

# SMT-based Schedule Synthesis for Time-Sensitive Networks

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TTTech Computertechnik AG



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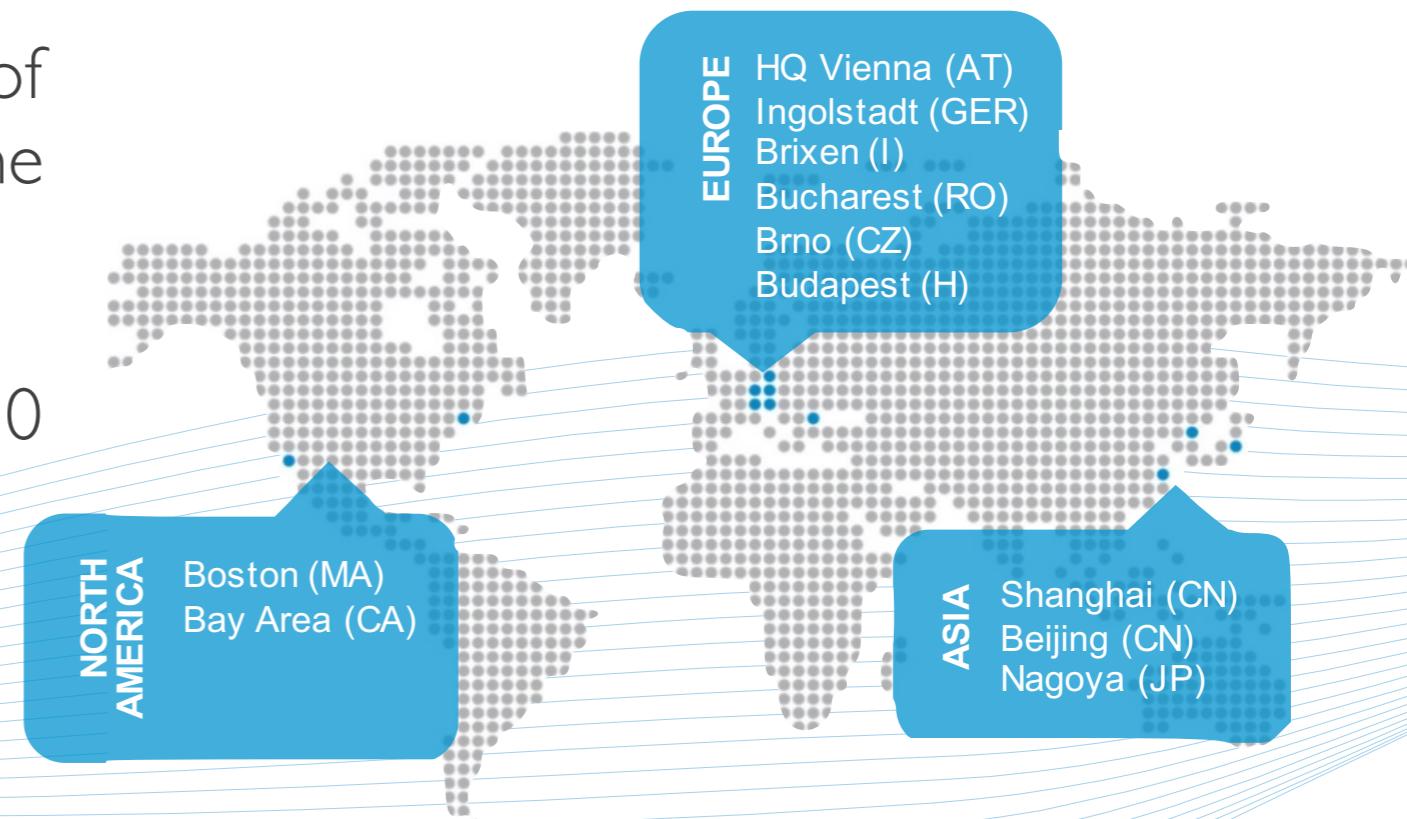
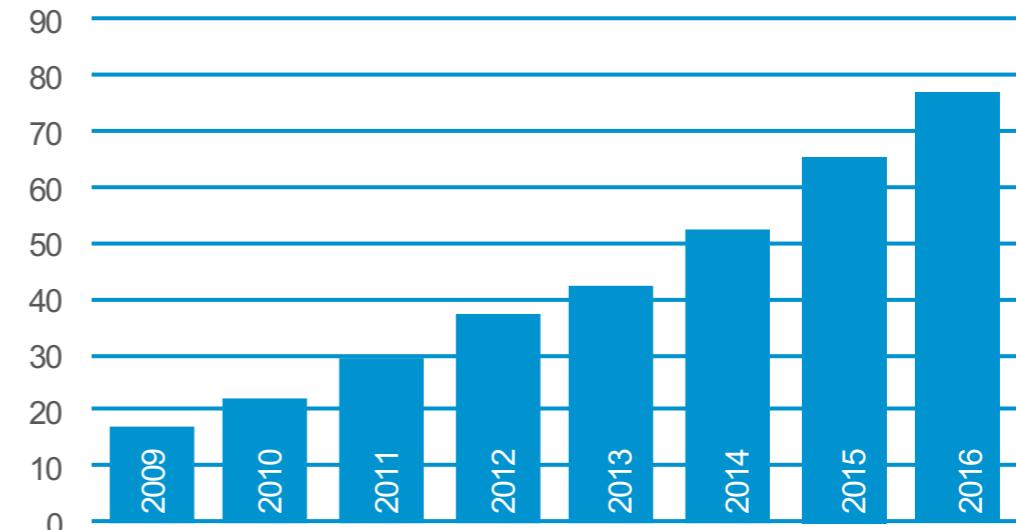
# Company Key Facts

**TTTech** provides highly reliable and networked electronic systems with solutions based on time-triggered networking technology and modular building blocks for safety controllers

**Globally** oriented high-tech company, headquartered in Vienna, Austria

**Innovation** leadership - successful transfer of ground breaking research to high-volume production

More than **540** employees with offices in 10 countries (2016)



# R&D Funded Projects at a Value of 20 MEUR

Ensuring Reliable Networks



- **Aerospace:** Airbus, Boeing, Diehl, Honeywell, Liebherr, Safran, Thales, UTC Aerospace Systems etc.
- **Automotive:** Audi, AVL, Continental, Delphi, Denso, Valeo, Volvo, etc.
- **Industrial:** Alstom, IBM, Sysgo, Thales Austria, etc.
- **Off-Highway:** Palfinger, Schwing, etc.
- **Semiconductors:** ams AG, Infineon, Intel, NXP, ON Semiconductor, etc.
- **EC-funded projects** in ARTEMIS, DREAMS, ENABLE-S3, ECSEL, ITEA 1&2, Eurostars, Greencars, Cleansky, Marie Curie and other R&D Projects directly funded in FP5, FP6, FP7, H2020
- **US programs:** NASA, DARPA, NSF
- **Universities:** Vienna University of Technology, Berkeley University of California, DTU, Chalmers University of Technology, KTH, University of Siegen, University of Kaiserslautern, etc.
- **Research Organizations:** Austrian Institute of Technology, Barcelona Supercomputing Center, CEA, Technalia, Fortiss GmbH, Fraunhofer Society, SRI, TNO, etc.



Strategic R&D of time-triggered communication platforms, prototypes for electronic modules, on-board software and safety platform elements for relevant future application domains

# R&D Funded Projects at a Value of 20 MEUR

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## R&D Cooperation with Industry

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## International Research Network

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# How will the future look like?

Autonomous & Near Autonomous Operations

**\$1.9 Trillion**

Economic impact of near autonomous cars by 2025



Real-Time Internet of Things



**25+ Billion**

Embedded and intelligent systems by 2020

**Every 2nd**

Embedded device will be safety relevant by 2020



Safety & Reliability

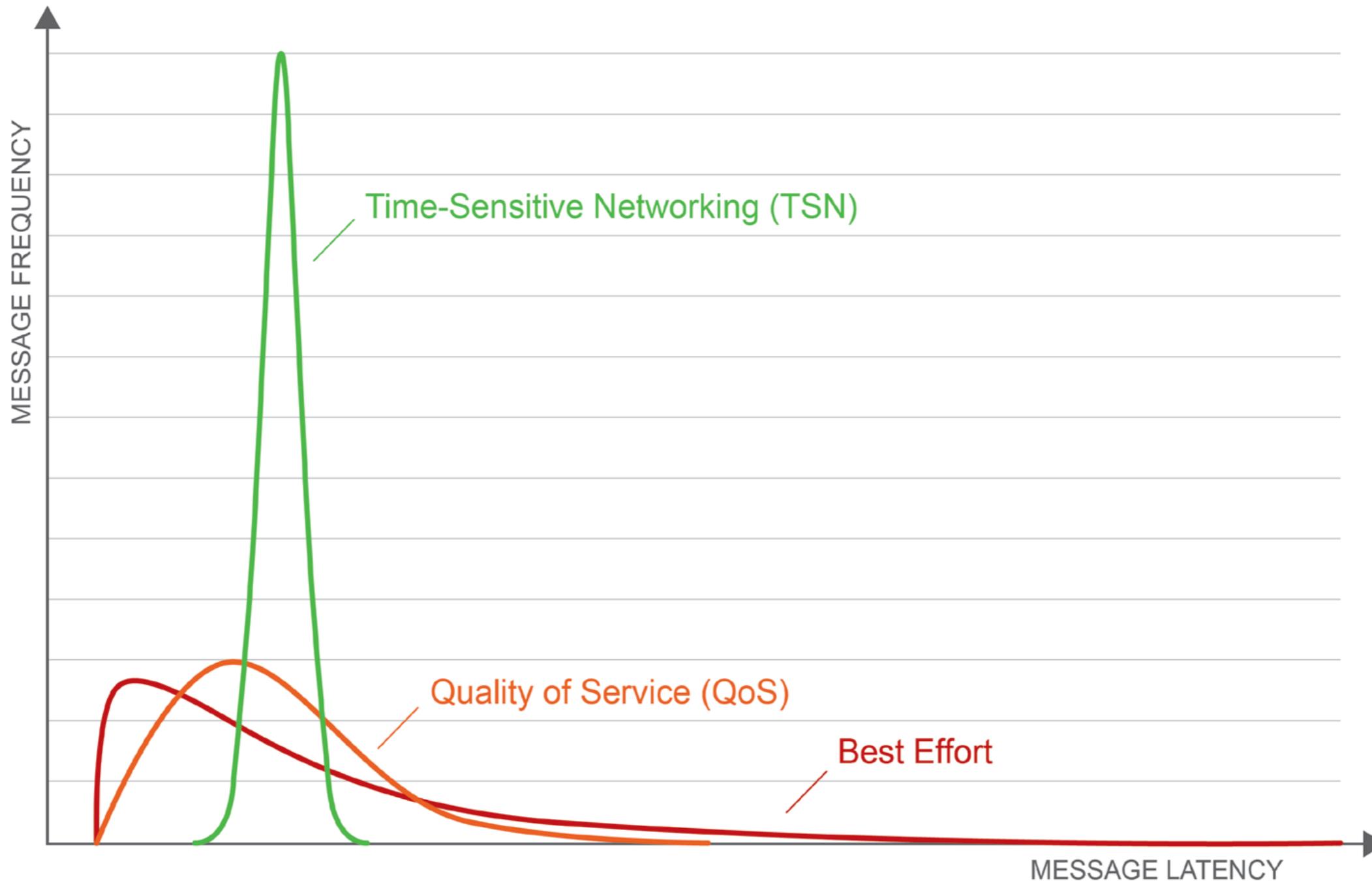


# Time-sensitive domains



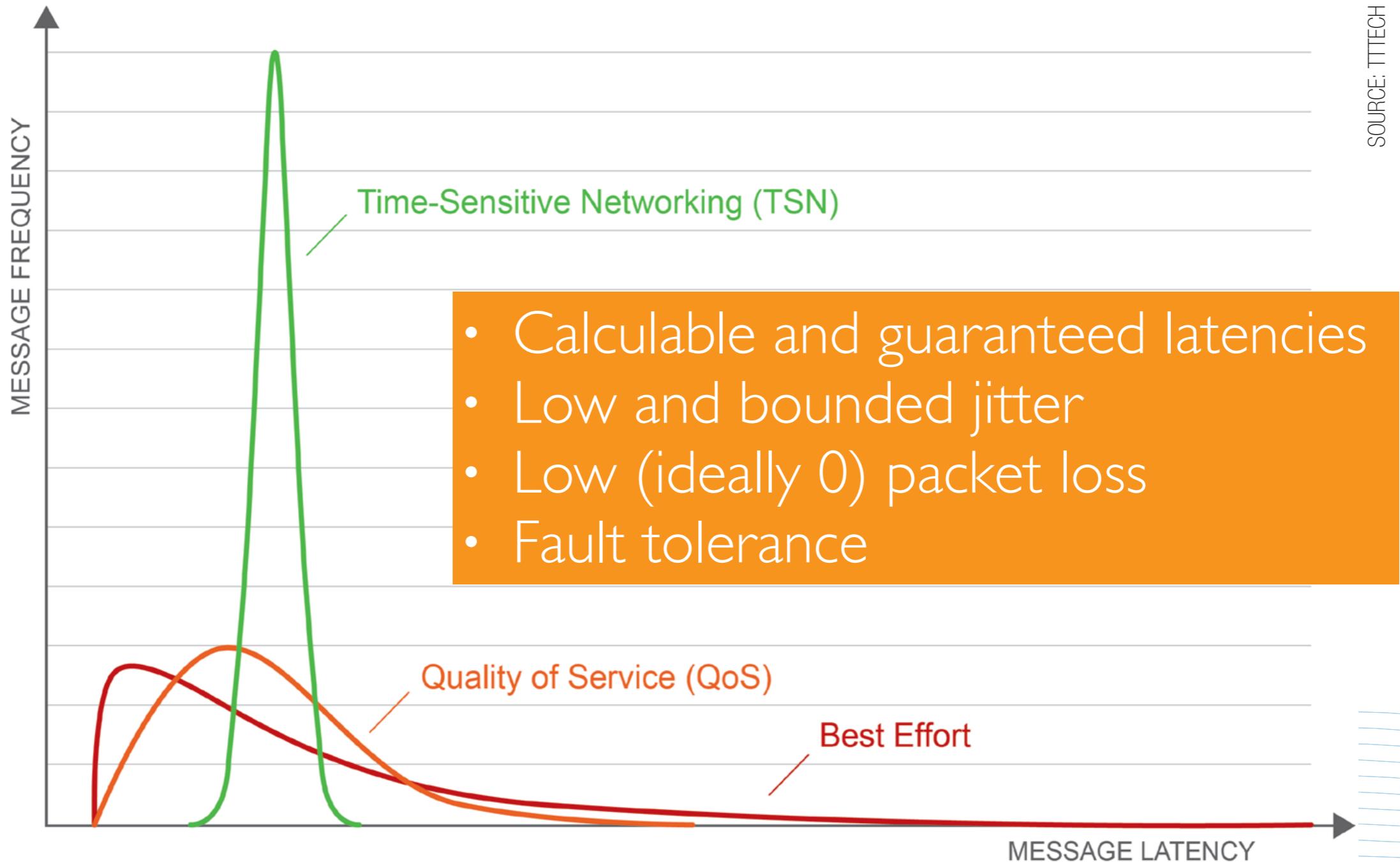
# Time-sensitive networking

SOURCE: TTTECH



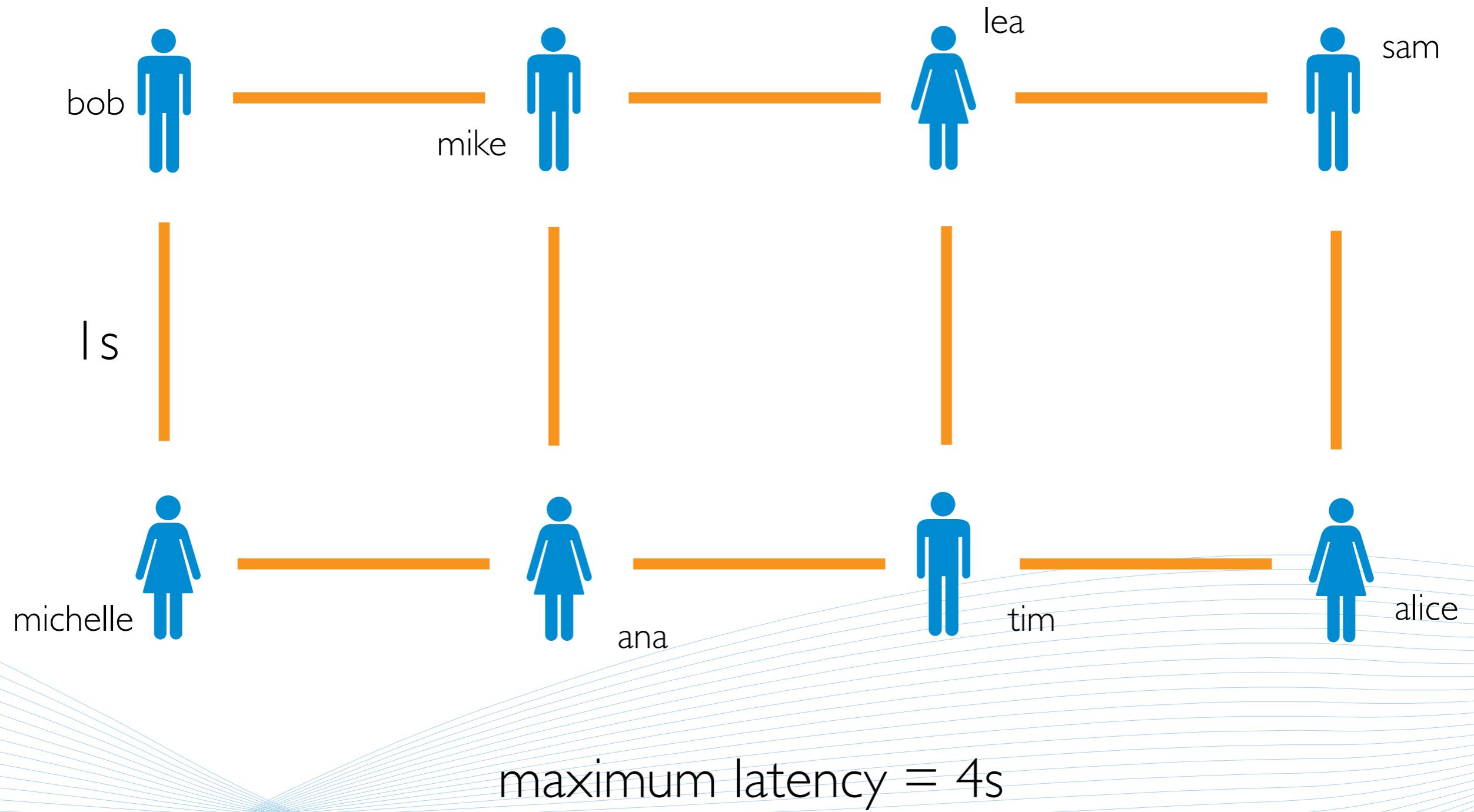
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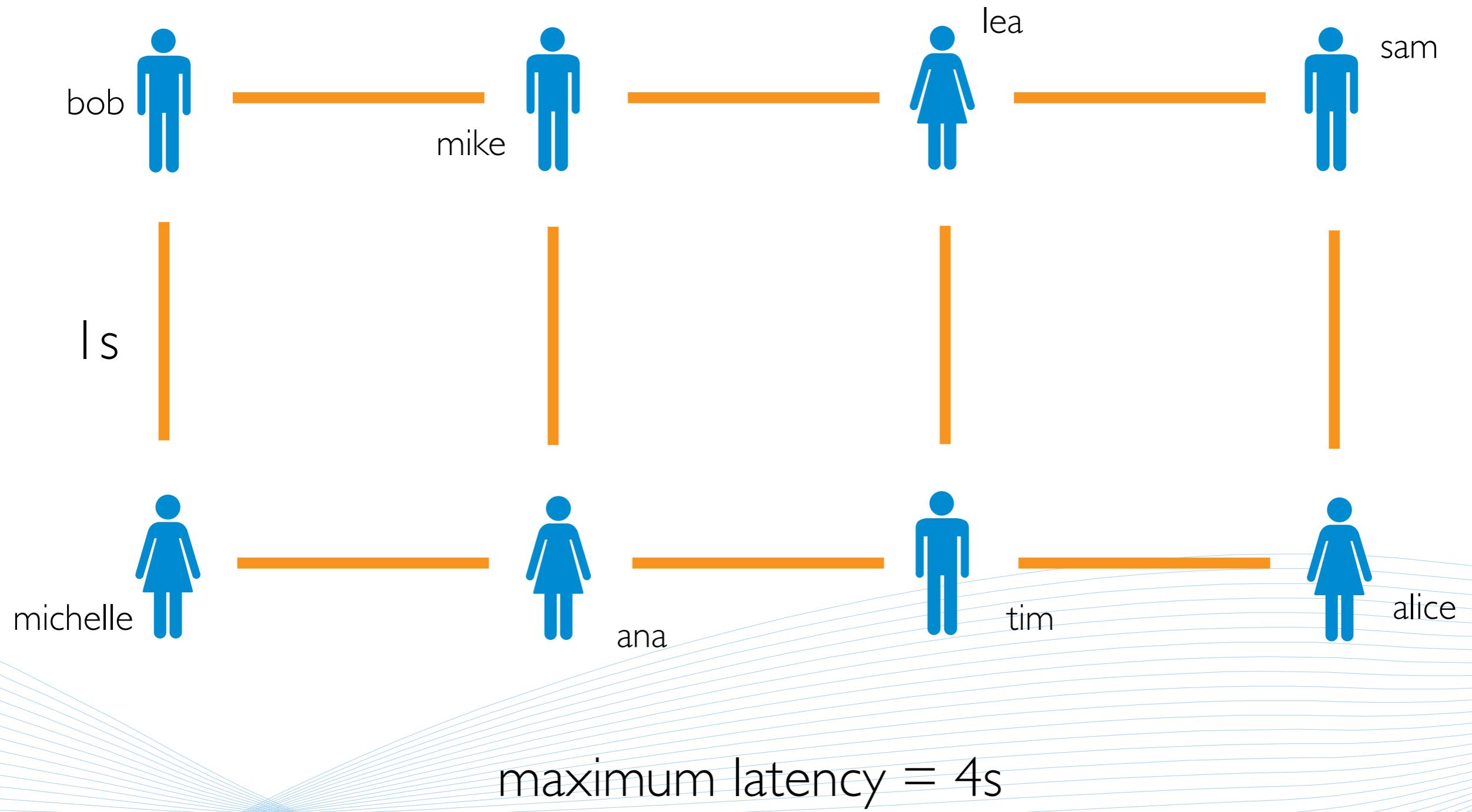
# Experiment

