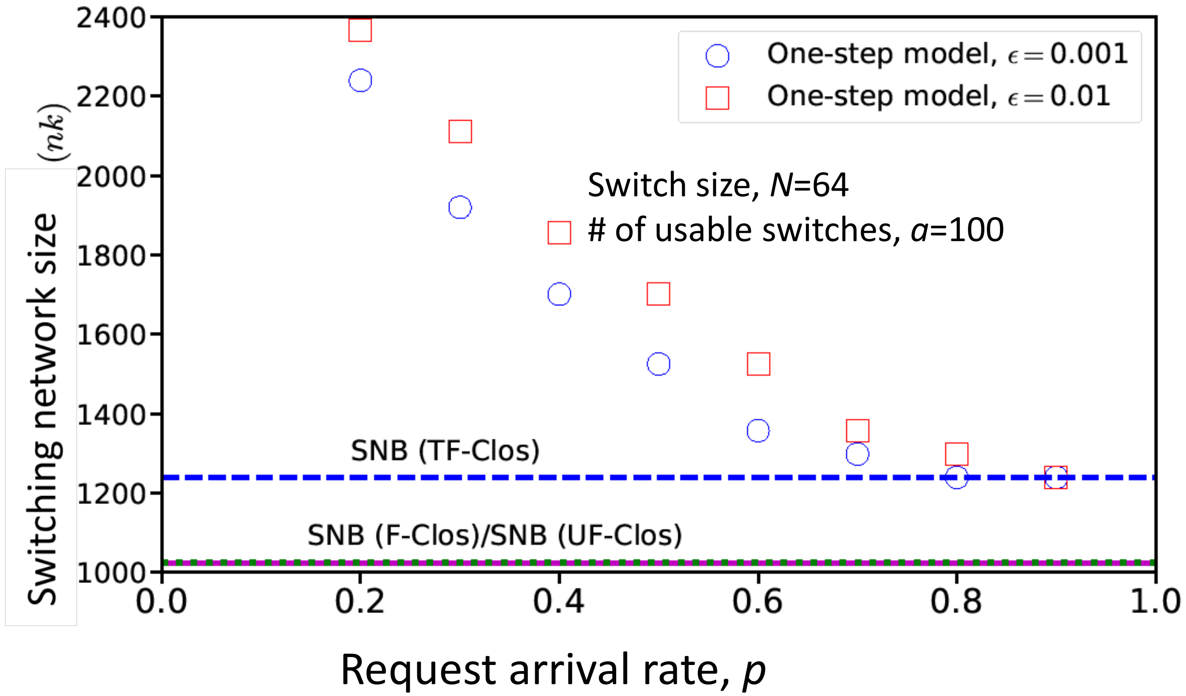
S-step design model [Taka, JOCN 2024] [Oki, ICTON 2024]

- The S-step model expands upon the two-step model, creating a more generalized TF-Clos design model that allows for varying the number of steps for intermediate switches.
- The admission process is performed by S steps to ensure an admissible blocking probability.
- Intermediate switches are partitioned into a maximum of S groups.
- [Oki, ICTON 2024] refines the constraints in the S-step design model.