t =



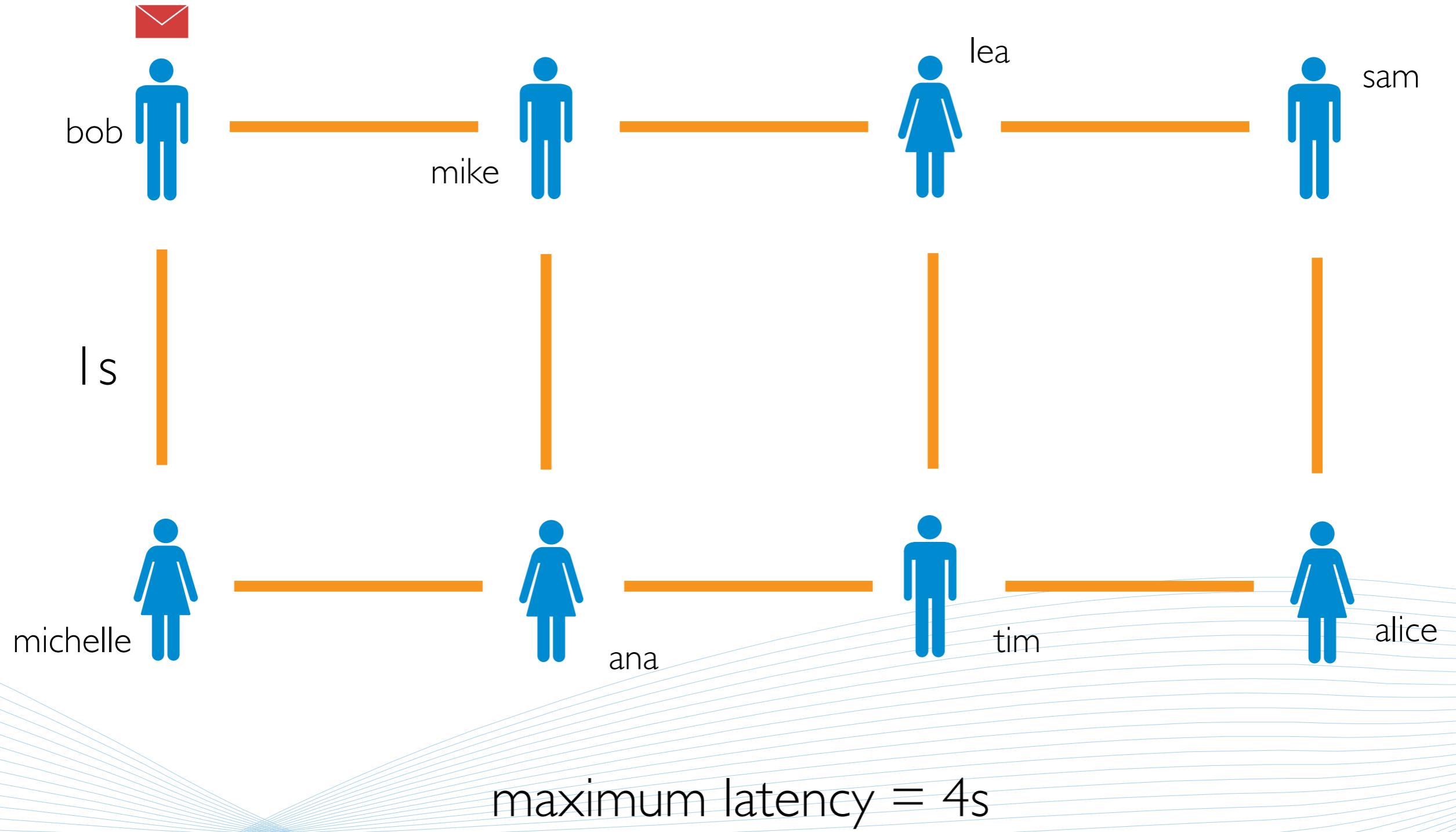
# Experiment

t = 0



# Experiment

t = 0

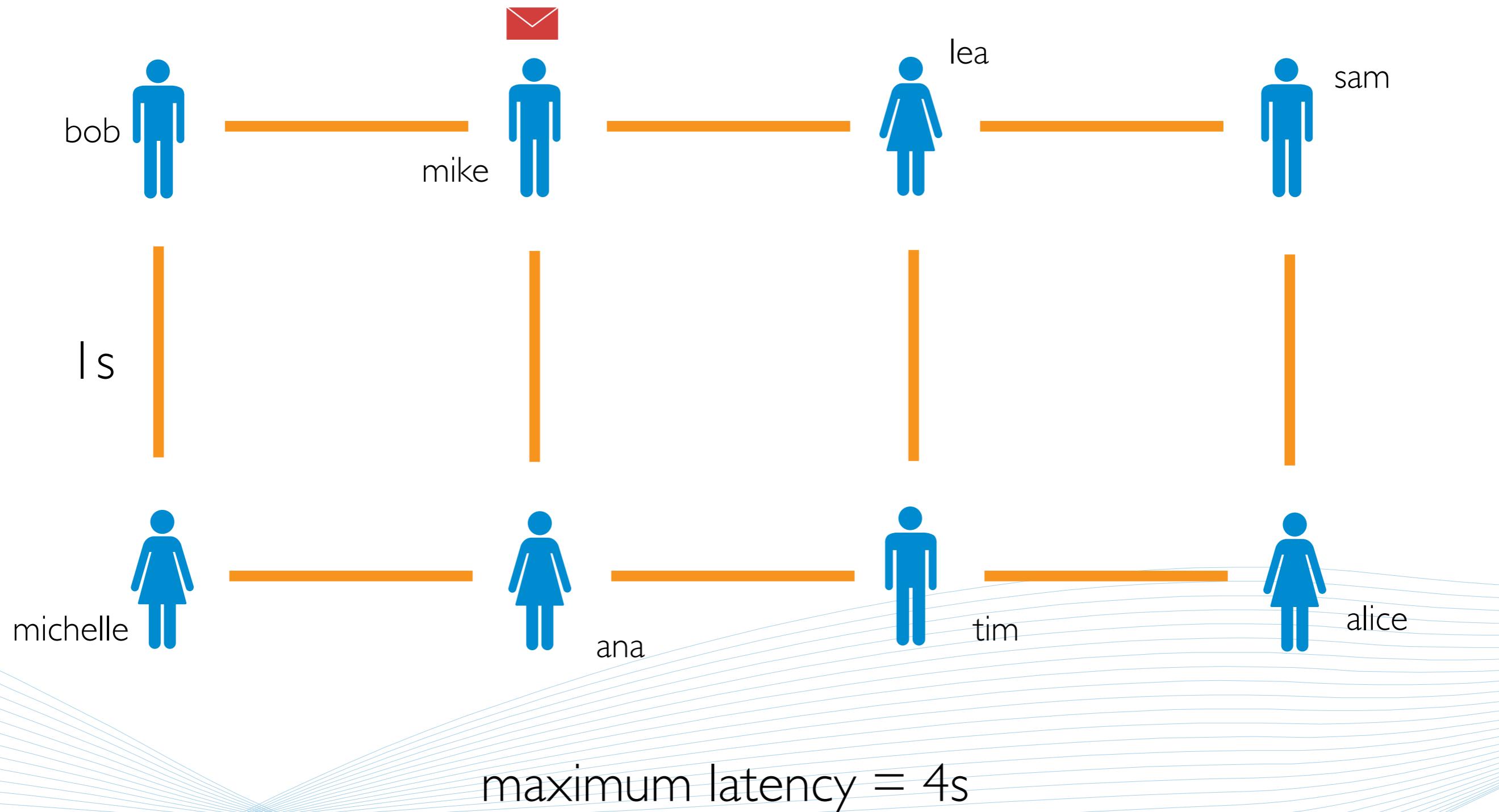


# Experiment

Ensuring Reliable Networks

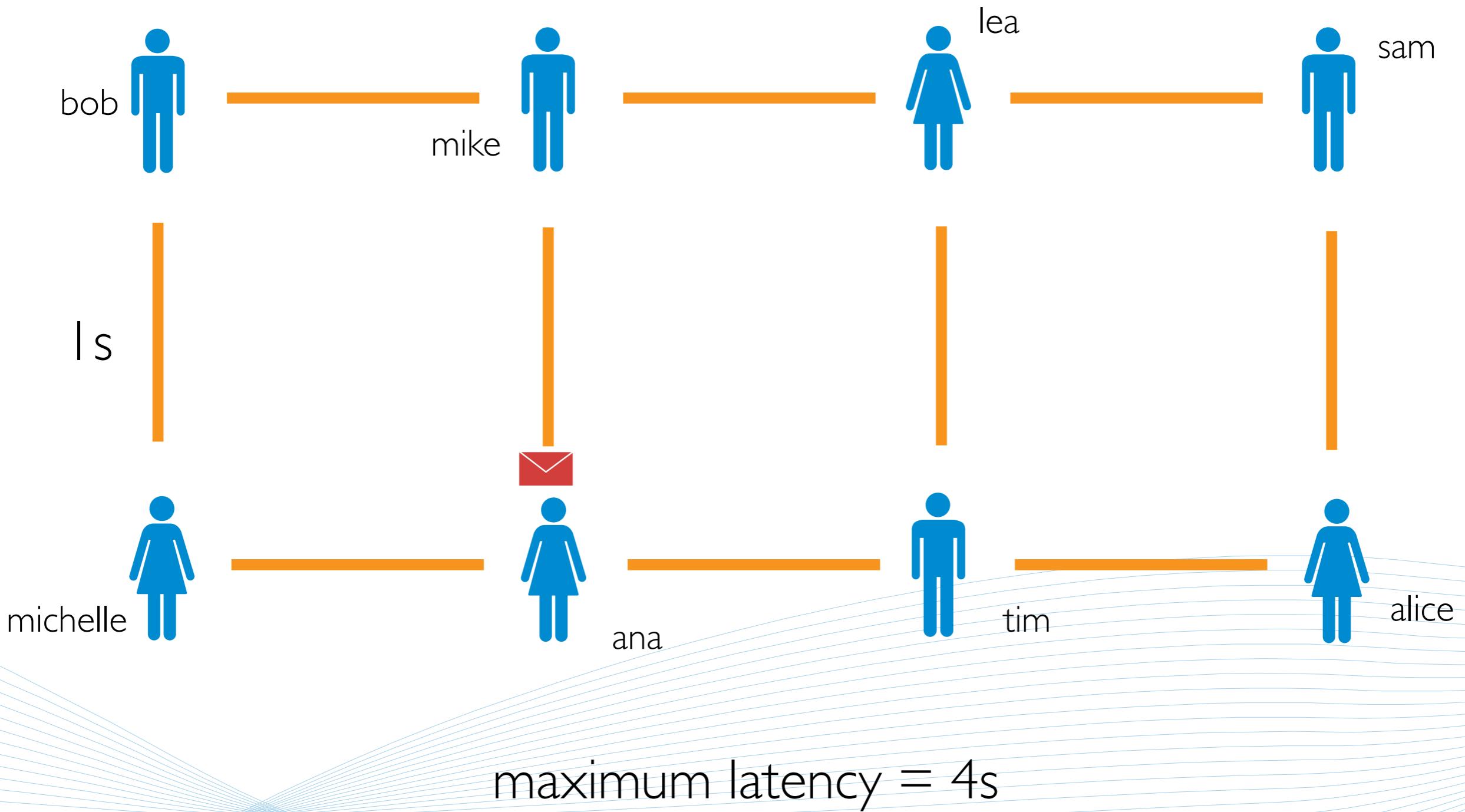
**TTTech**

$t = 0$



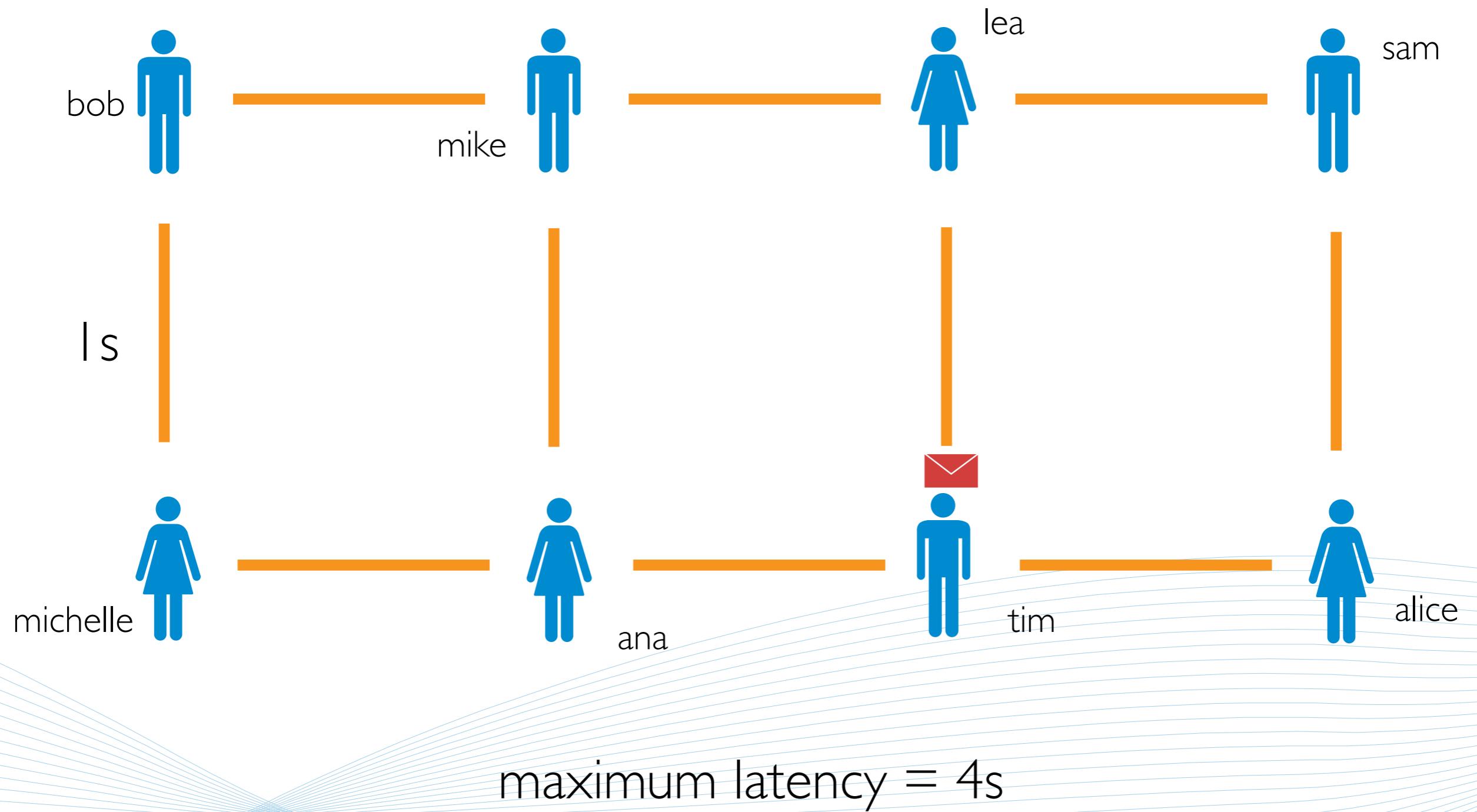
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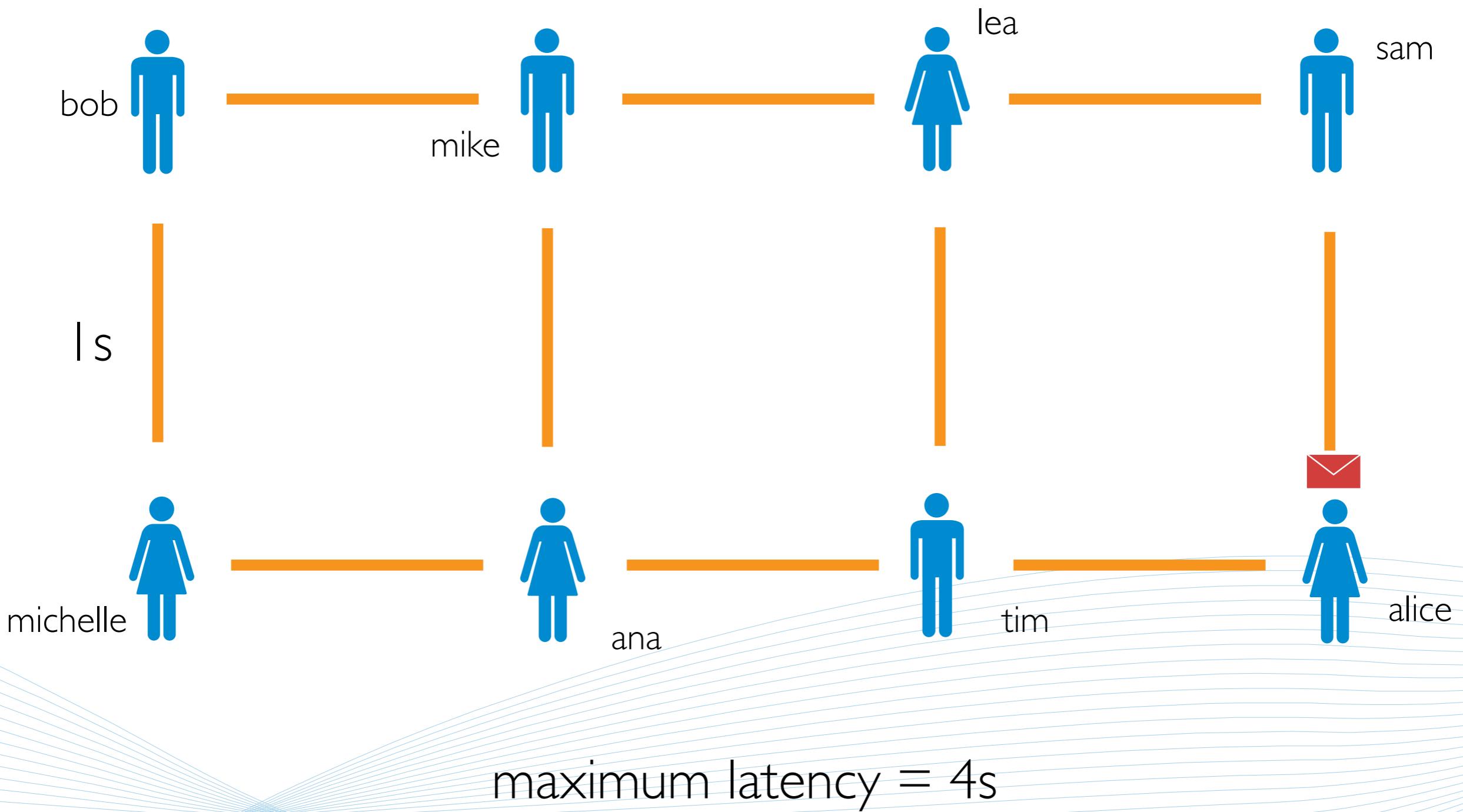
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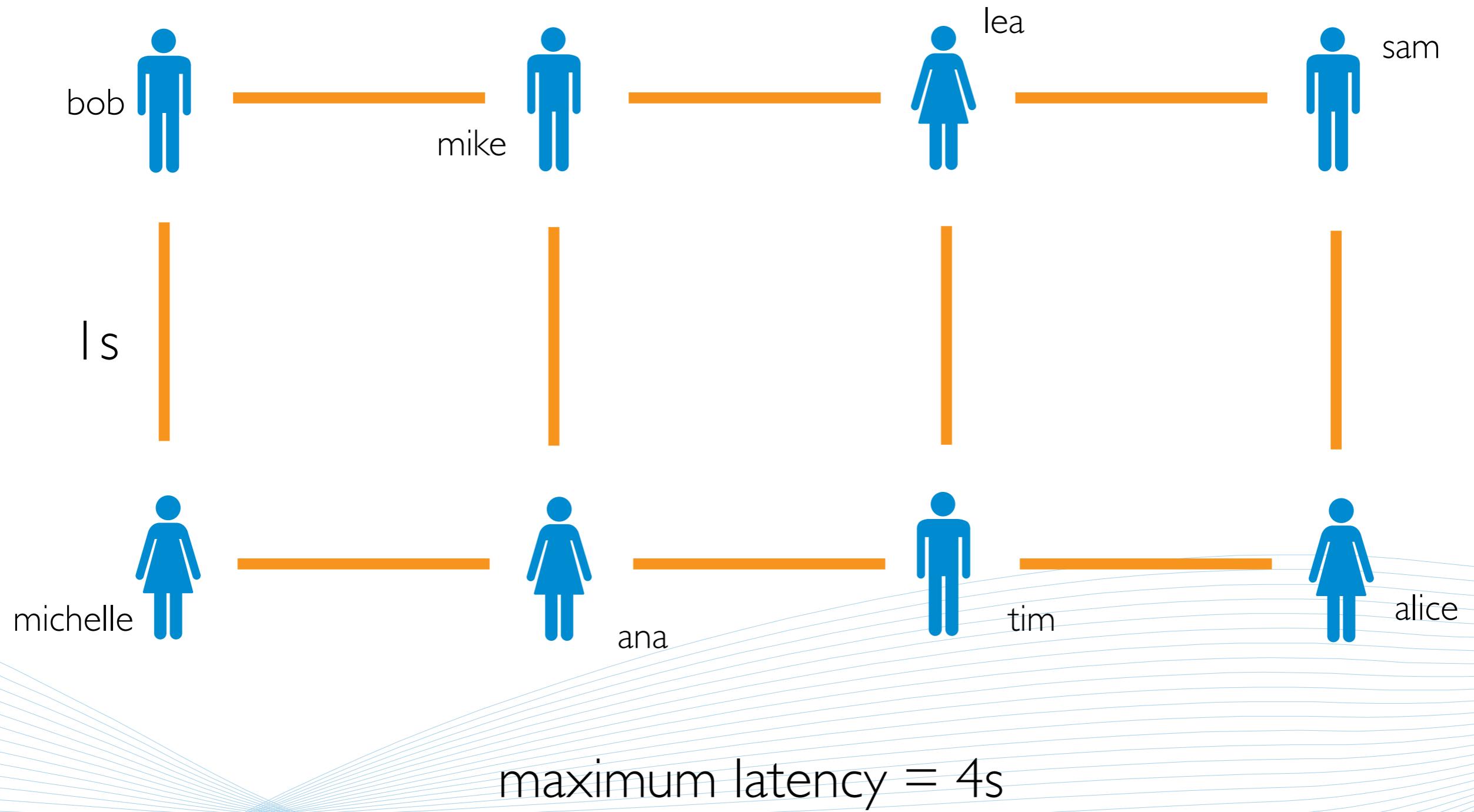
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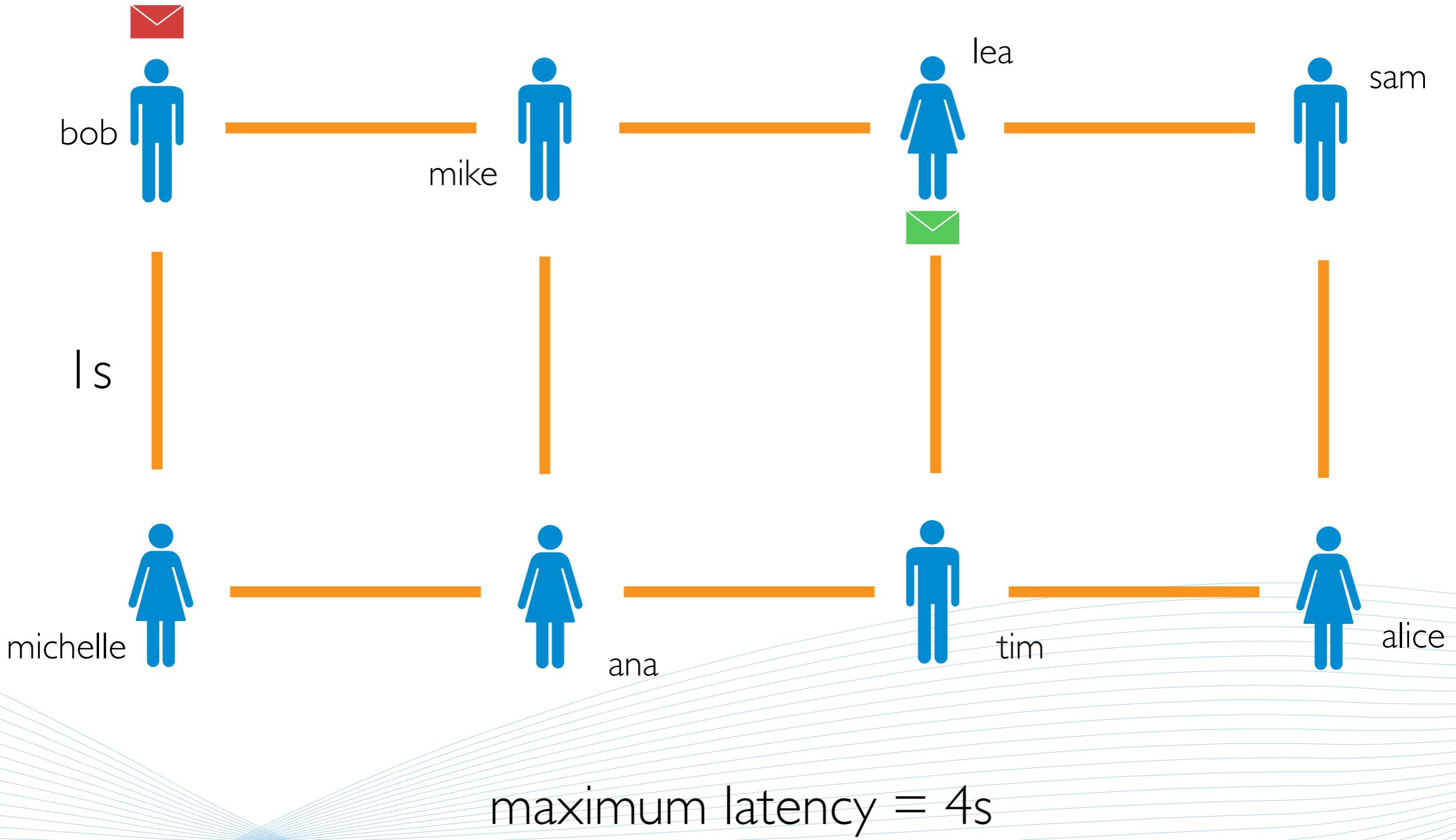
# Experiment

t = 0



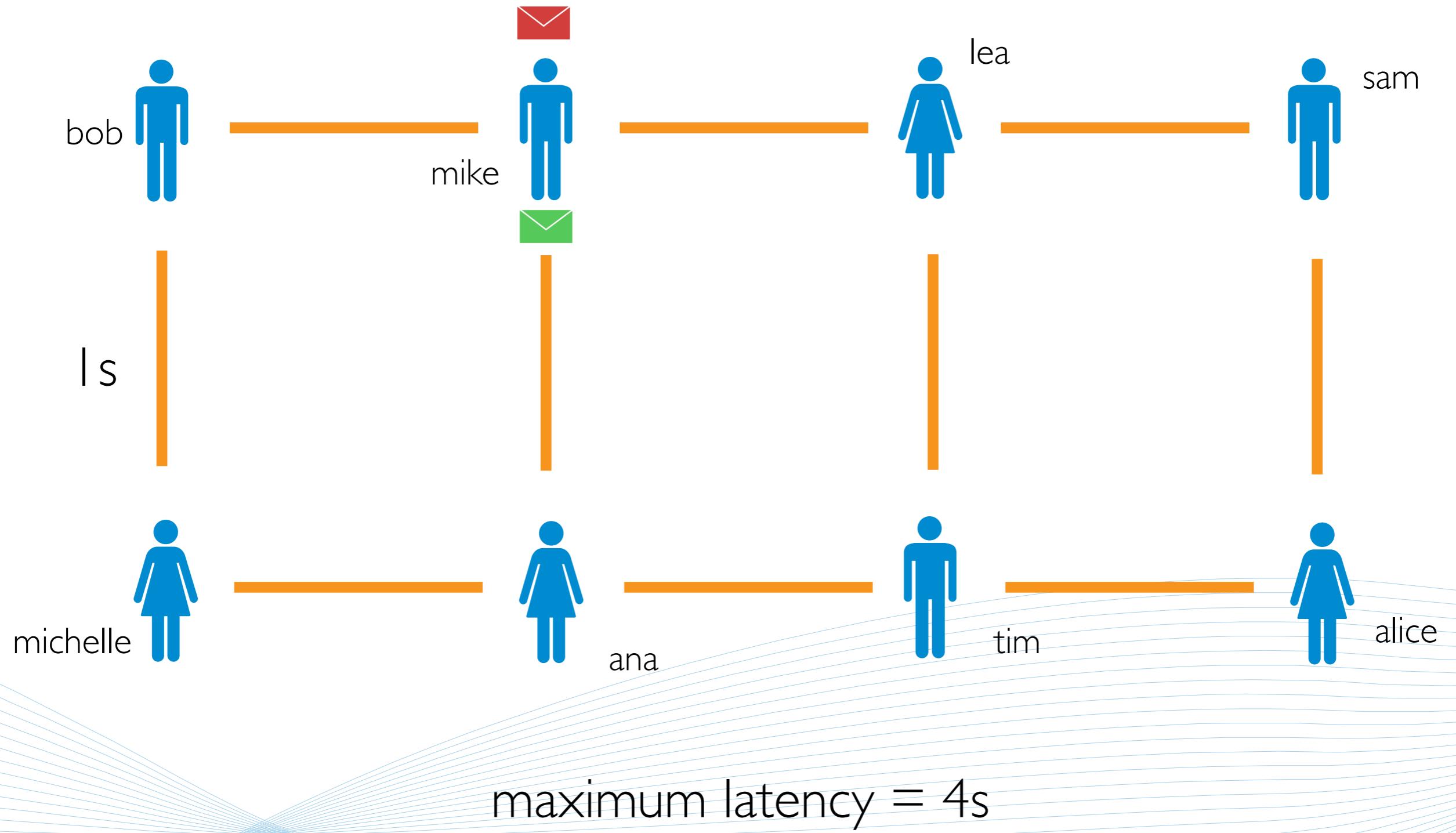
# Experiment

t = 0



# Experiment

$t = 1$

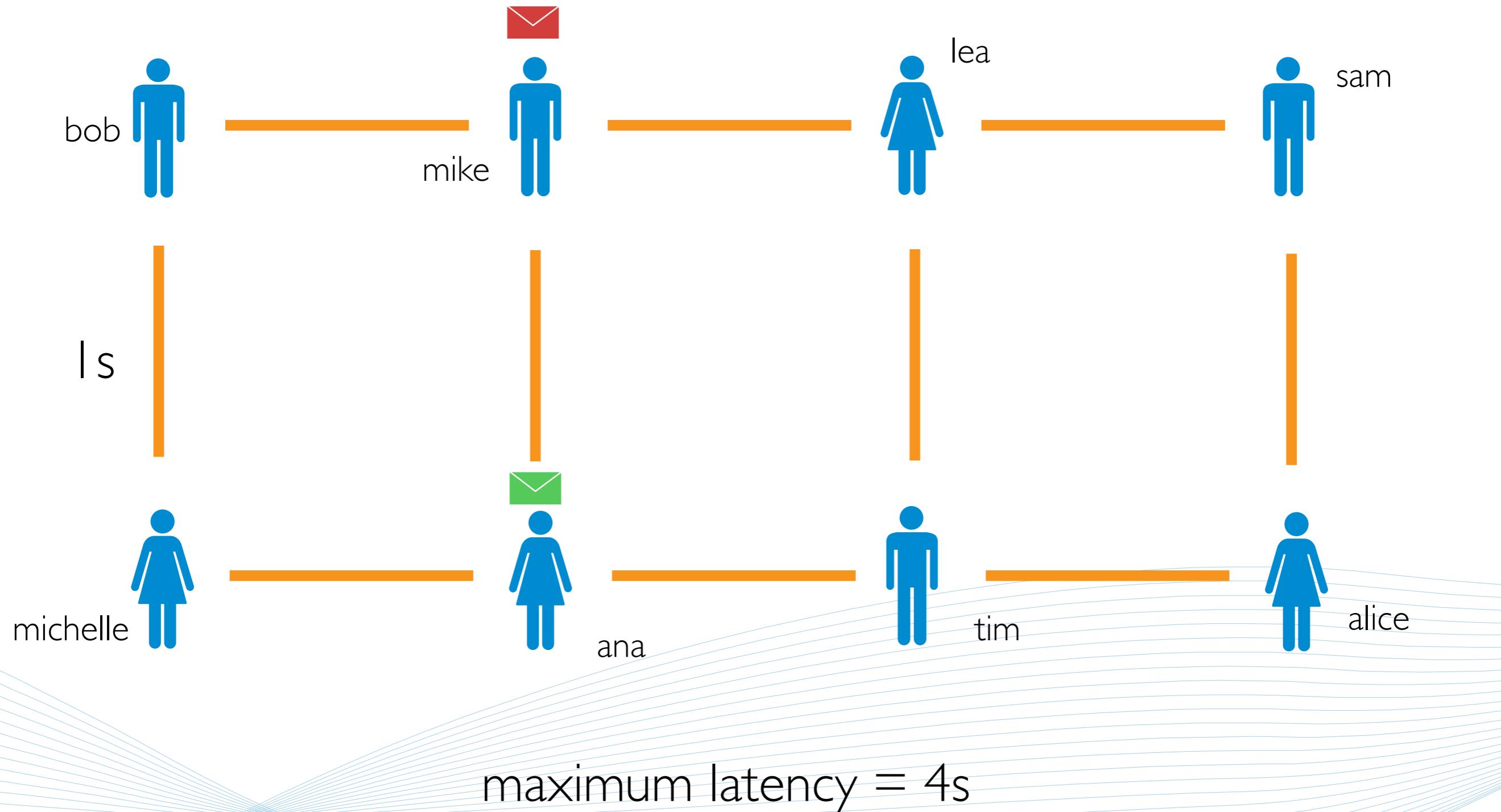


# Experiment

Ensuring Reliable Networks

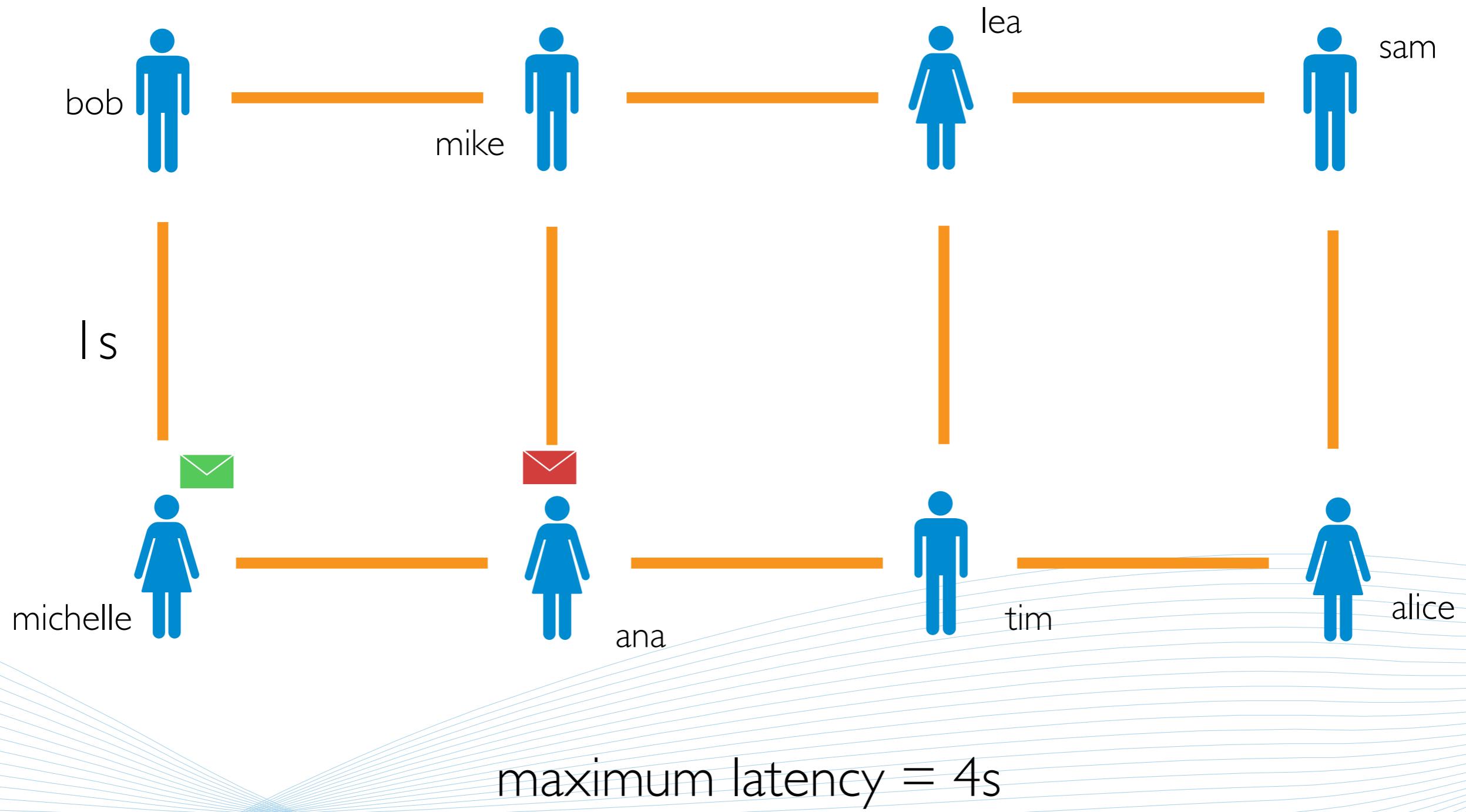
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t= 2