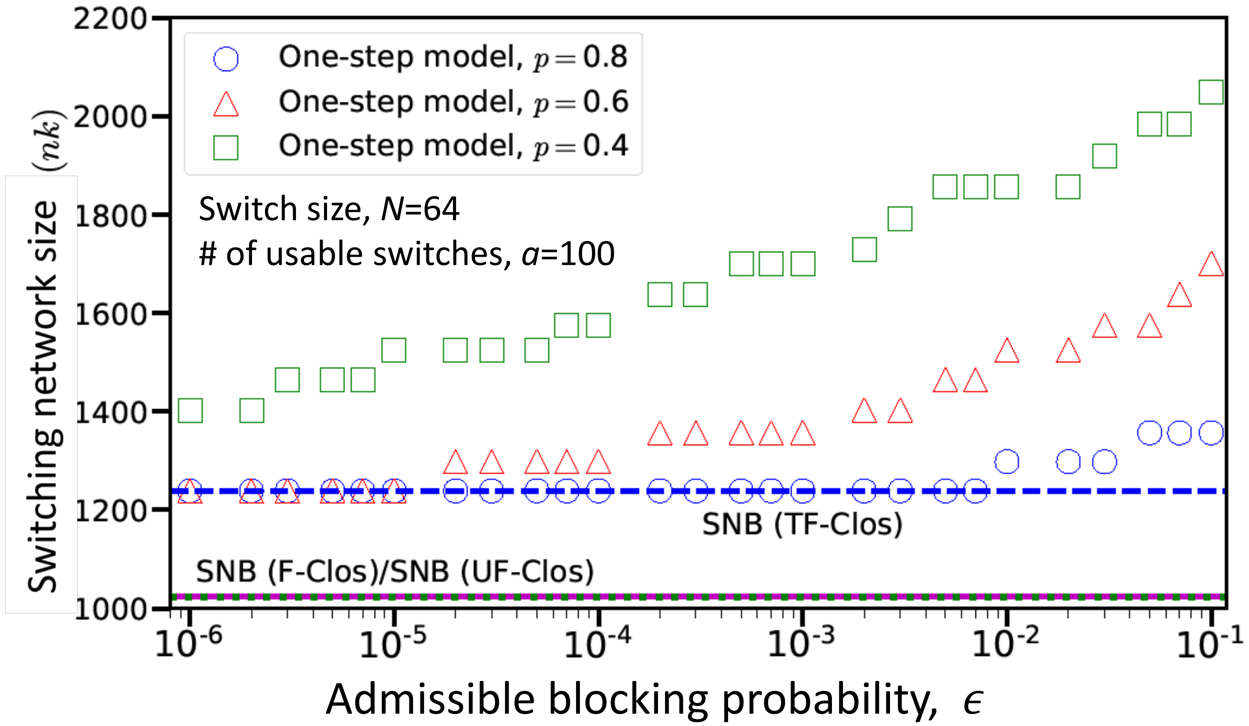


Performance of one-step design model guaranteeing admissible blocking probability (ABP)

- The one-step design model increases the switching network size as an arrival request rate decreases.
  - One-step model is a special case of *S*-



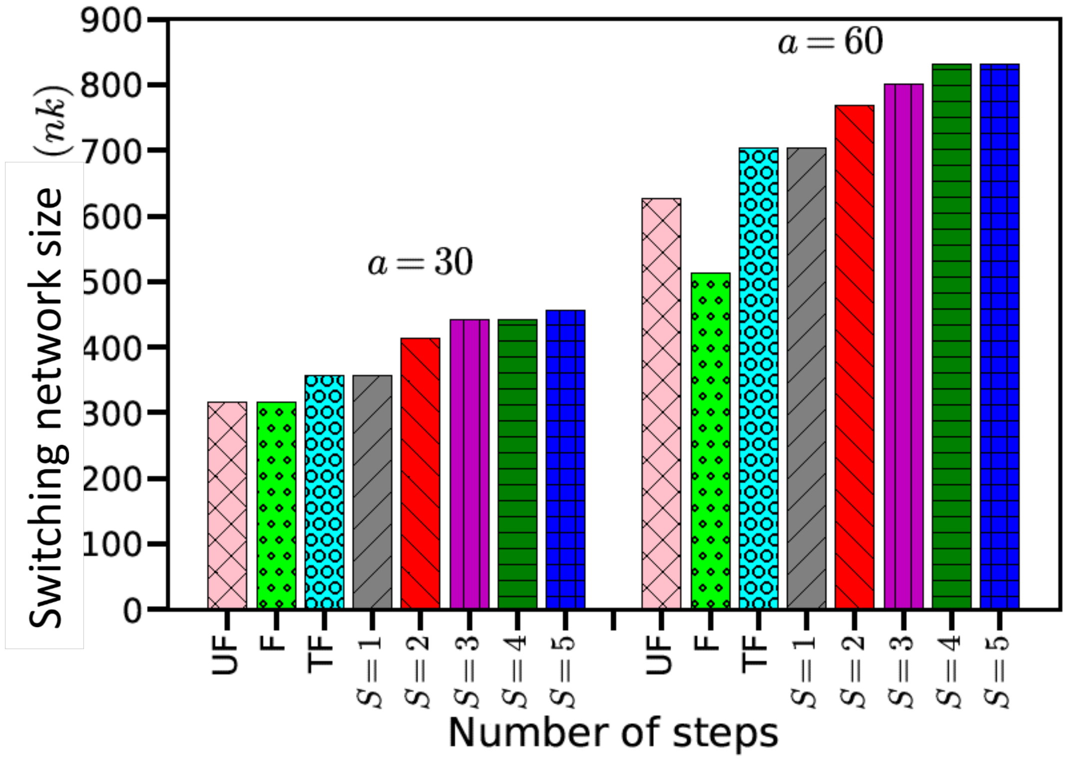
- The one-step design model increases the switching network size as ϵ increass.