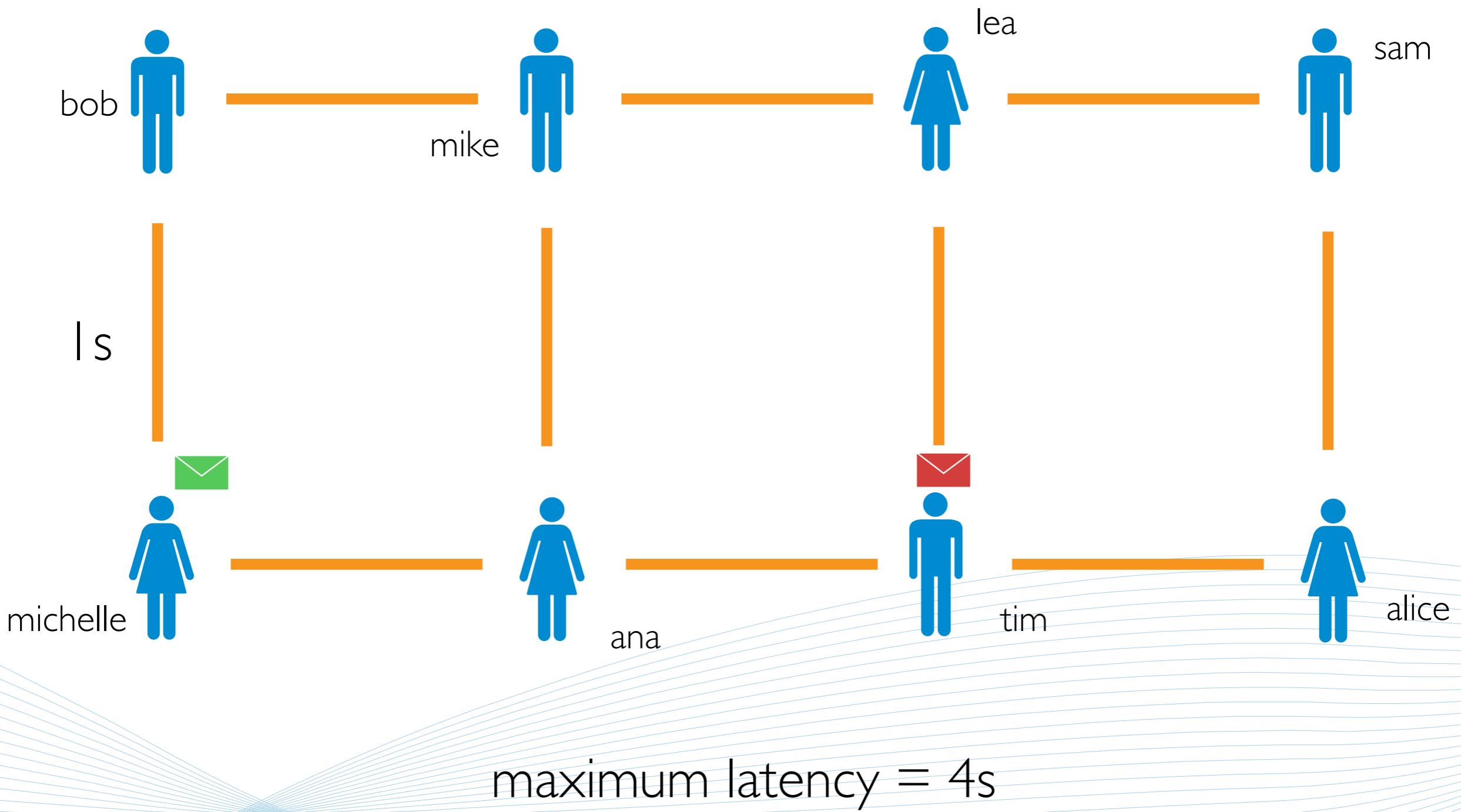
# Experiment

t = 3



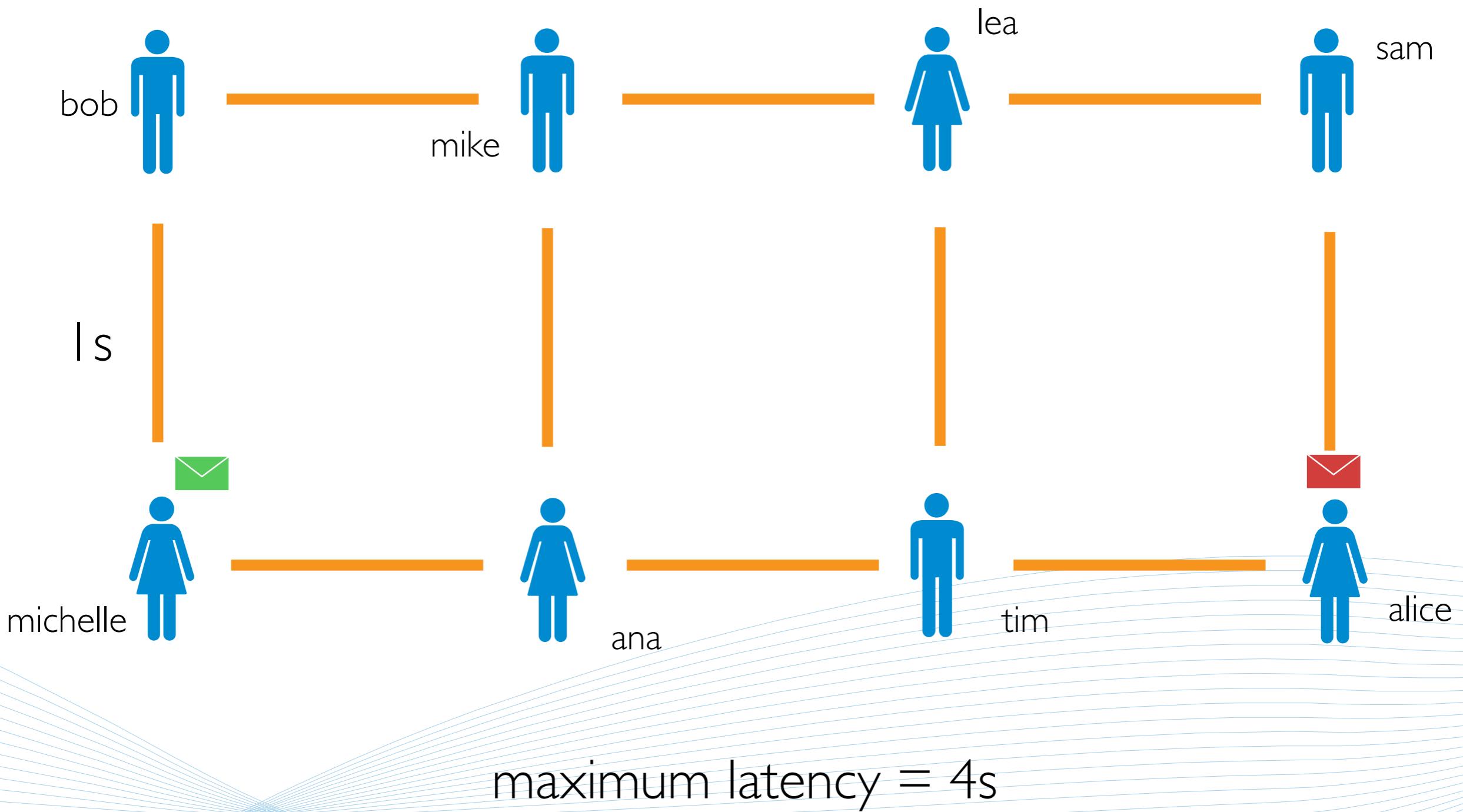
# Experiment

t = 4



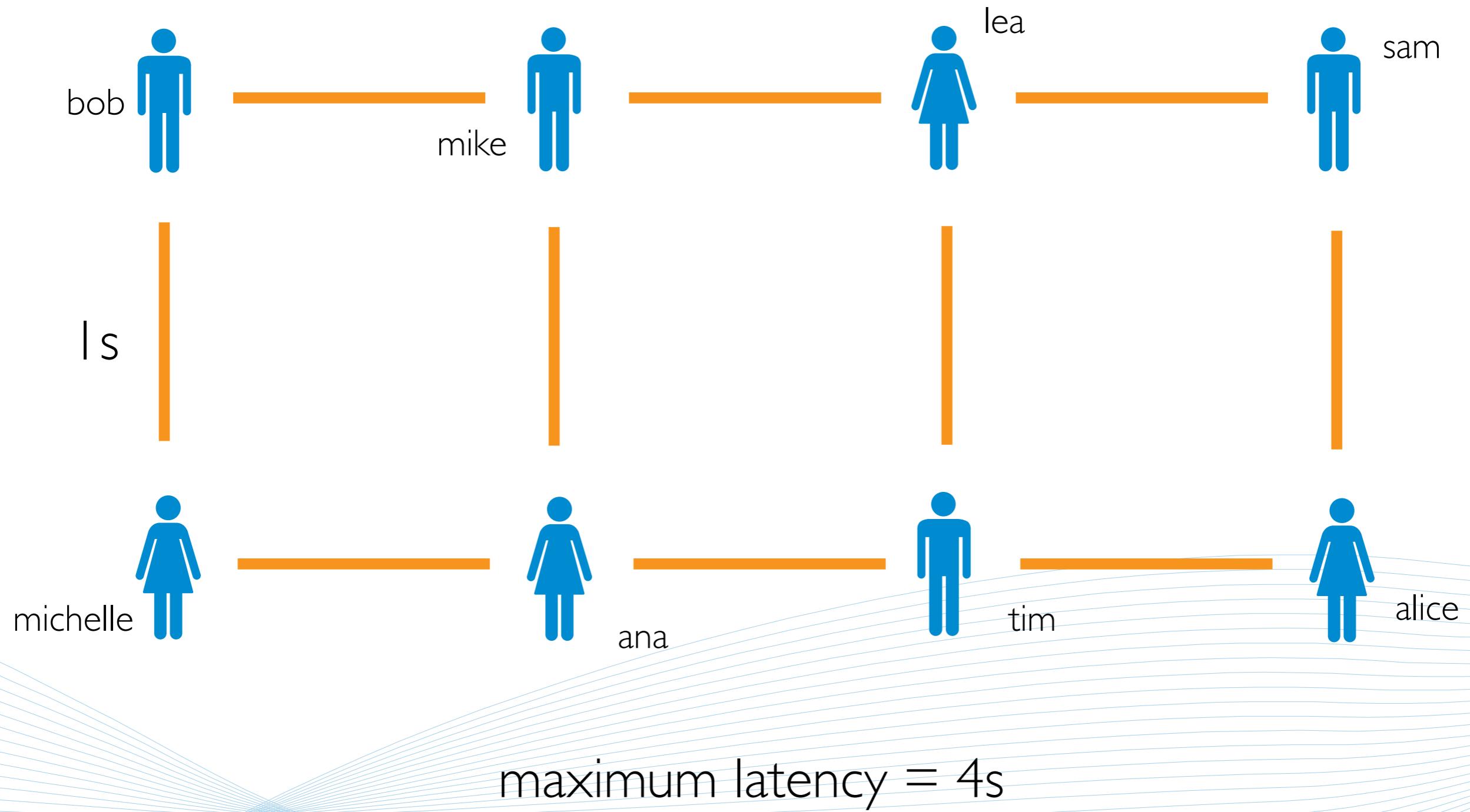
# Experiment

t= 5



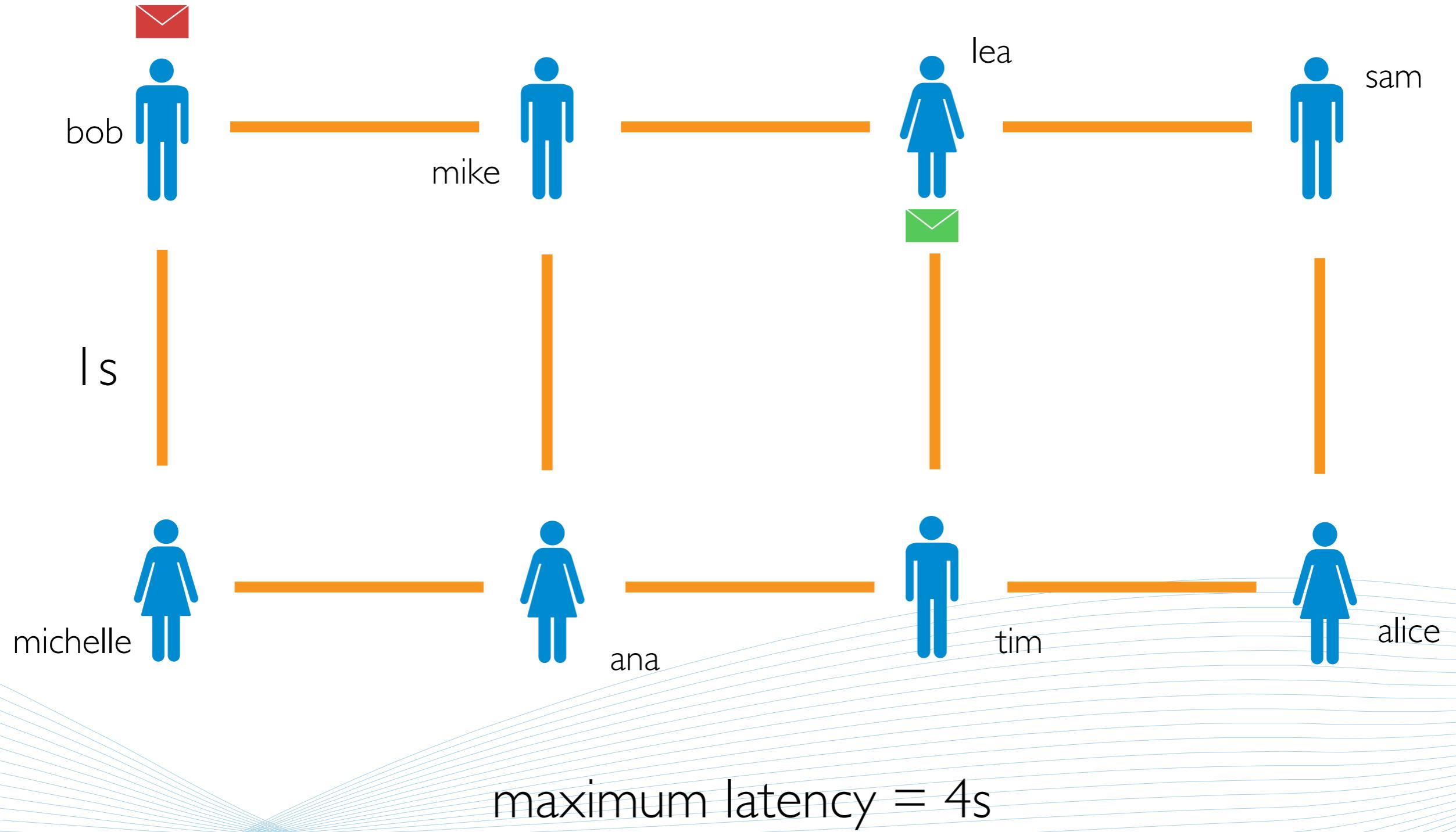
# Experiment

t =



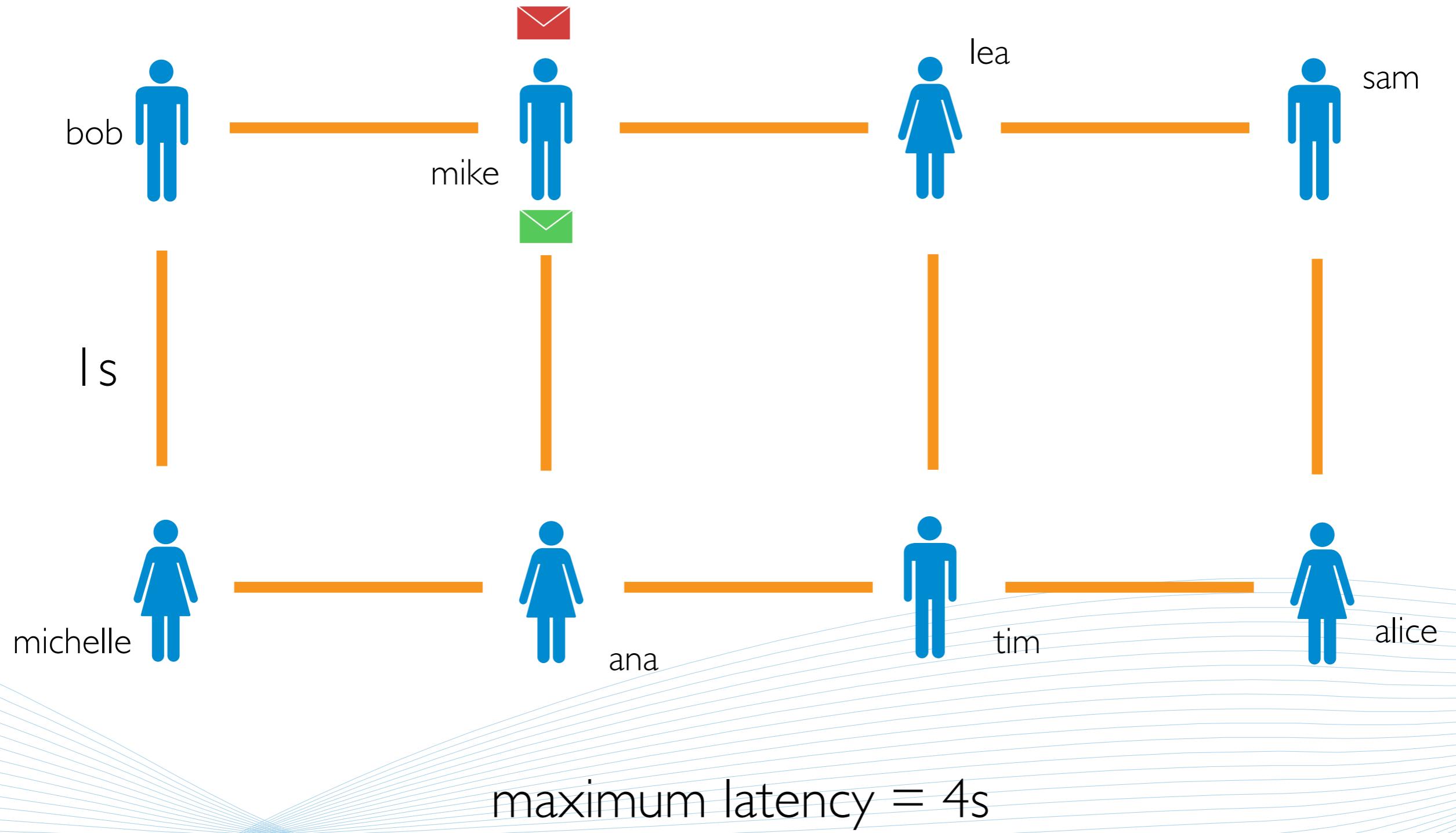
# Experiment

t = 0



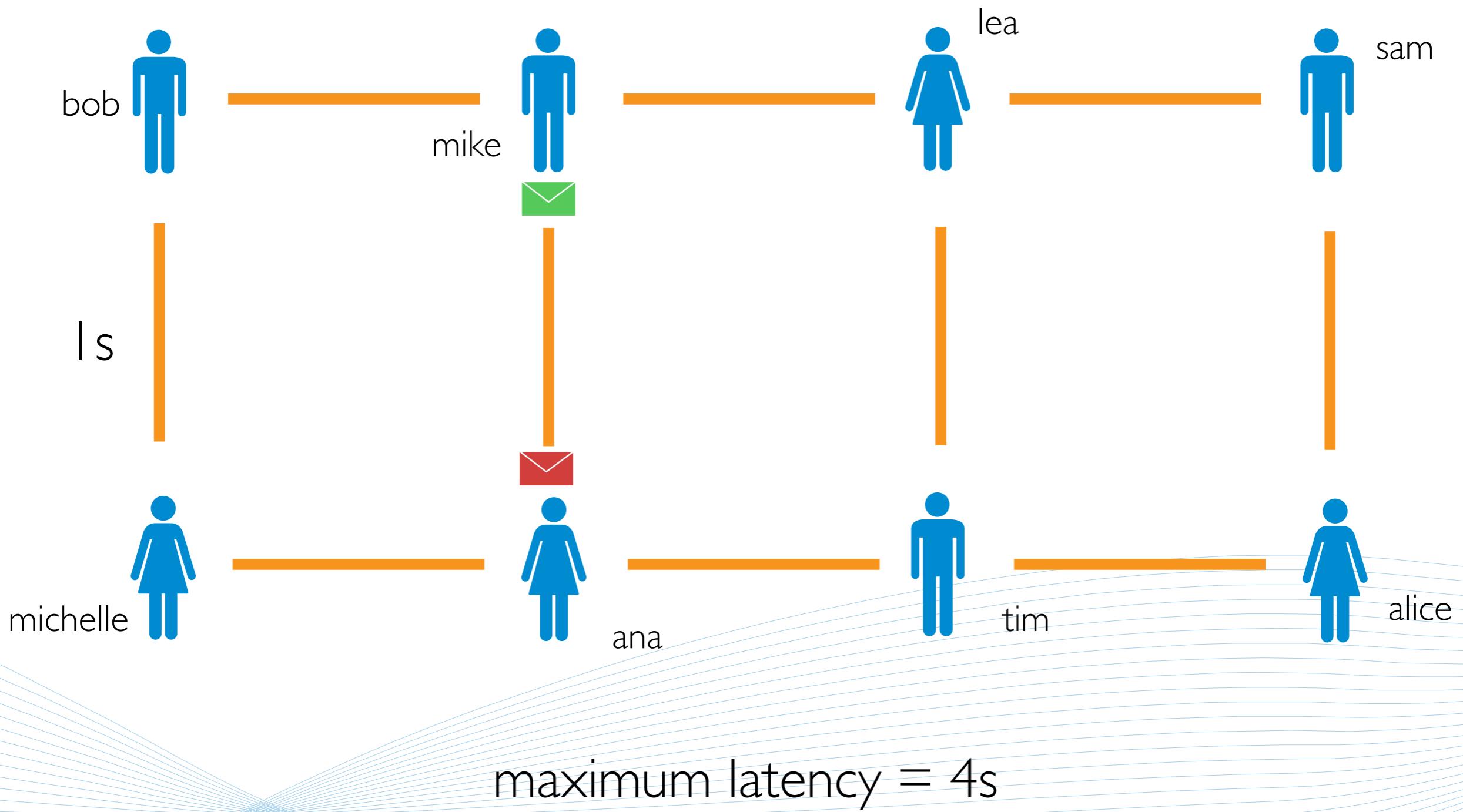
# Experiment

$t = 1$



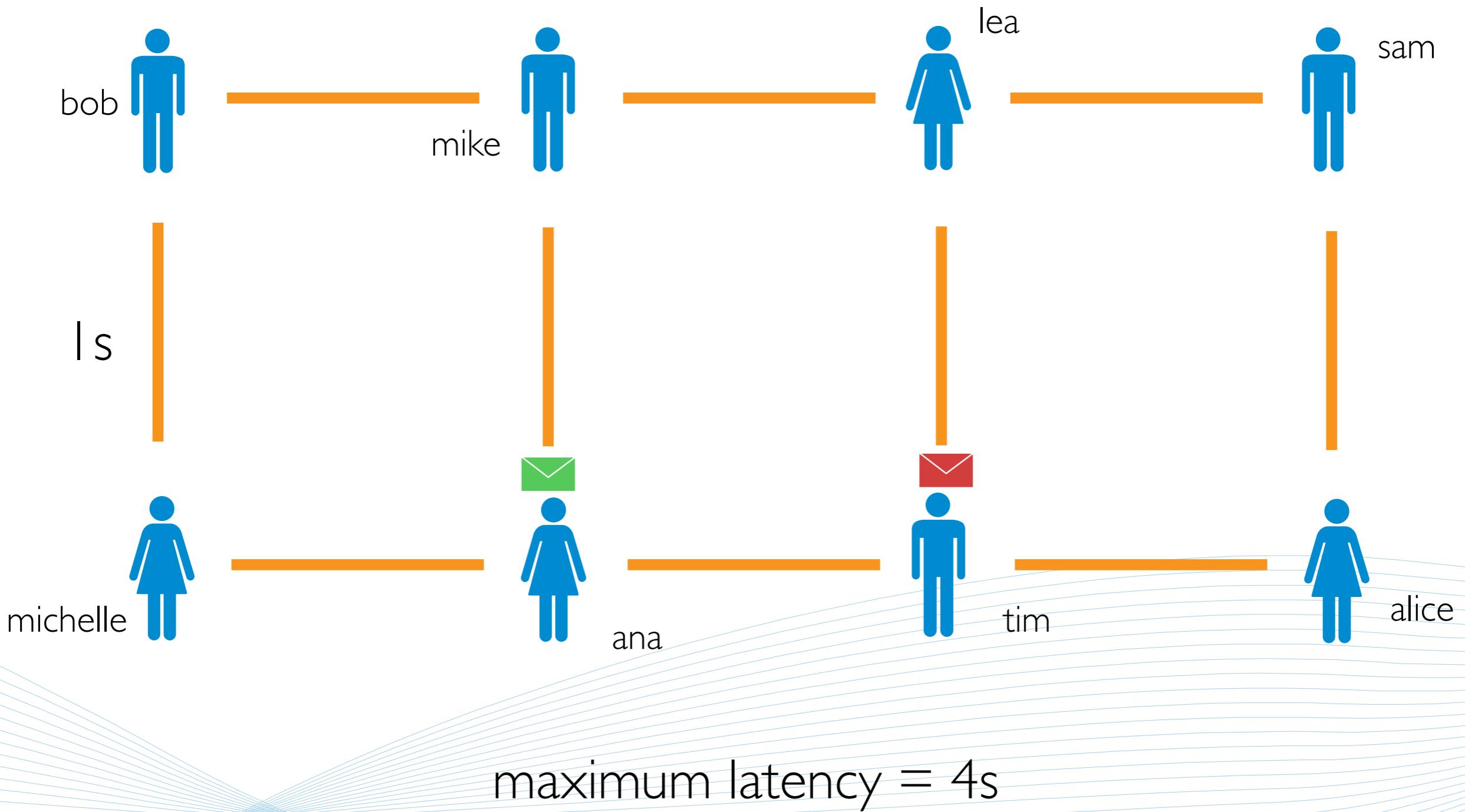
# Experiment

t = 2



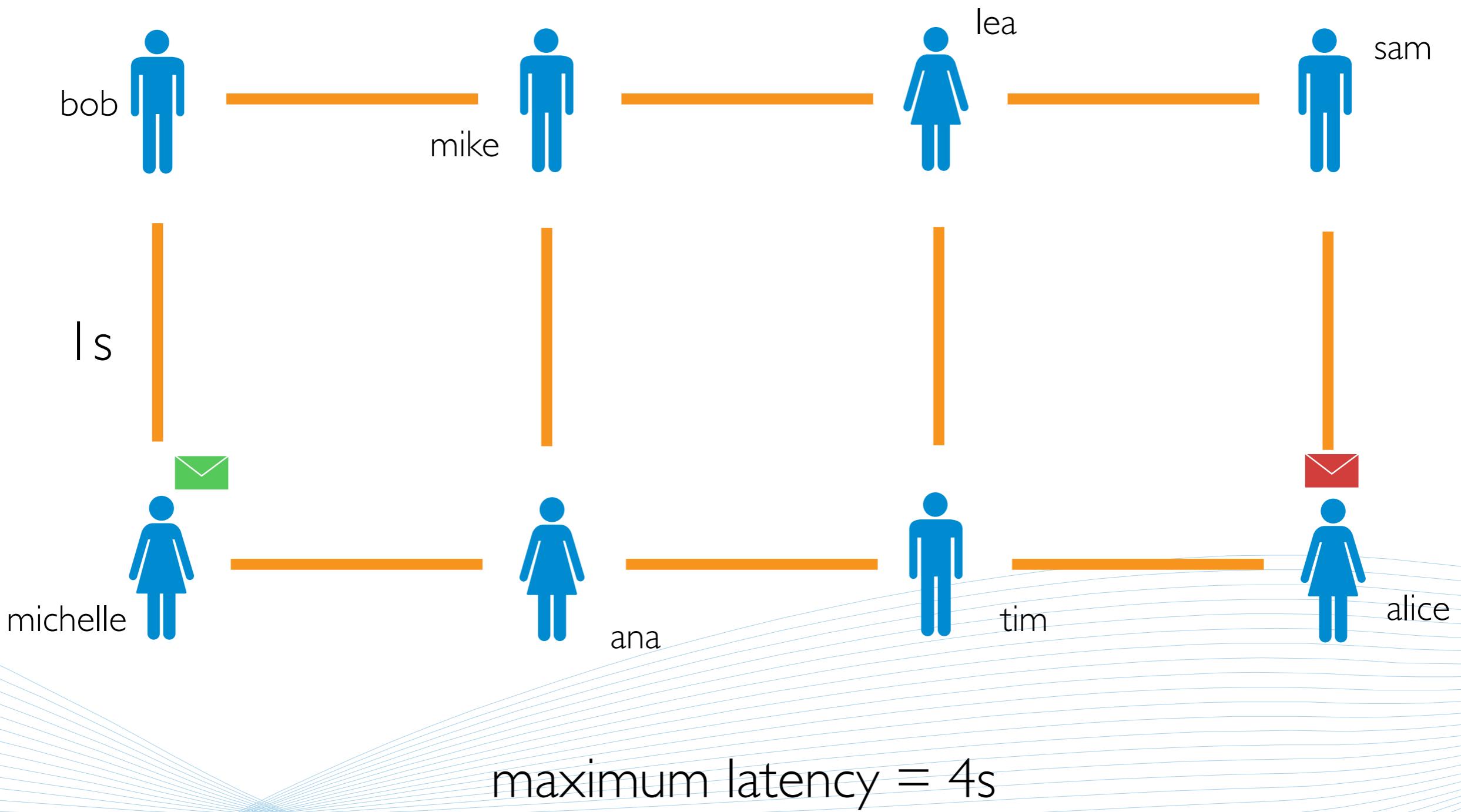
# Experiment

t = 3



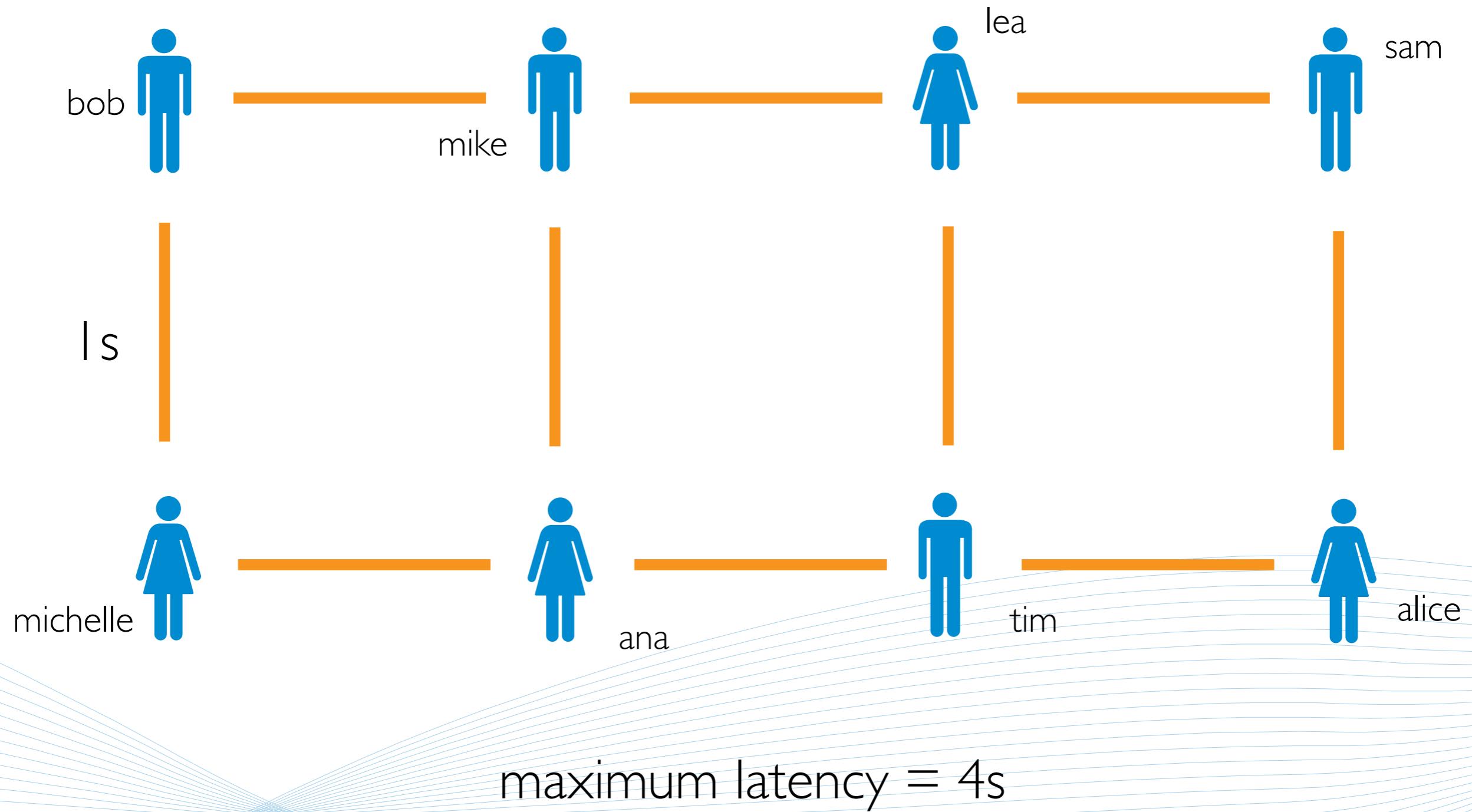
# Experiment

$t = 4$



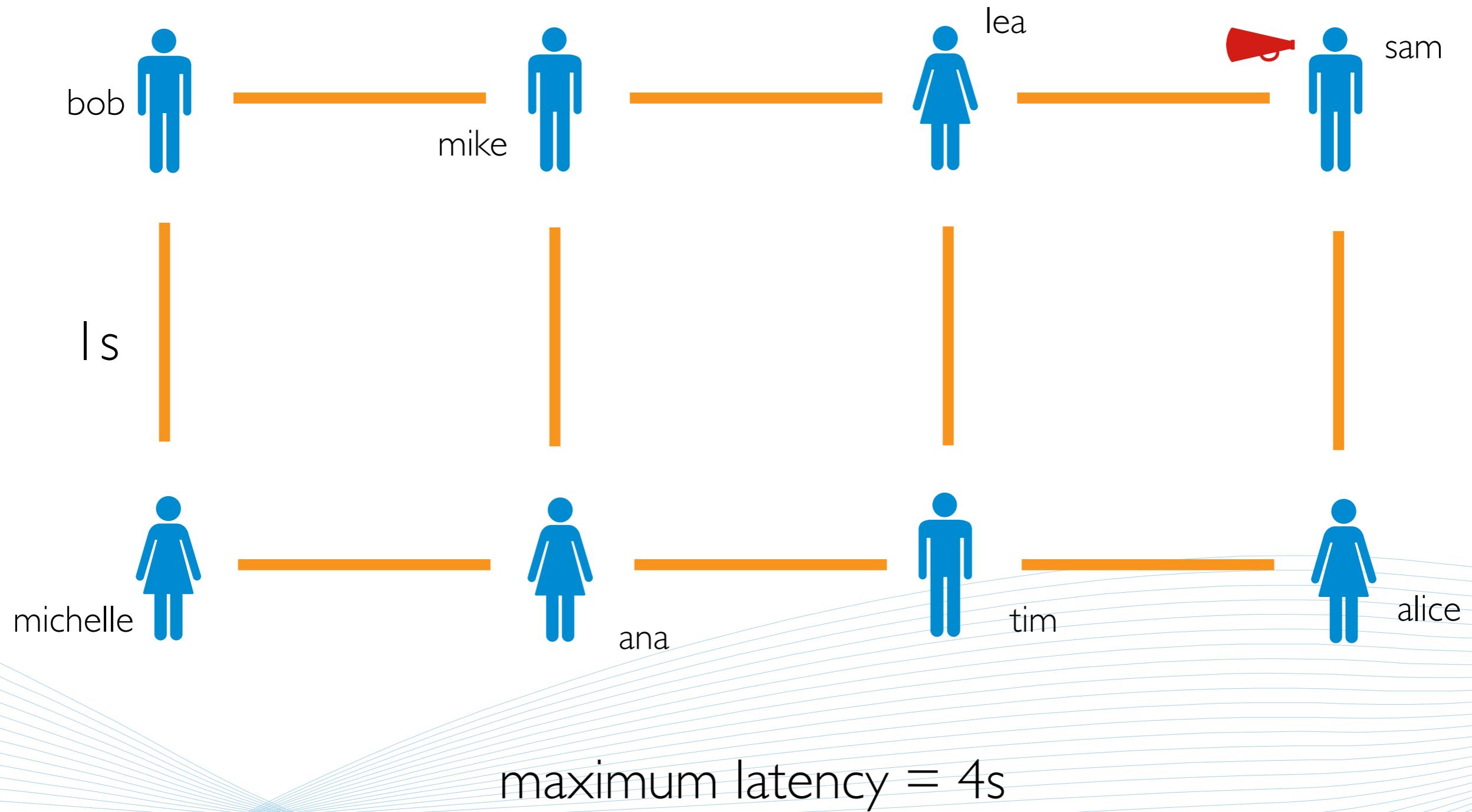
# Experiment

t =

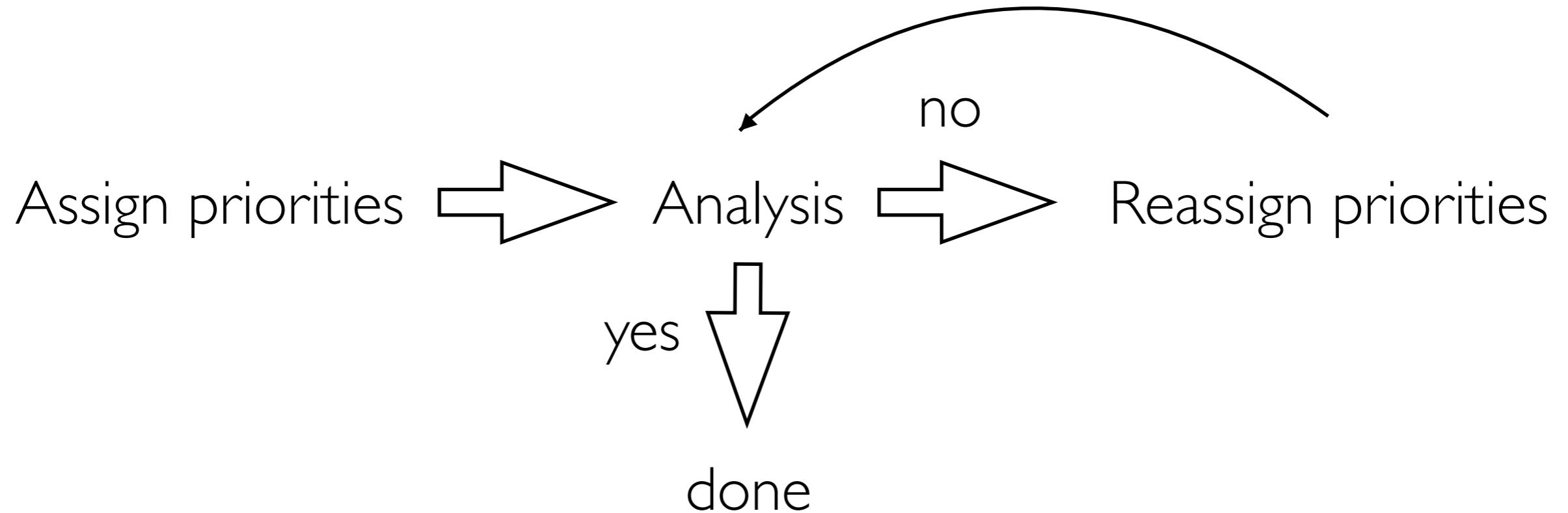


# Experiment

t =



# How?



## Compositionality?

Ensuring Reliable Networks