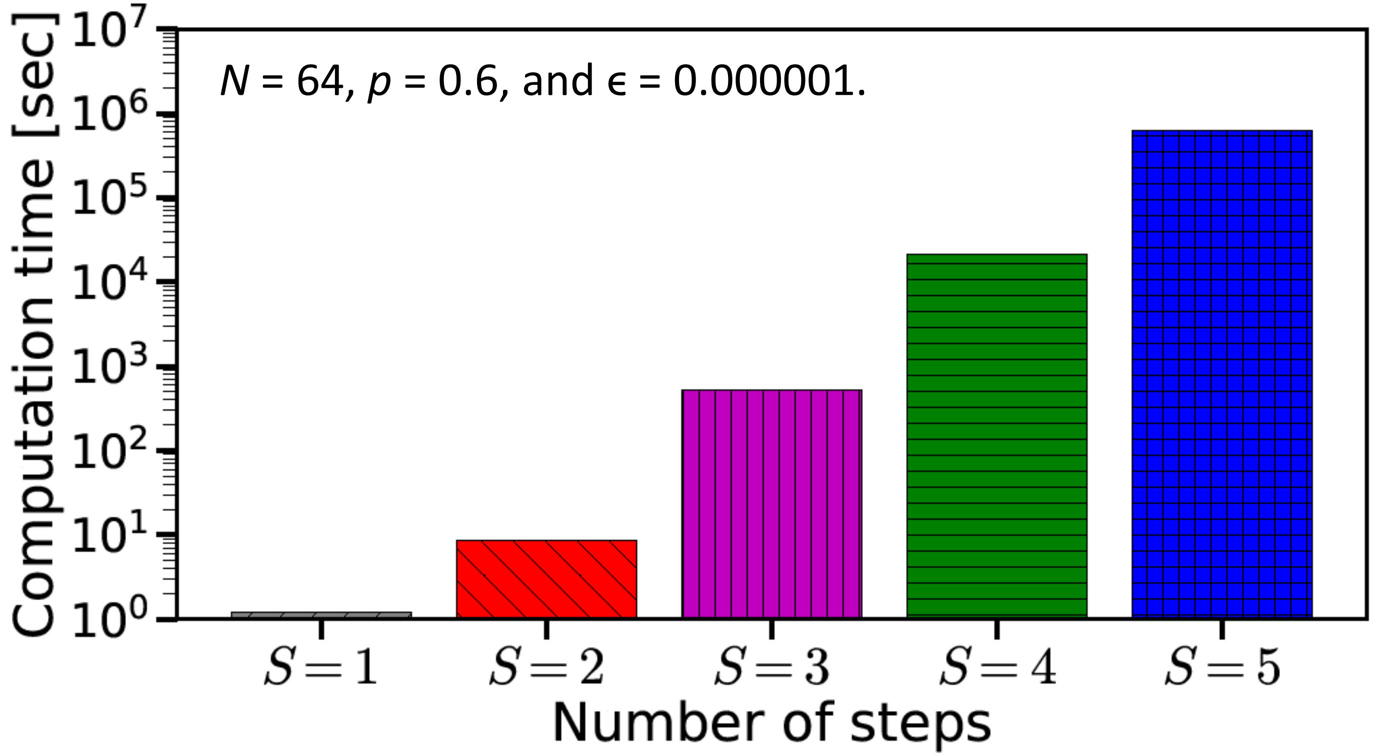


SNB: strict non-blocking
F-Clos: folded Clos, UF-Clos: unfolded Clos

Performance of *S*-step design model guaranteeing admissible blocking probability (ABP)

- The *S*-step design model increases the switching capacity as the number of steps, *S*, increases.
  - The computation time increases in an increase of *S*.