# Alternative

# Alternative



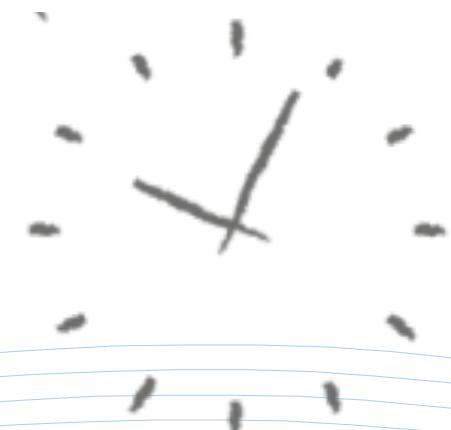
Sending and receiving of frames is done according to a global schedule.

# Alternative



Sending and receiving of frames is done according to a global schedule.

Devices (switches, end systems, etc.) have a common understanding of time.



# Technologies

CAN

Profinet

TTP

EtherCAT

TTEthernet

provides real-time and safety capabilities over Ethernet, in a way that is fully compatible with IEEE 802 Ethernet standards

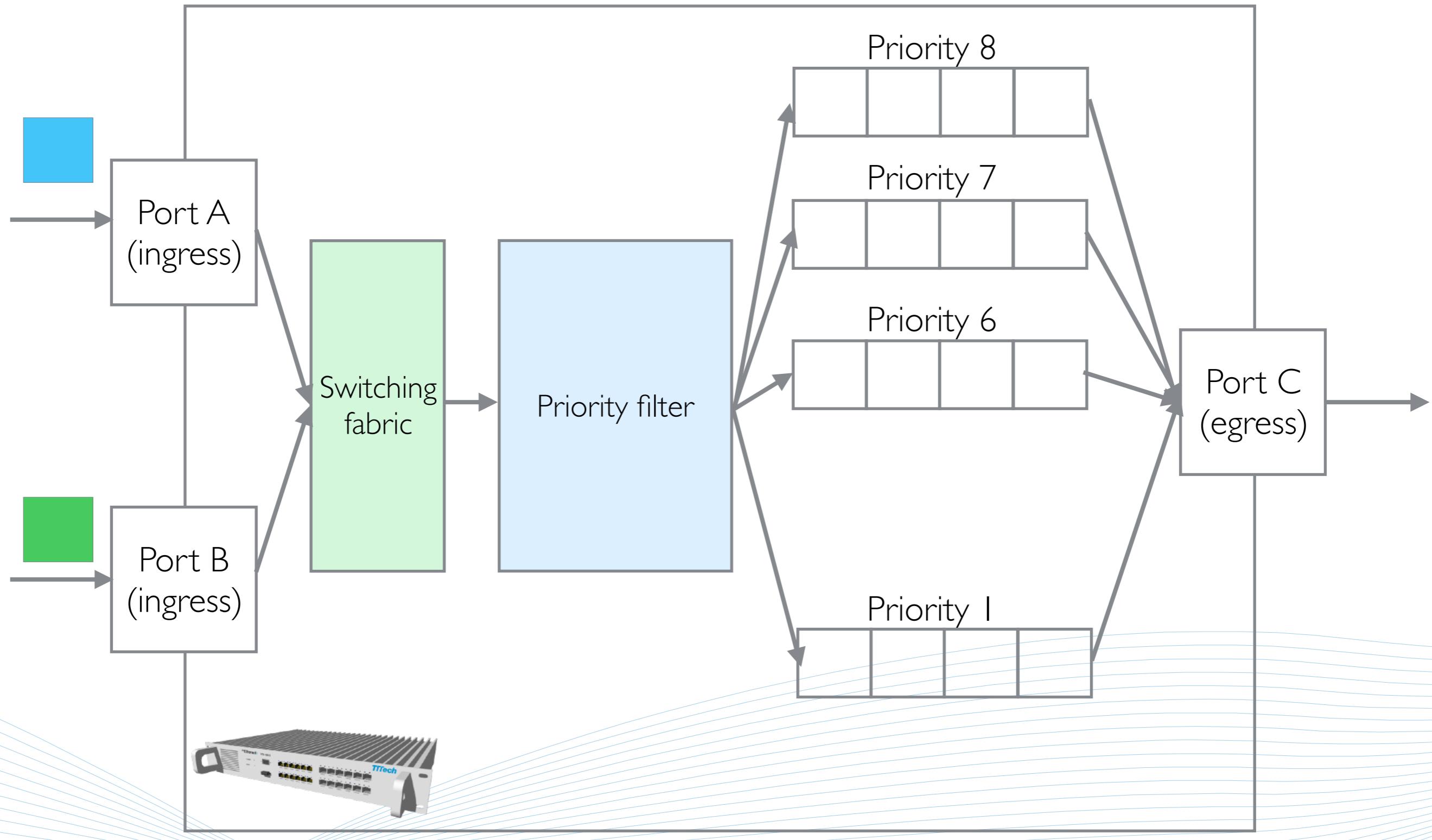
Proprietary

TSN

# Priority switch

Ensuring Reliable Networks

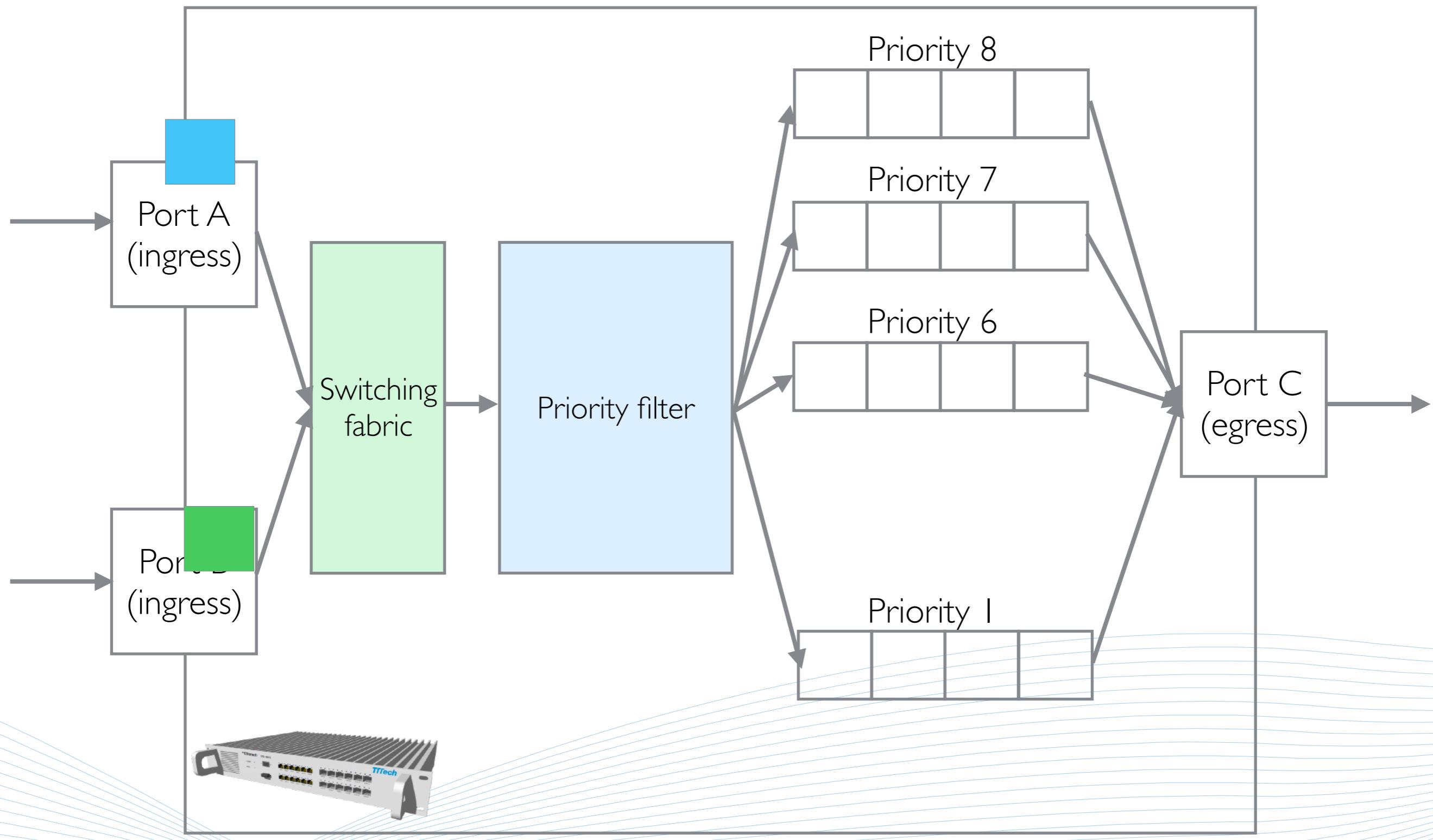
**TTTech**



# Priority switch

Ensuring Reliable Networks

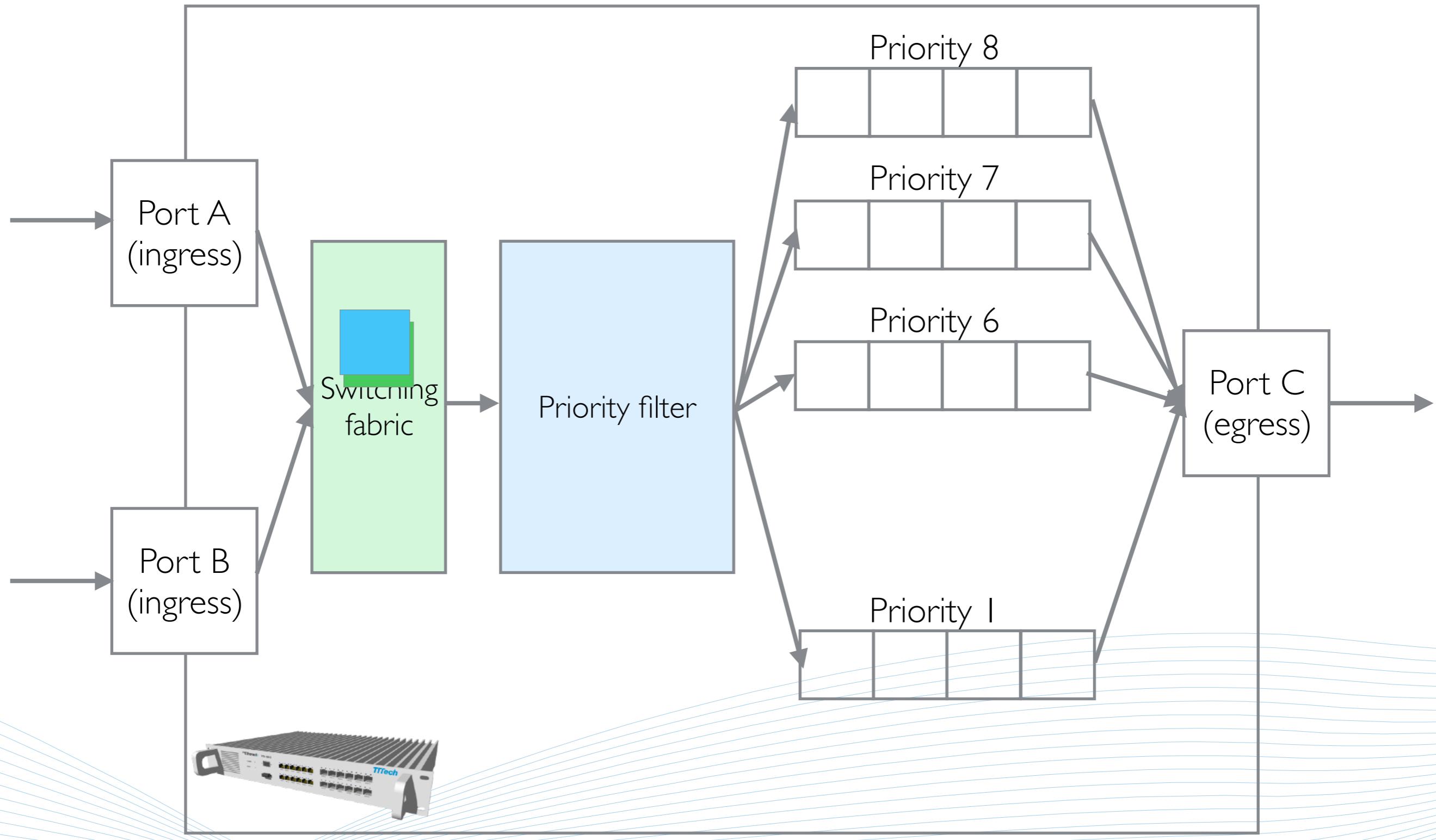
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Ensuring Reliable Networks

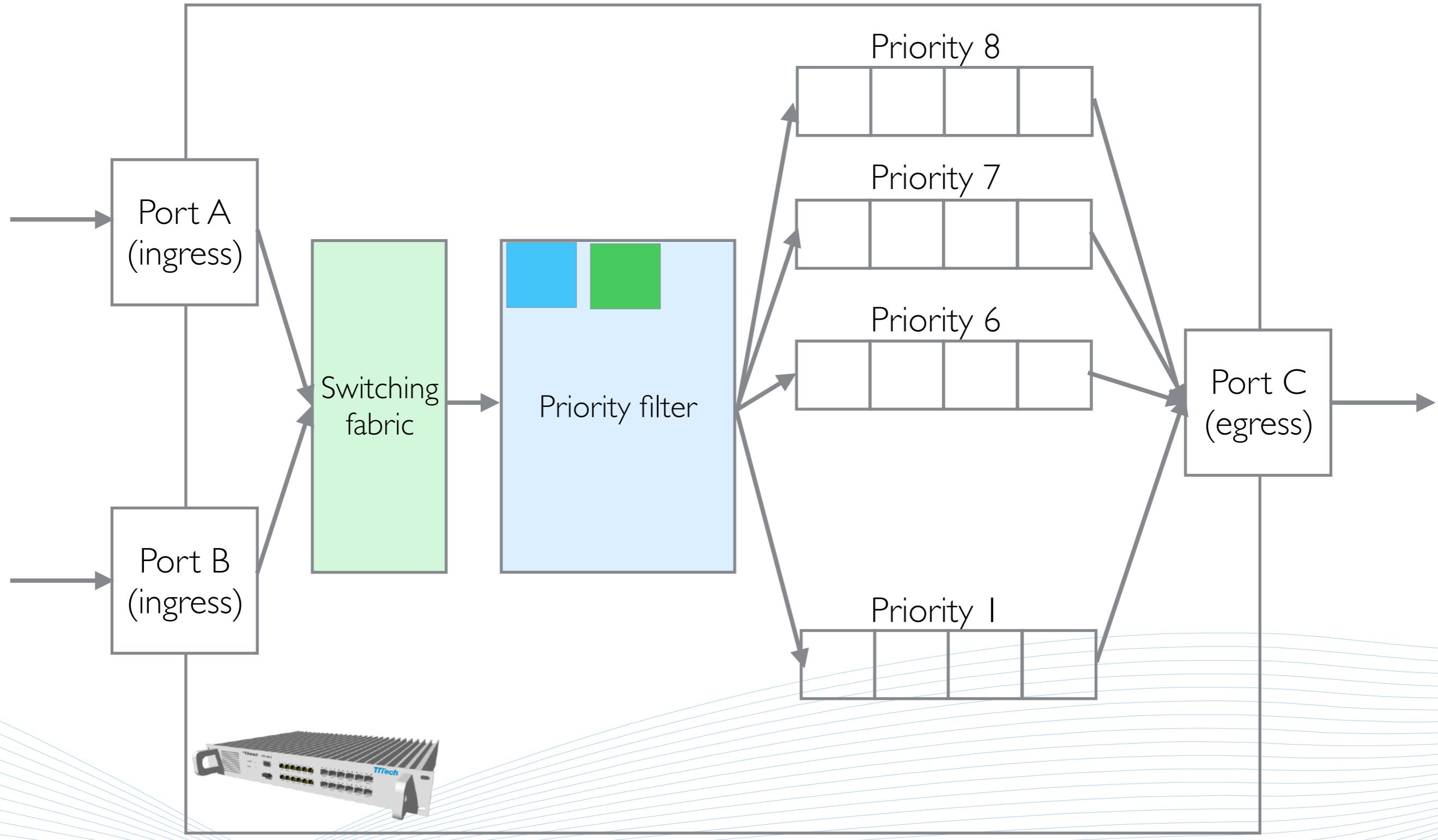
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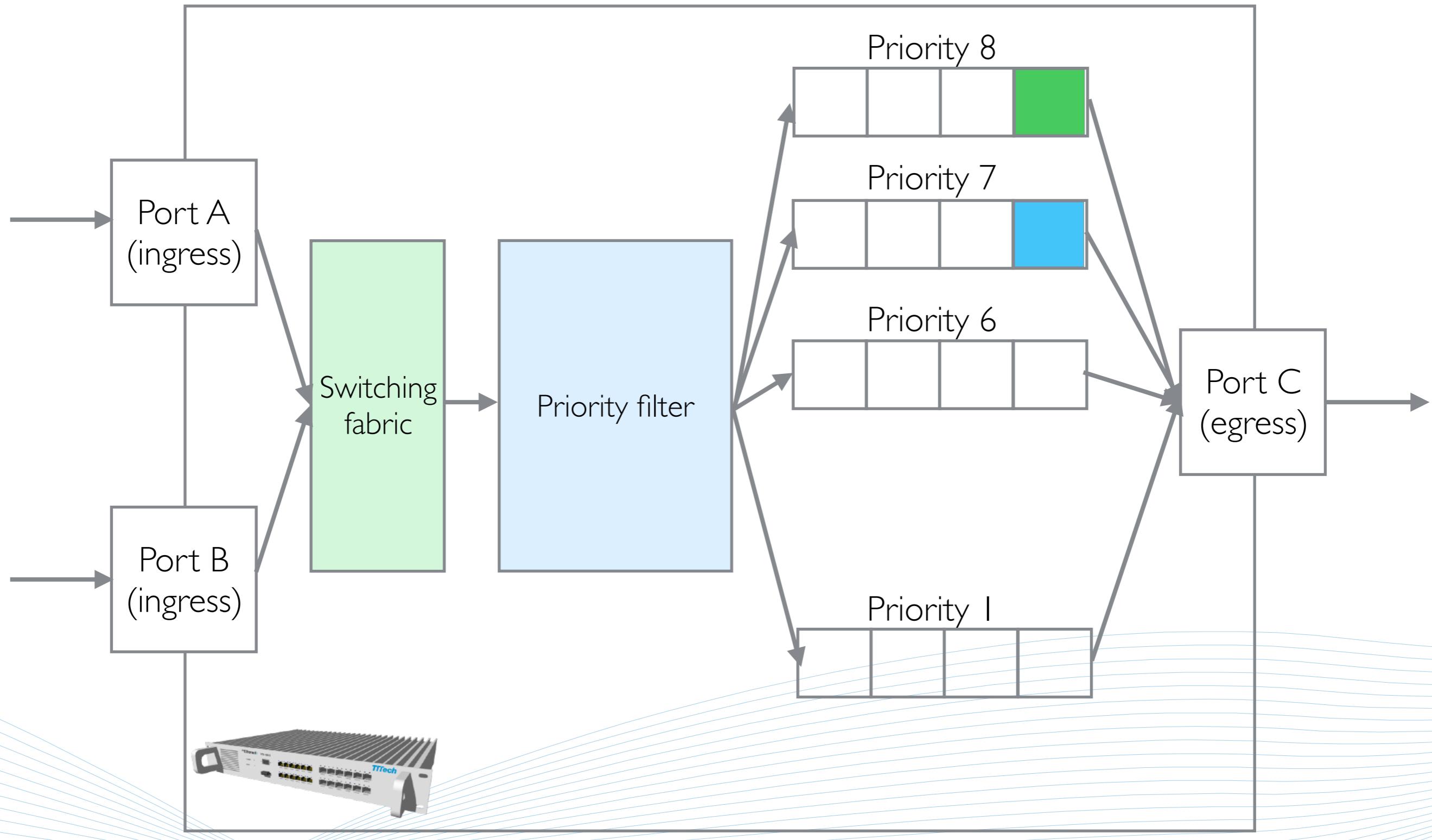
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# Priority switch

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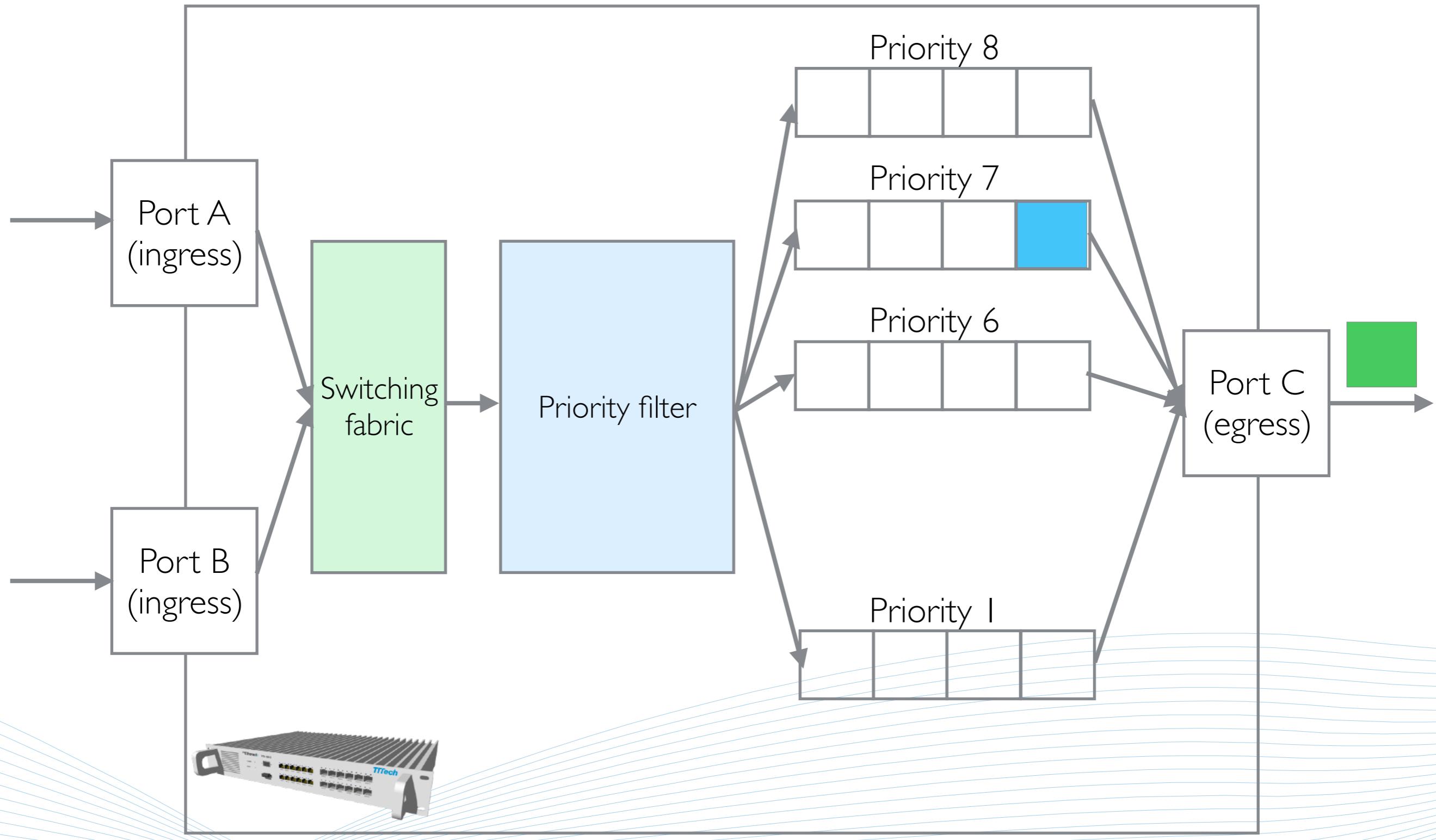
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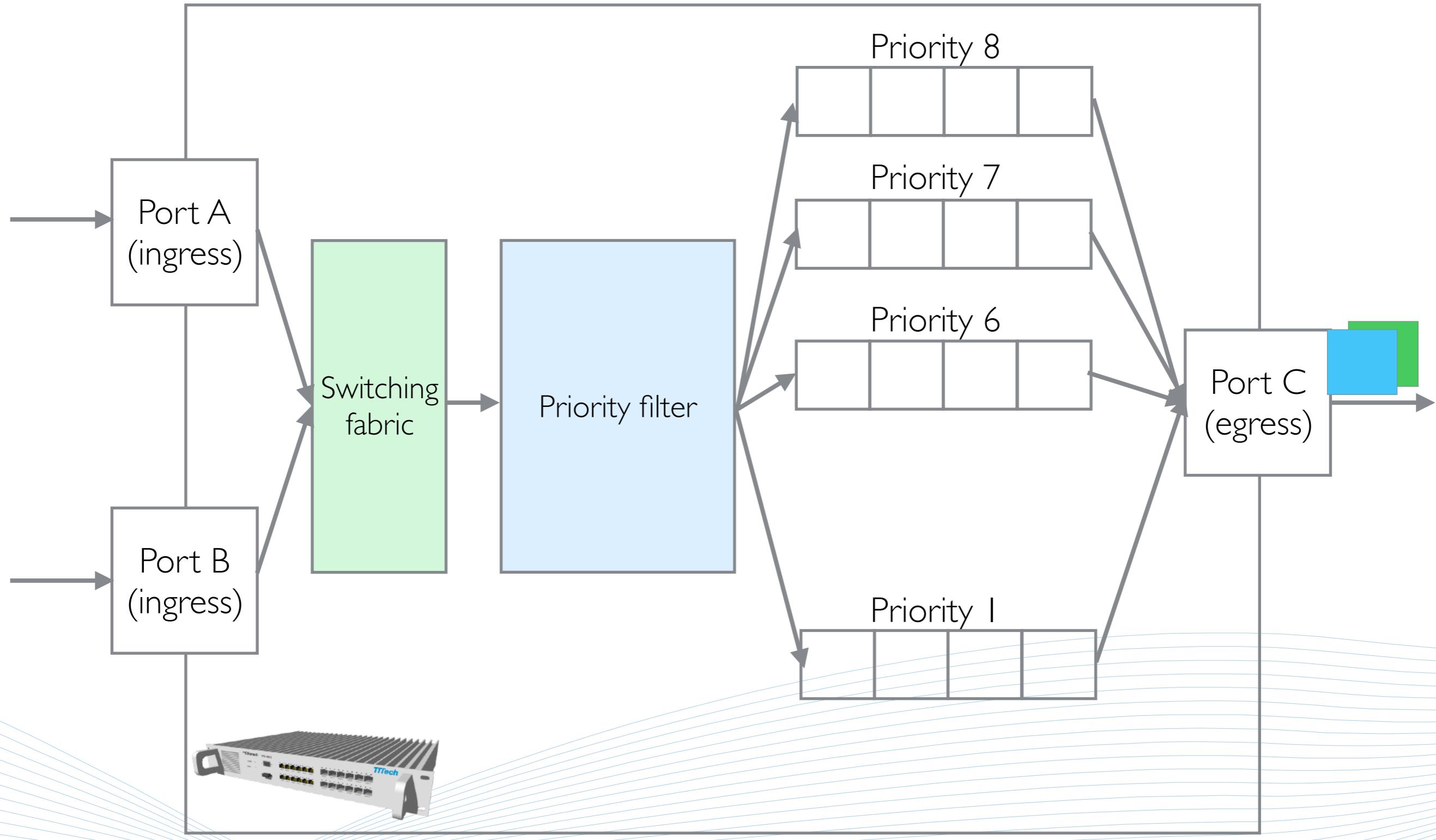
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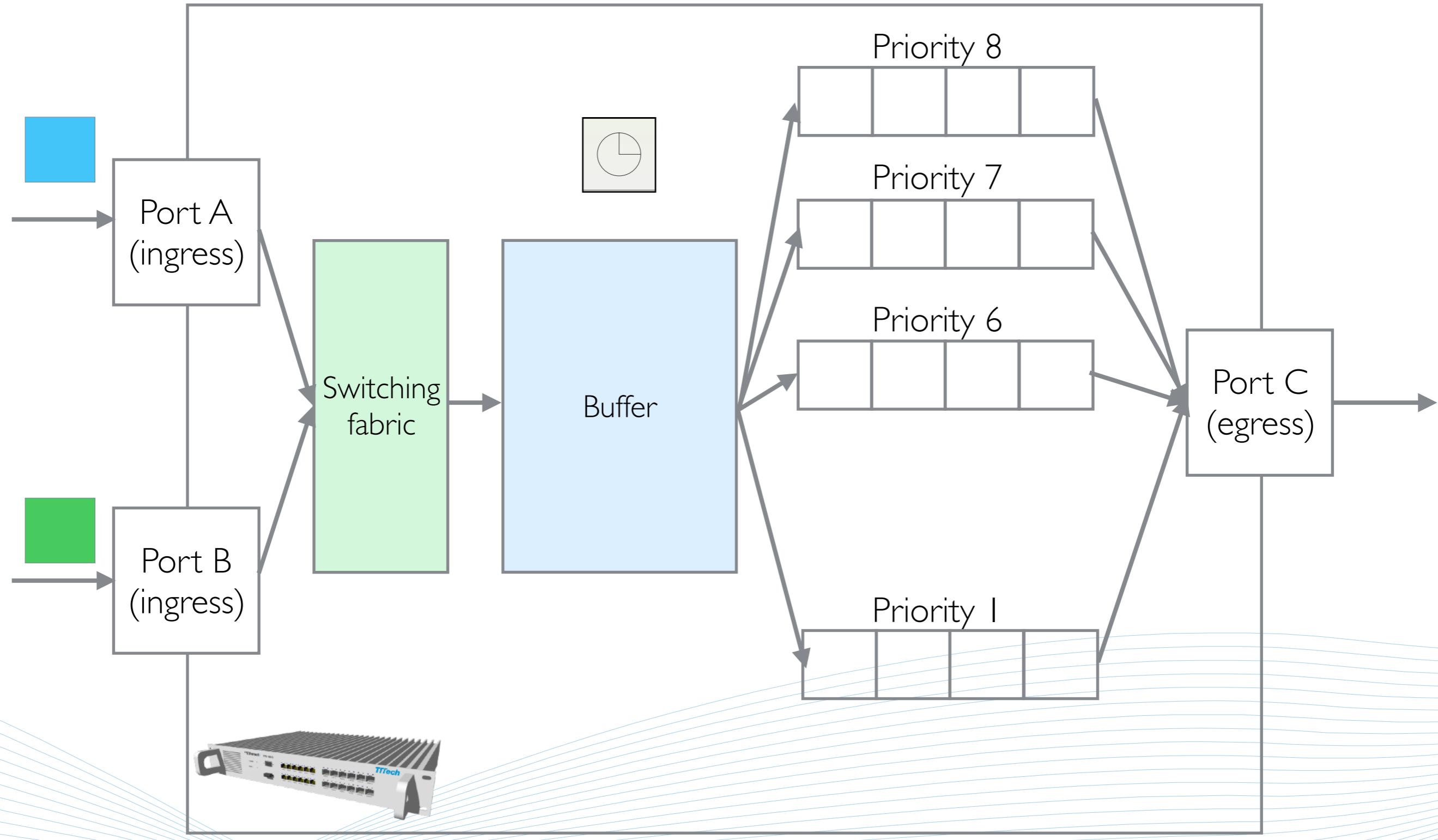
**TTTech**