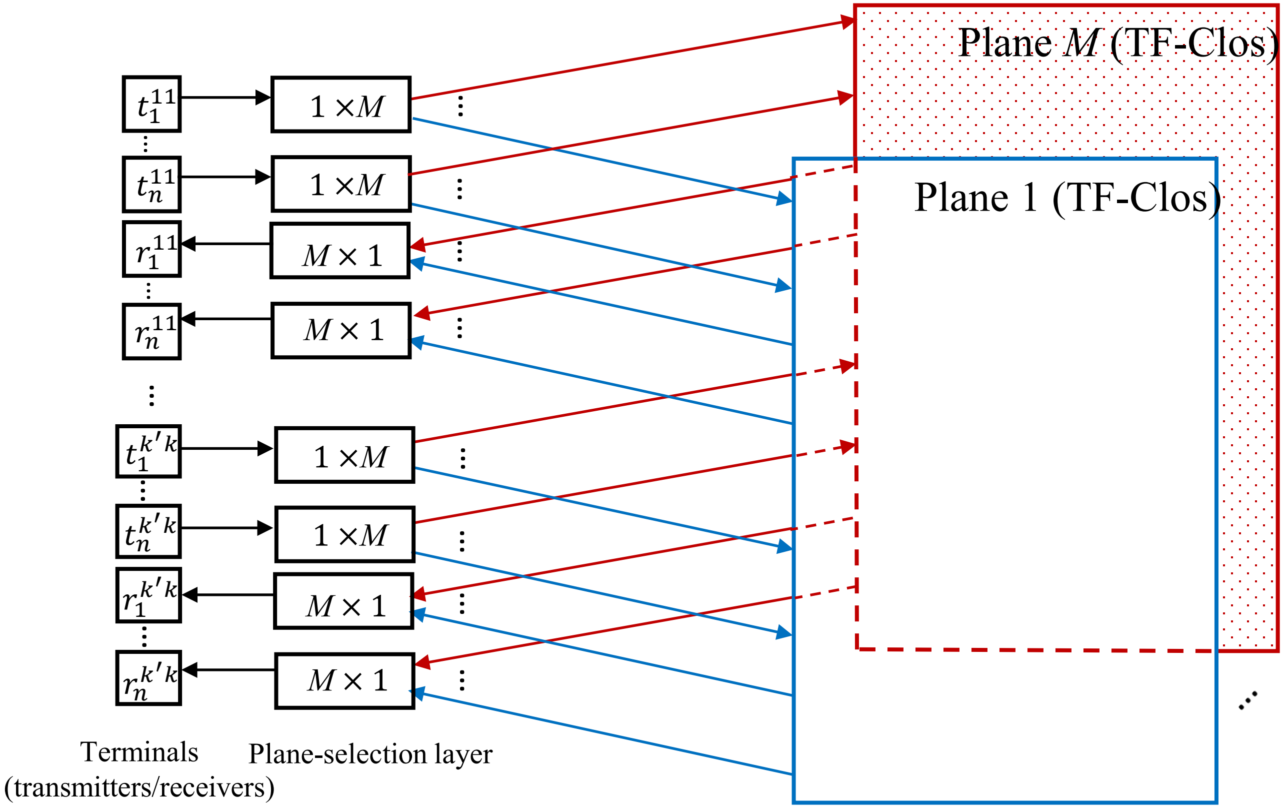




SNB: strict non-blocking
TF: twisted folded Clos, F: folded Clos, UF: unfolded Clos

Further expanding switching network size: Increasing number of planes [Oki, TNSM 2024]

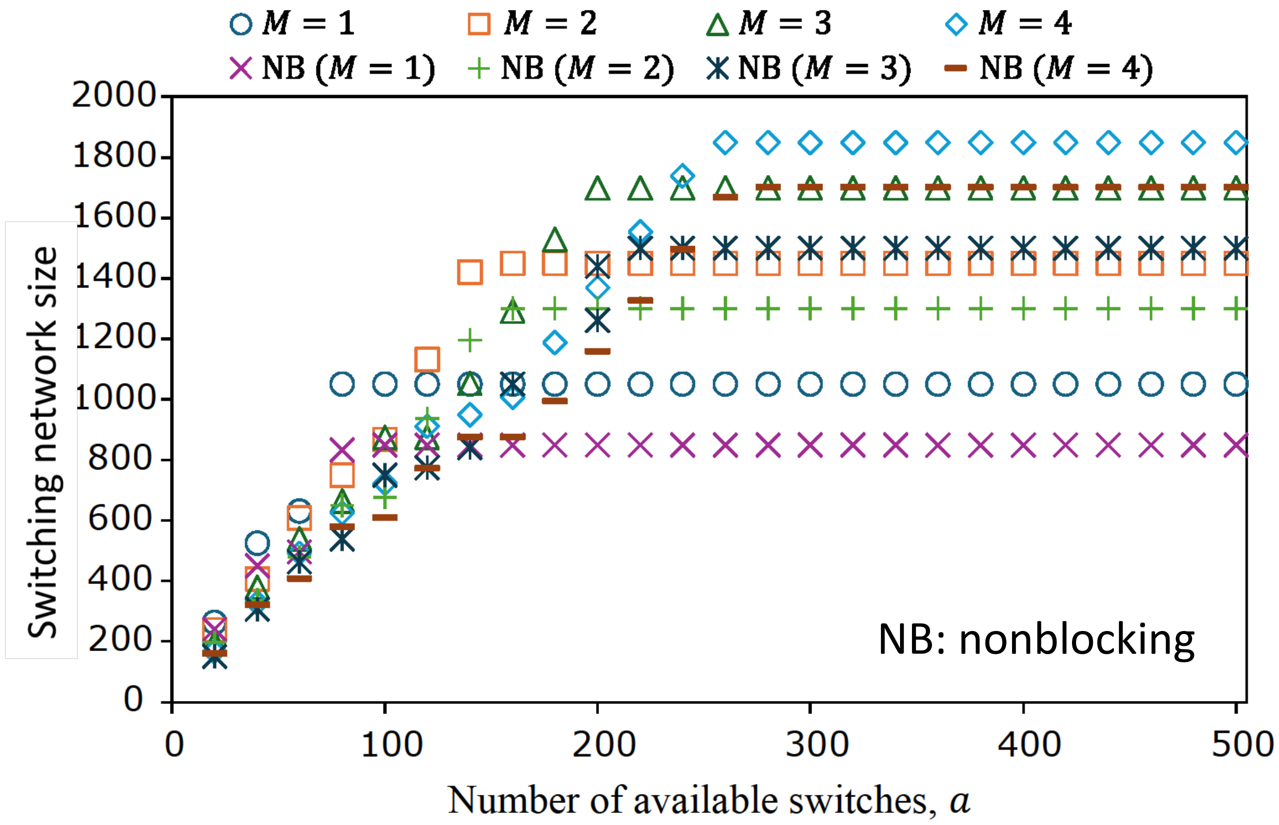
- Parallelizing TF-Clos into multiple planes
  - Utilizing multiple planes expands the switching network size compared to a single plane.

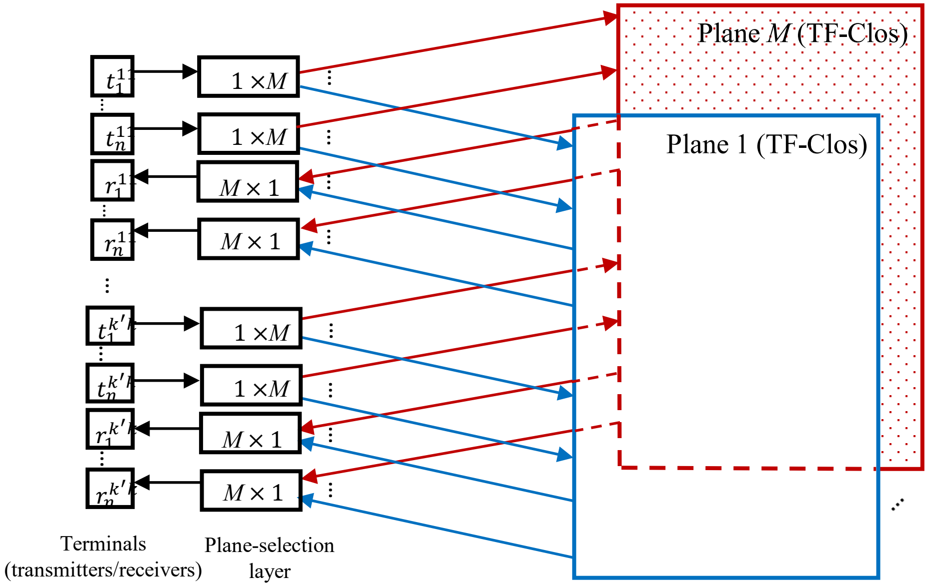


[Oki, TNSM 2024] E. Oki, R. Taniguchi, K. Anazawa, and T. Inoue, "Design of Multiple-Plane Twisted and Folded Clos Network Guaranteeing Admissible Blocking Probability," IEEE TNSM, online available.