# TTEthernet switch

Ensuring Reliable Networks

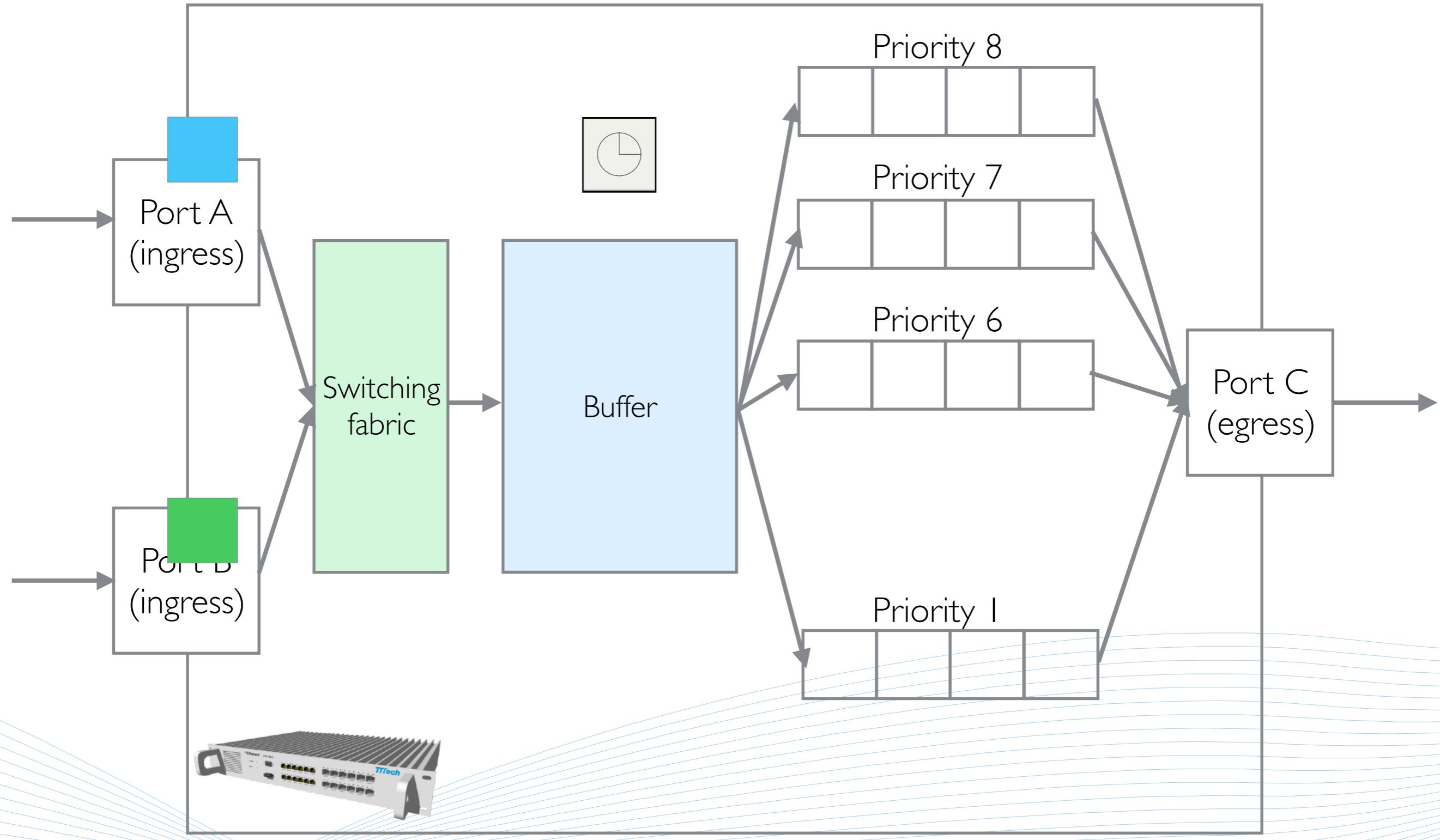
**TTTech**



# TTEthernet switch

Ensuring Reliable Networks

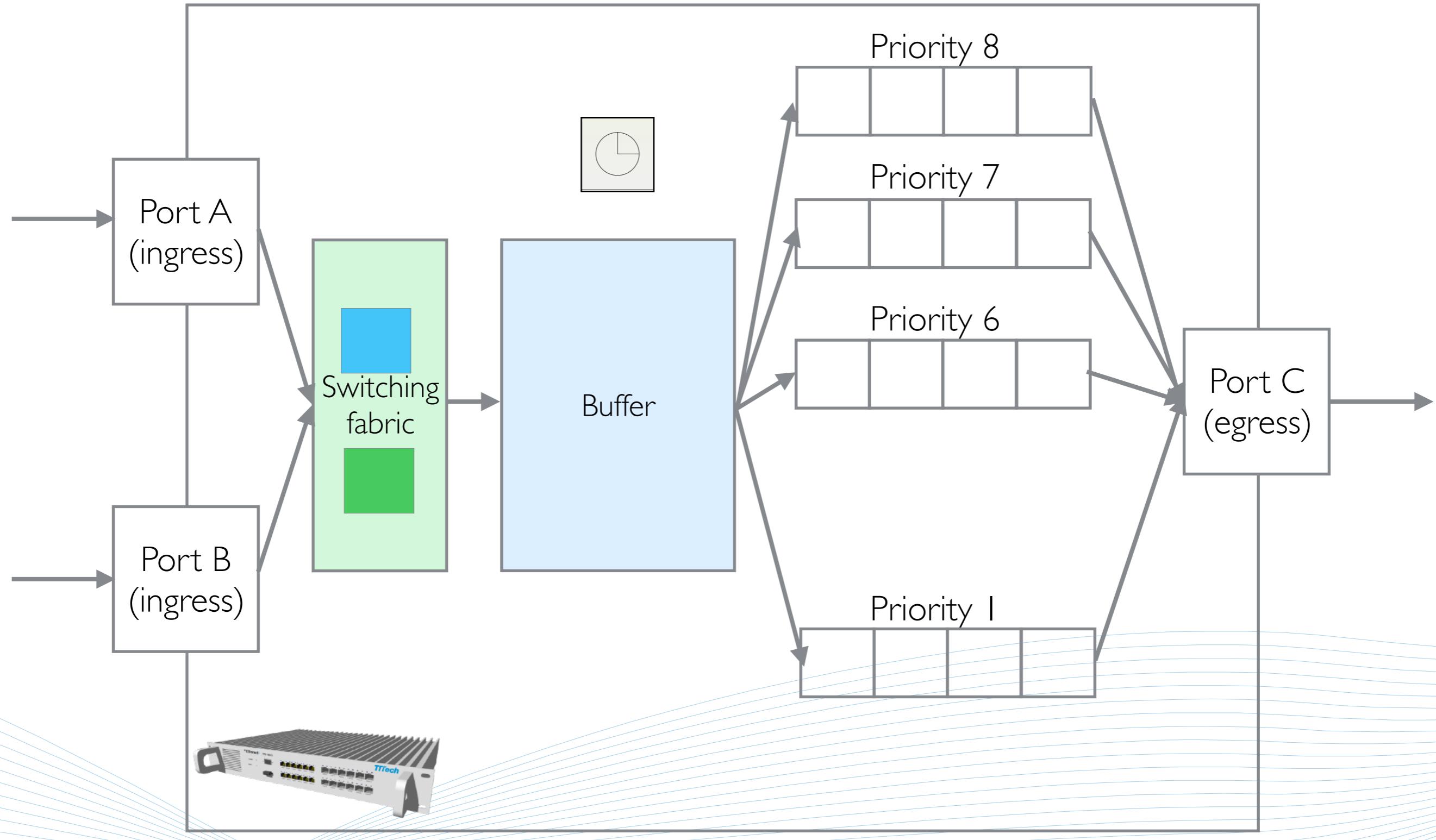
**TTTech**



# TTEthernet switch

Ensuring Reliable Networks

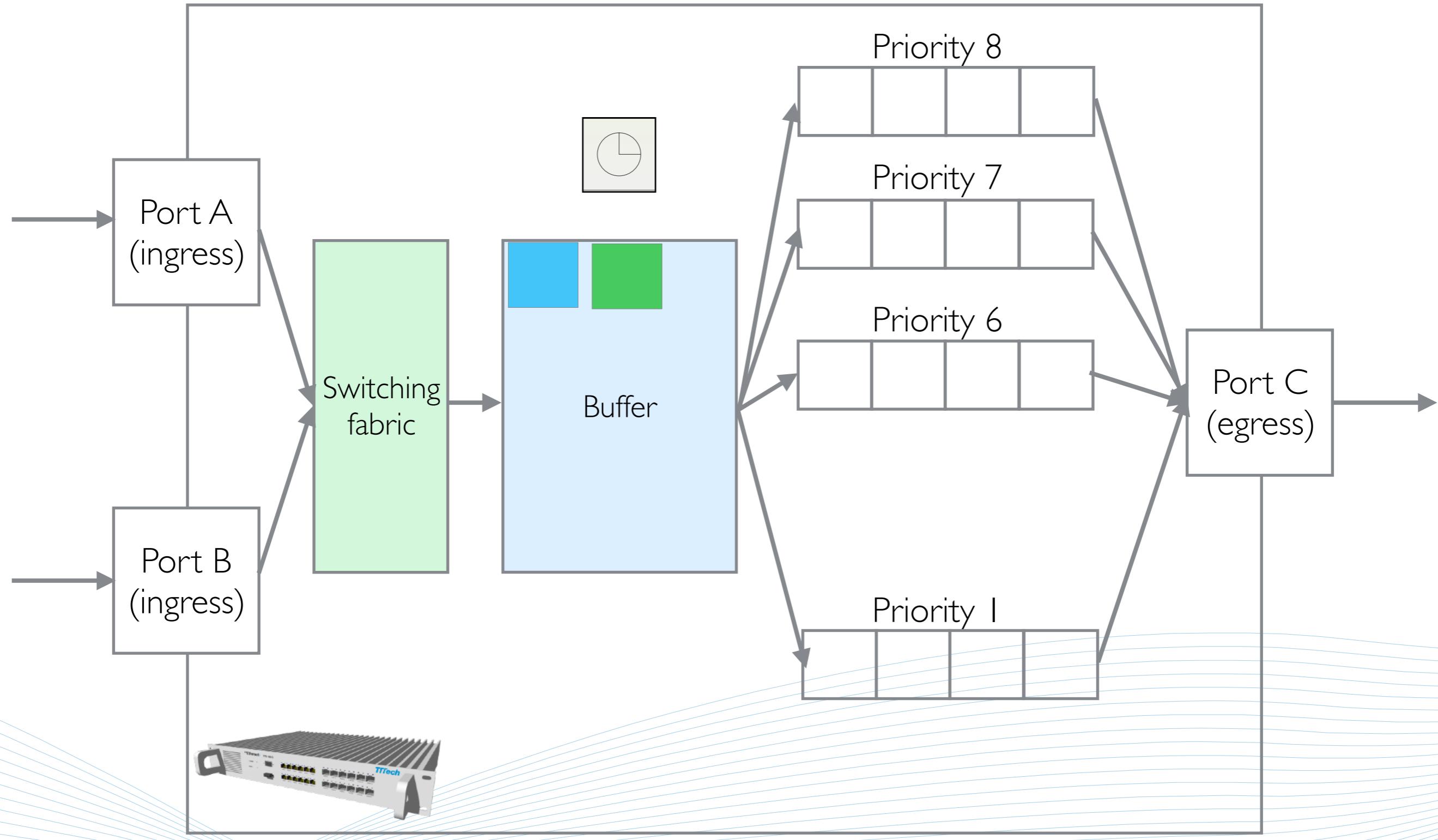
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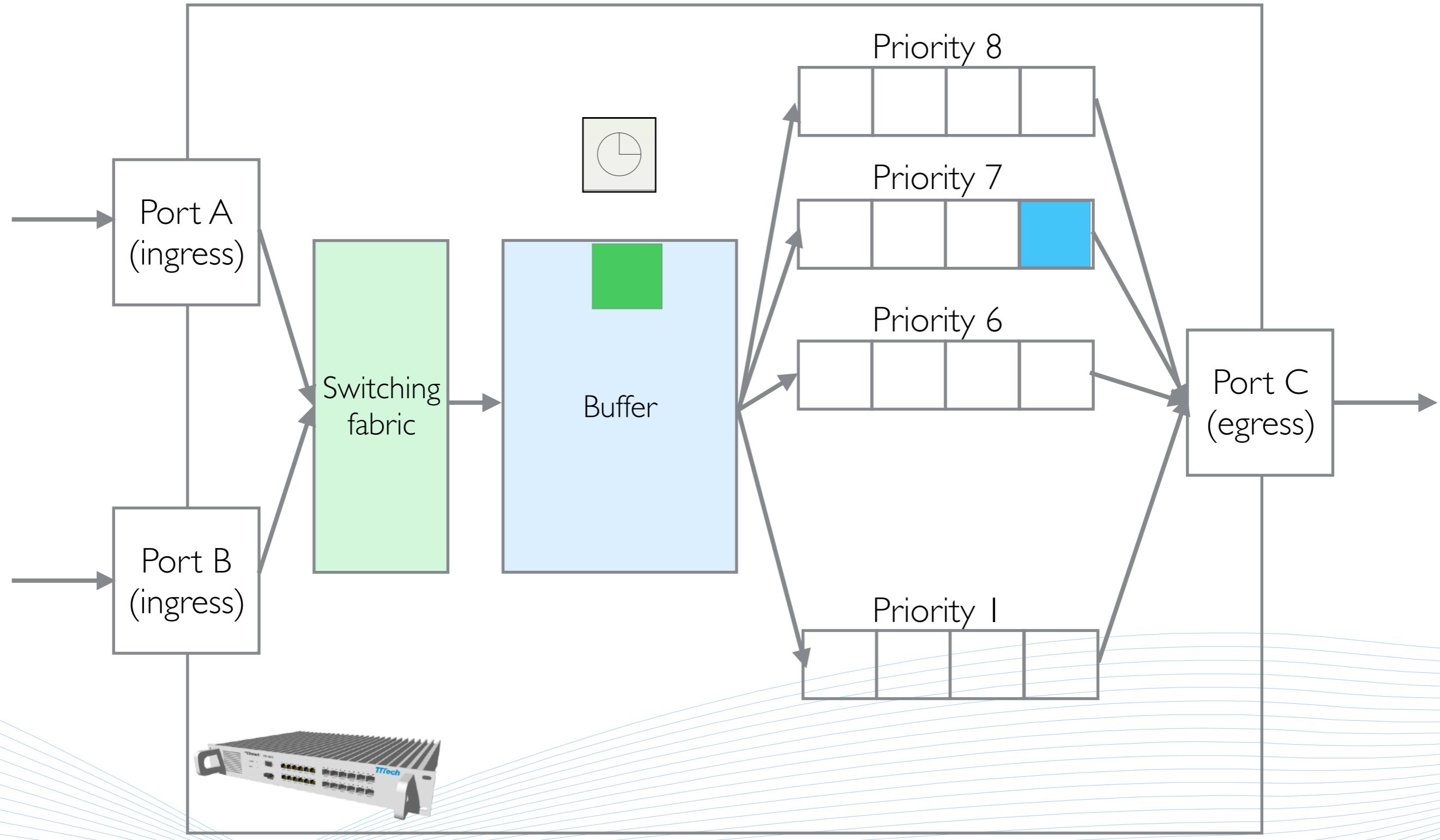
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# TTEthernet switch

Ensuring Reliable Networks

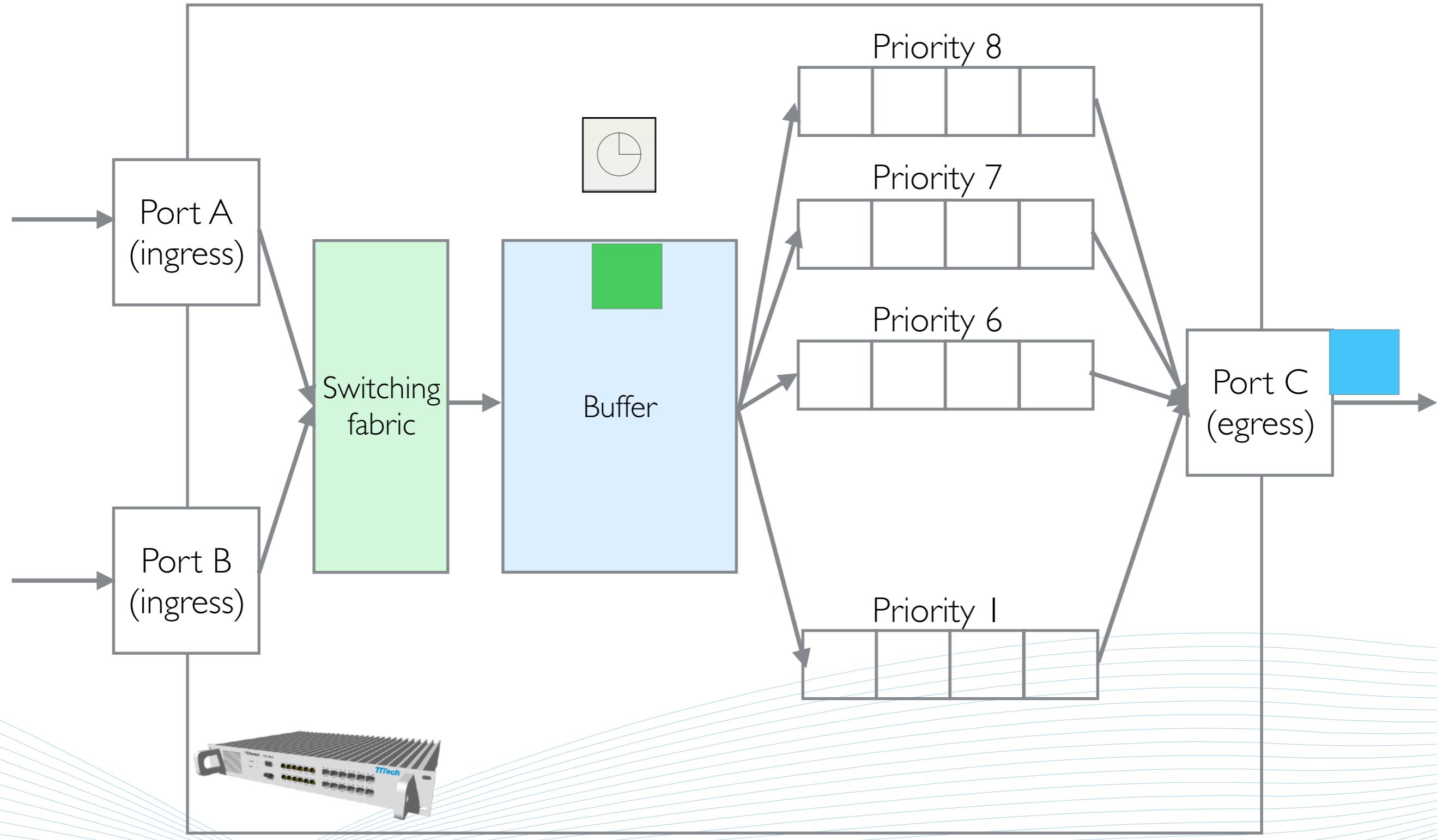
**TTTech**



# TTEthernet switch

Ensuring Reliable Networks

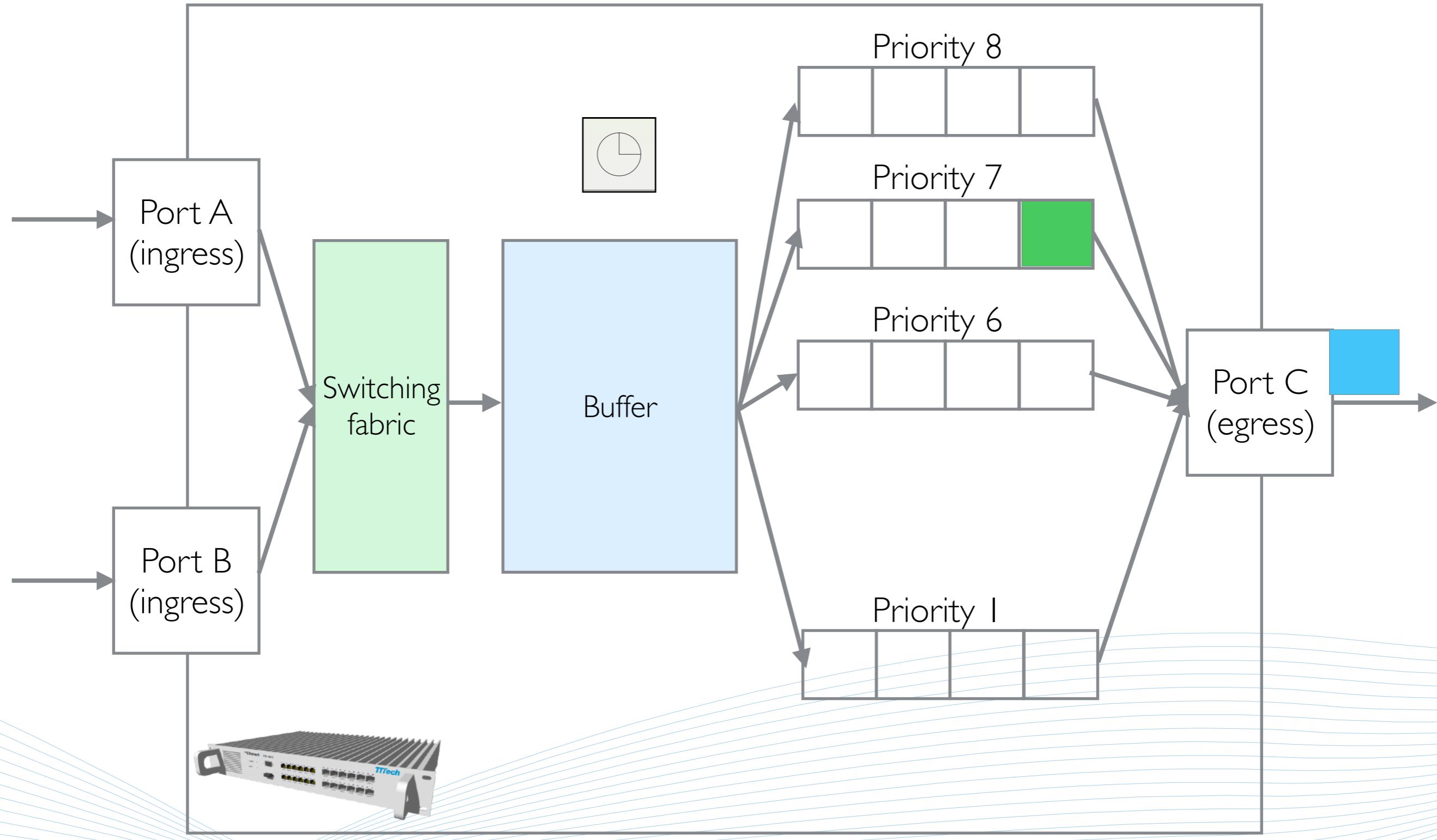
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Ensuring Reliable Networks