Effect of parallelizing TF-Clos into multiple planes

- Increasing the number of planes, M, expand the switching network size while guaranteeing admissible blocking probability ε.

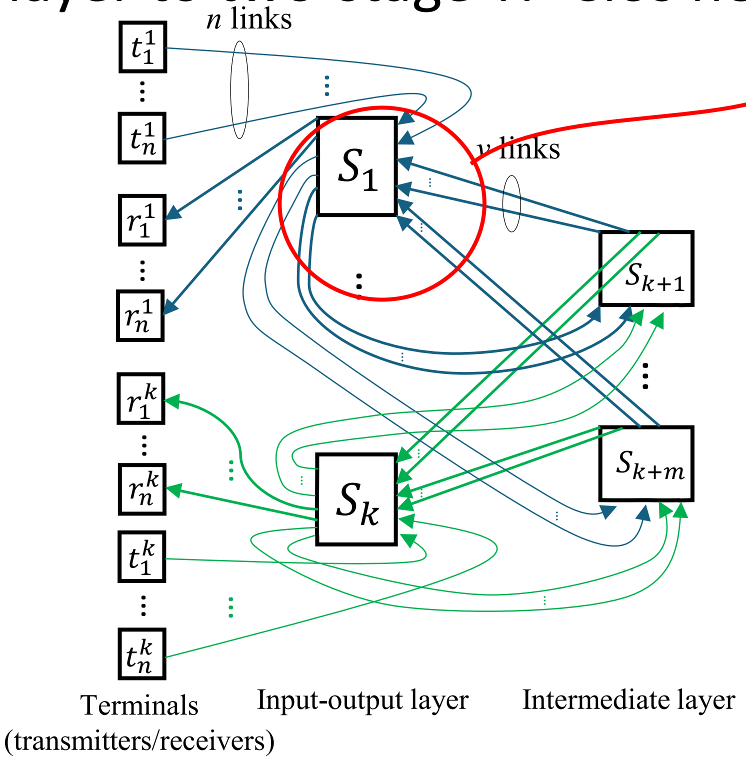


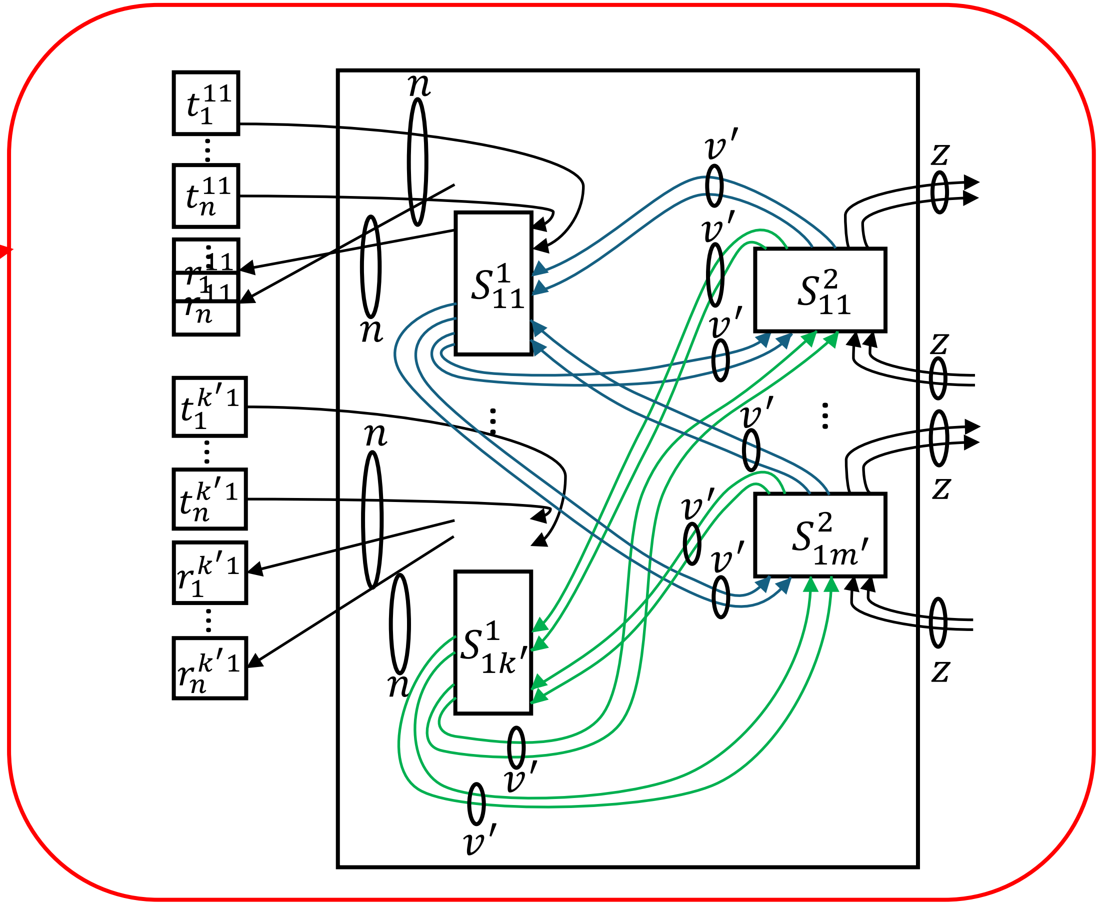


Switch size N=50, request active probability p=0.6, admissible blocking probability ε=0.1

Further expanding switching network size: Increasing number of stages [Taniguchi, JOCN 2024][Oki, JOCN 2025]

- Two stages -> three stages
  - Expanding a switch in the input-output layer to two-stage TF-Clos network





[Taniguchi, JOCN 2024] R. Taniguchi, T. Inoue, K. Anazawa, and E. Oki, "Optical Circuit Switched Three-Stage Twisted-Folded Clos-Network Design Model Guaranteeing Admissible Blocking Probability," JOCN, Nov. 2024.

[Oki, JOCN 2025] E. Oki, R. Taniguchi, K. Anazawa, and T. Inoue, ``Design Model of Three-Stage Folded Clos Network with Decoupled First Stage Guaranteeing Admissible Blocking Probability,'' JOCN, vol. 17, no. 4, pp. 309-323, Apr. 2025.

Key strategies for scaling optical circuit-switched networks while ensuring blocking performance in data centers

- How to connect switches between different stages
  - Update the network structure from folded Clos (F-Clos) to twisted and folded Clos (TF-Clos)
- How to ensure admissible blocking probability
  - Localize the blocking point with admissible connection control (CAC)
- How to relax design-problem constraints in
  - Allow for varying the number of steps for intermediate switches with CAC.
- How to further expanding switching network size
  - Increasing number of planes
  - Increasing number of stages

Summary

- Background
  - Packet switching versus circuit switching
  - Optical circuit switching in data center
  - Optical switches
  - Basics of switching networks
  - Clos network
    - Strict non-blocking (SNB) condition
- Twisted-folded Clos network (TF-Clos)
  - TF-Clos design with SNB to maximize switching capacity
- Increasing switching network size
  - Allowing admissible blocking probability
  - TF-Clos design models with guaranteeing admissible blocking probability
- Further expanding switching network size
  - Increasing the number of stages
  - Parallelizing TF-Clos into multiple planes
- Future work:
  - Handling different traffic rates generated at different terminals
    - The traffic rate generated at each terminal can differ.

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課題

1. TF-ClosとF-Closで、SNB条件で、スイッチングネットワークサイズが最も大きくなる構成を求めよ。 *N*と*a*は、以下のように与えられている。TF-ClosとF-Closのそれぞれの構成・caseで、*n*, *k*, *m*, *v*を示せ。
    1. Case 1: (*N*, *a*) = (6, 4)
    2. Case 2: (*N*, *a*) = (5, 6)
2. 上記の構成・caseをそれぞれ図示せよ。
3. TF-Closのスイッチングネットワークサイズは、常に、F-Closよりも大きいか、または、等しい、ことが分かっている。これを証明せよ。

課題（続き）

4. TF-Closにおけるtransceiver (transmitterとreceiverペア)のoptical power budget (dB)を求めよ。power lossは、光ファイバ、光スイッチのみで発生し、以下の条件が与えられている。power budgetの算出において、マージンを考慮しない。
    - ファイバの伝搬損失係数: 0.35dB/km
    - 光スイッチの挿入損失: 1.6dB
    - スイッチ間距離: 500m
    - 端末 (transmitter/receiver)-スイッチ間距離: 500m

- 補足
    - Optical power budget: 光通信システムで、送信側から受信側に光信号を伝送する際に許容できる総光パワー損失量
    - transmitterとreceiver間において、光スイッチの経由数、光ファイバの長さが光パワーの損失に影響を及ぼす。