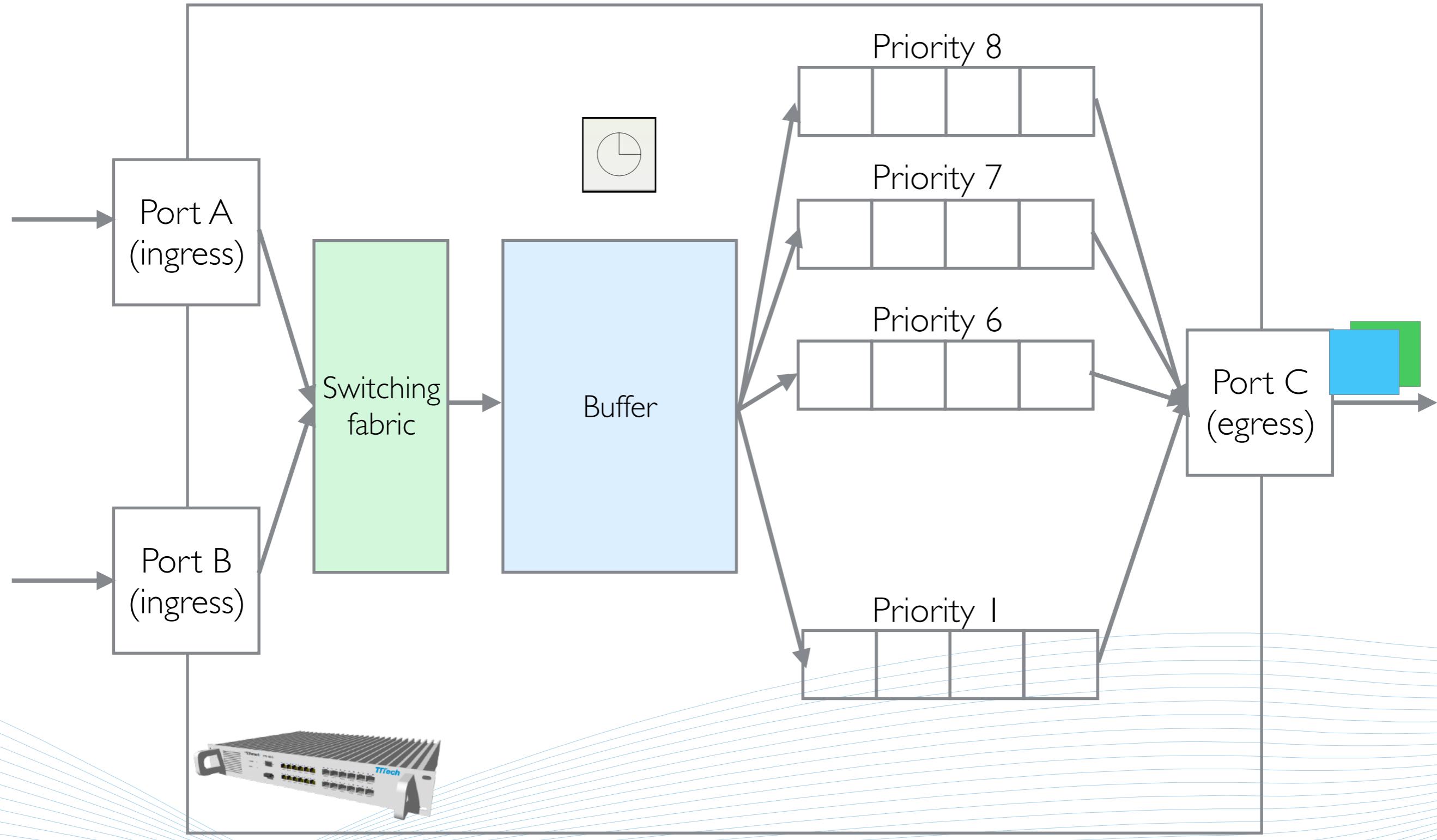
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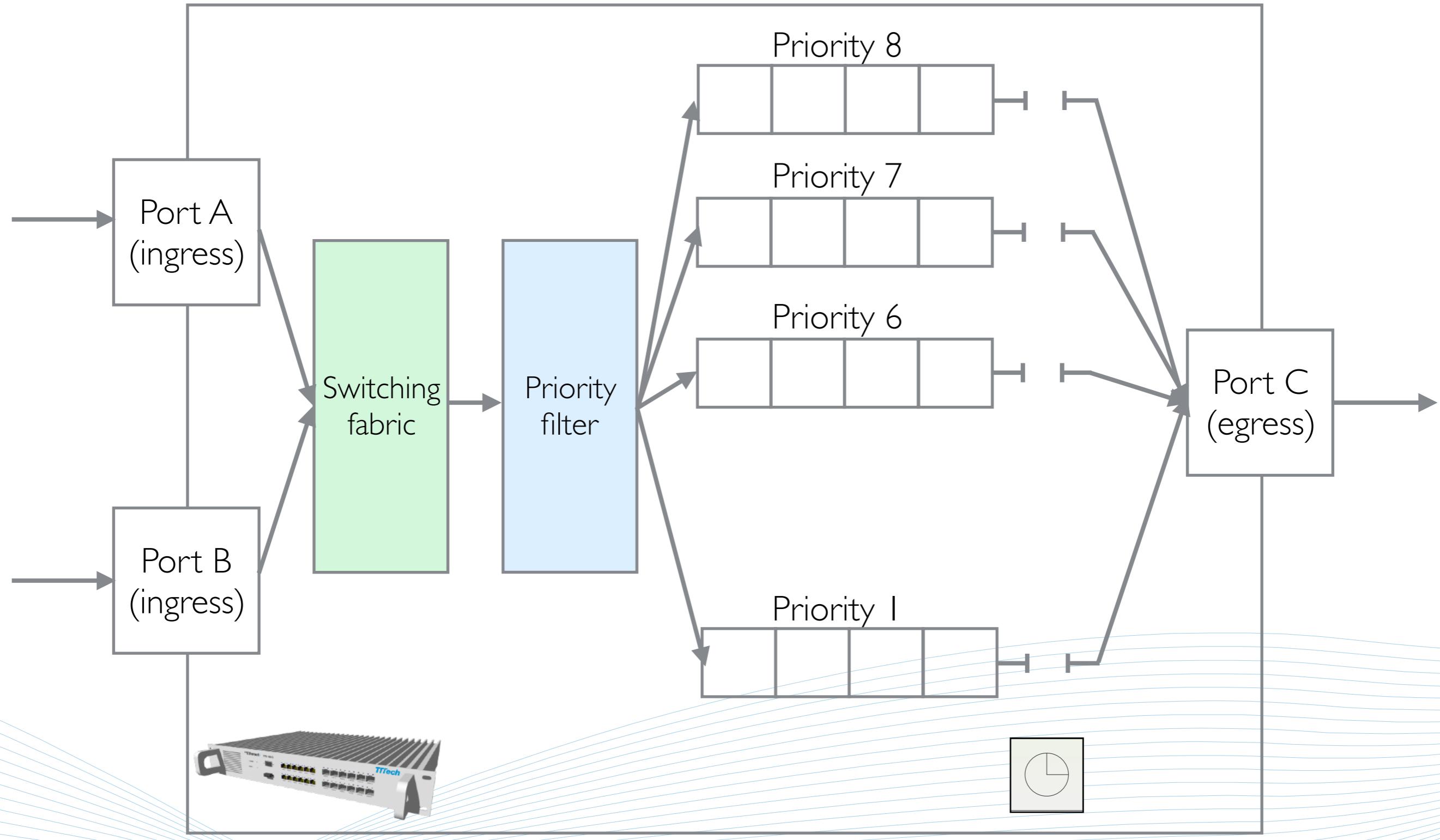
**TTTech**



# TSN switch

Ensuring Reliable Networks

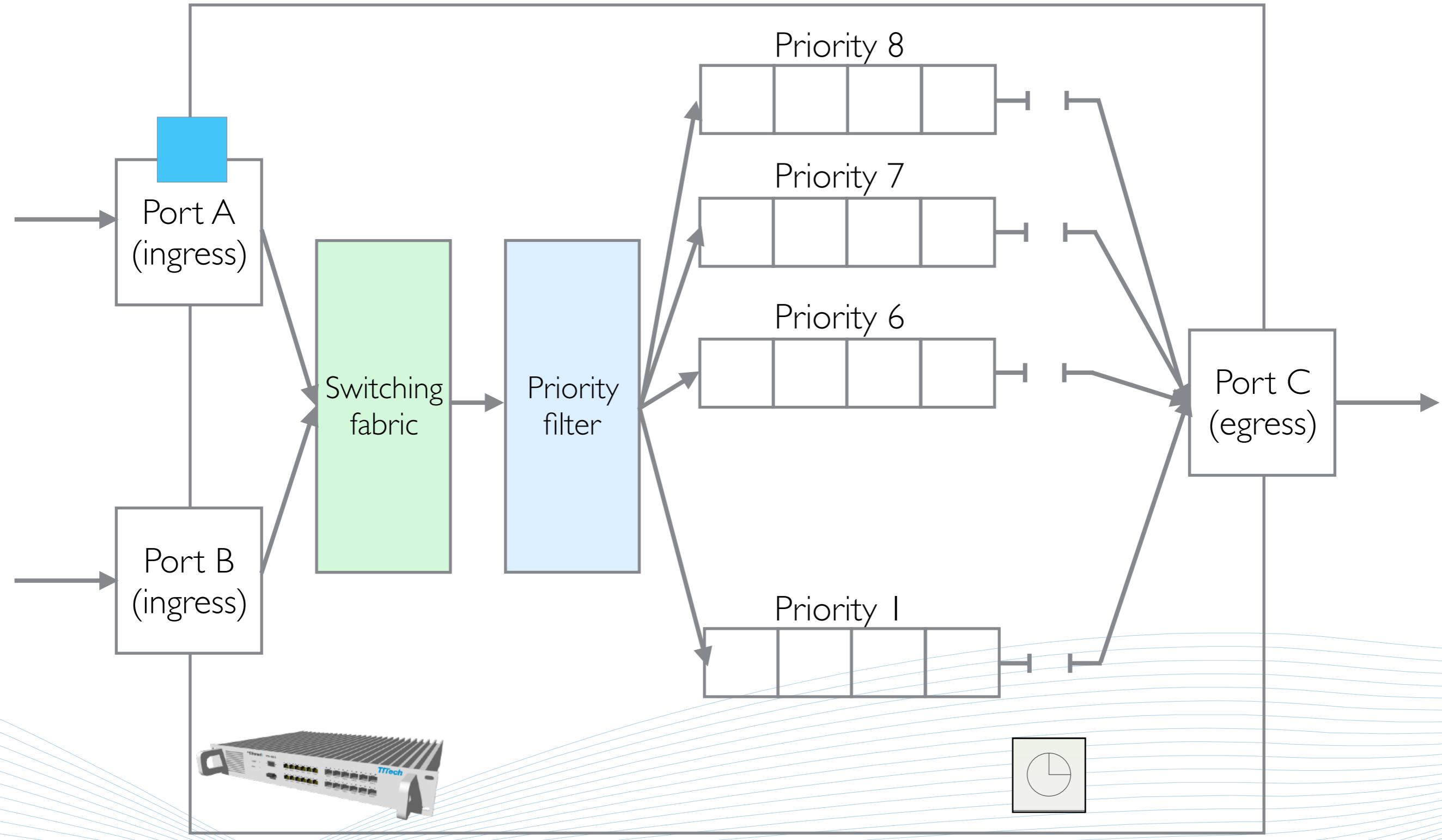
**TTTech**



# TSN switch

Ensuring Reliable Networks

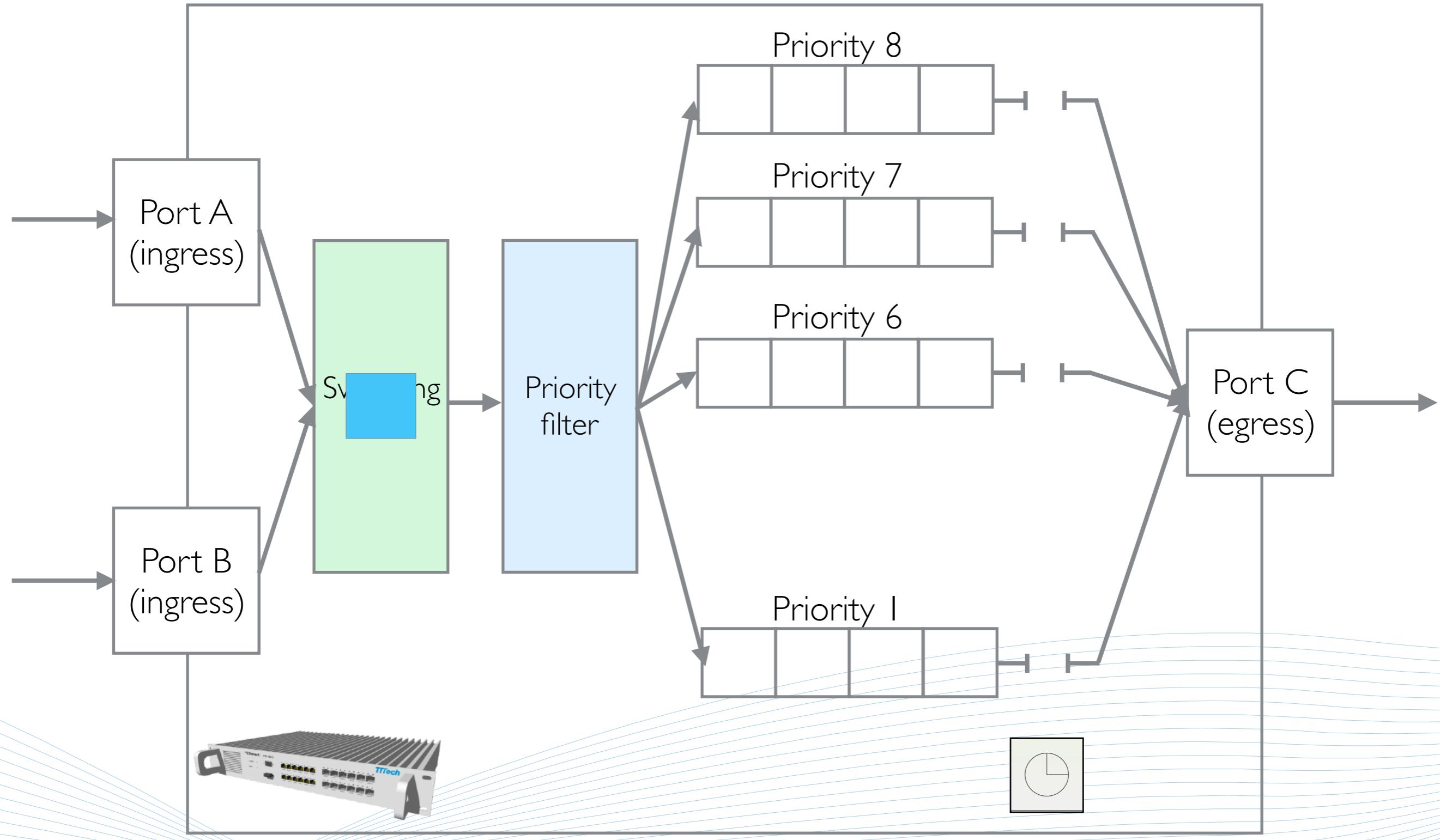
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# TSN switch

Ensuring Reliable Networks

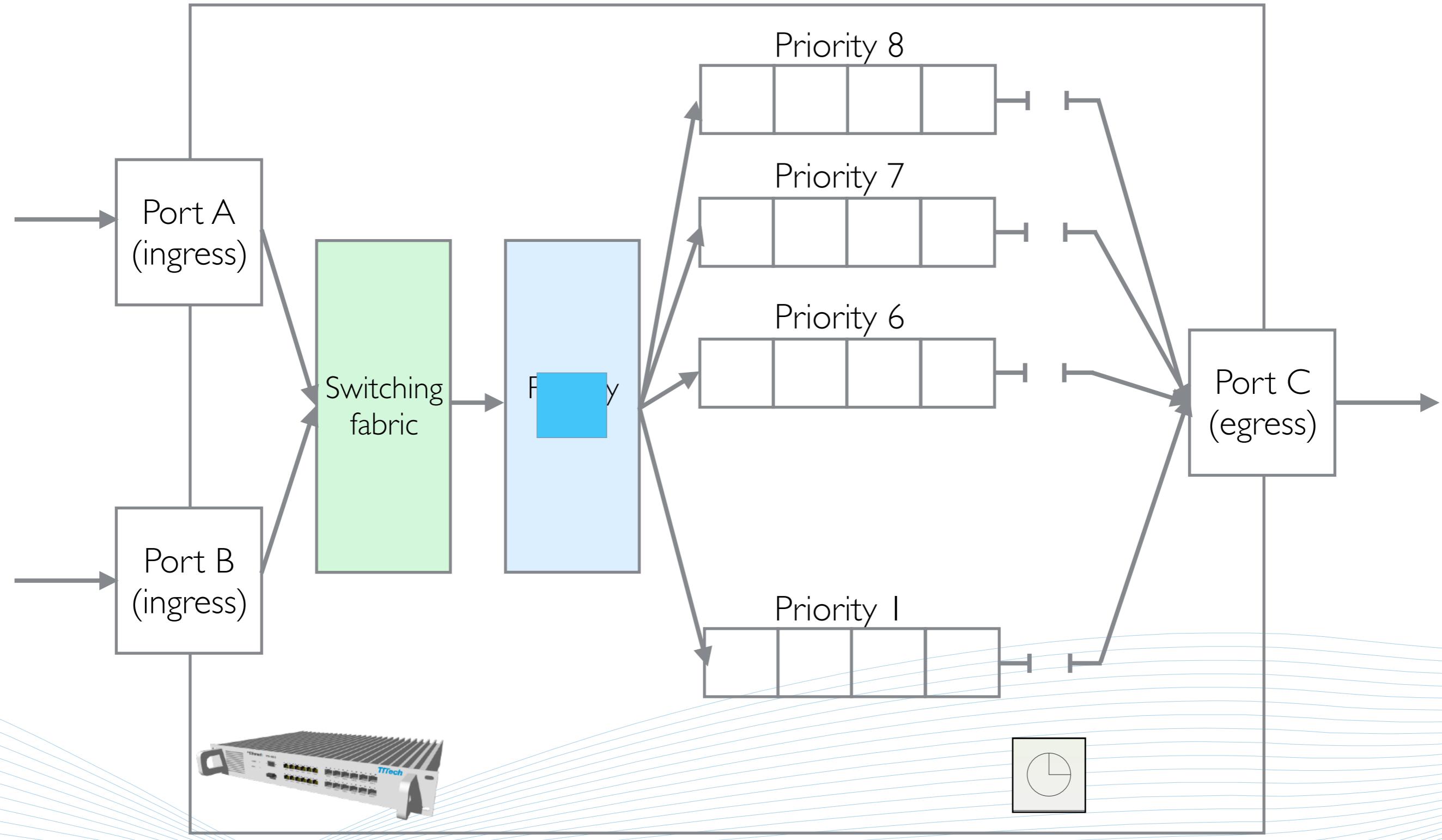
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# TSN switch

Ensuring Reliable Networks

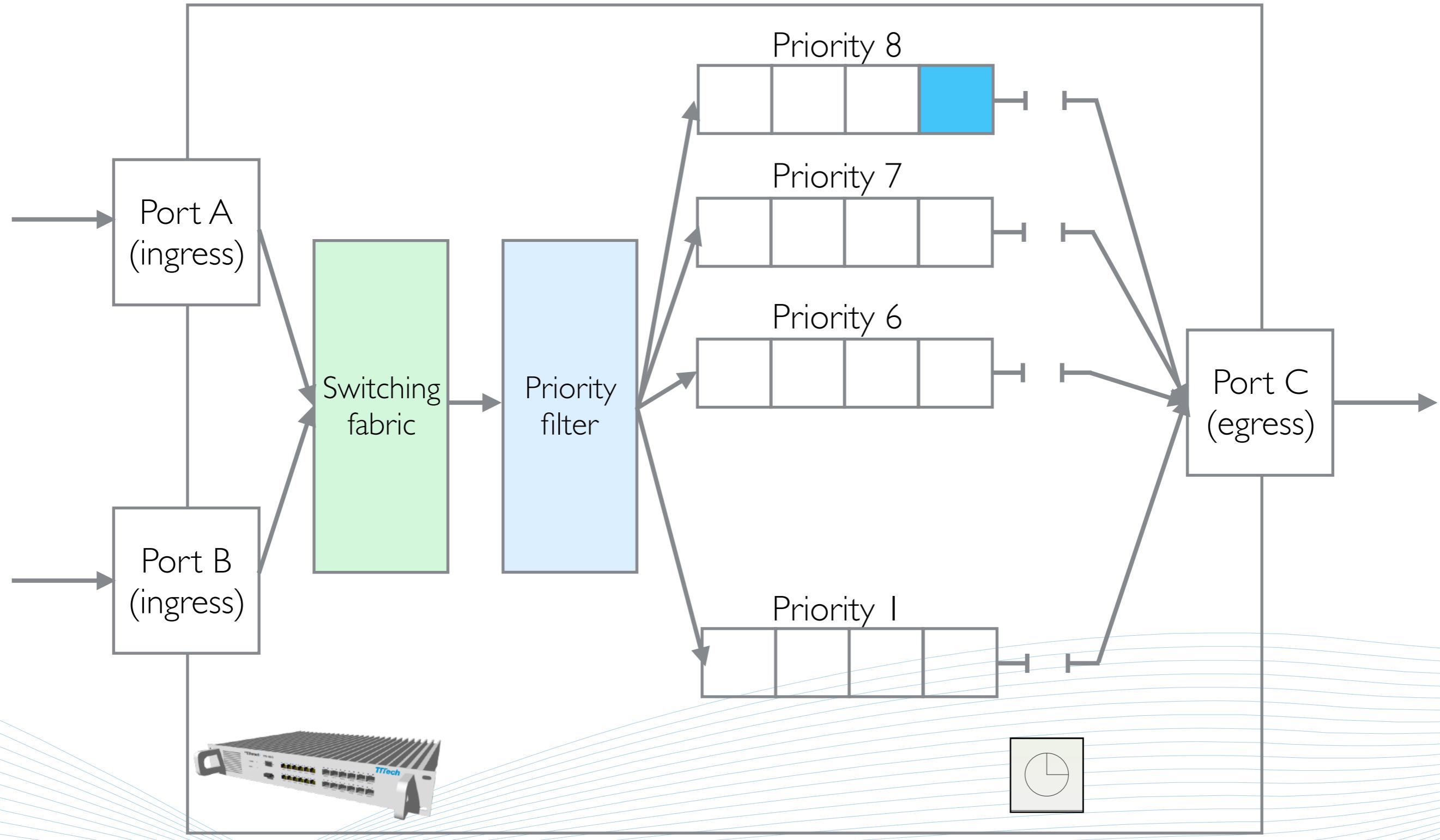
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# TSN switch

Ensuring Reliable Networks

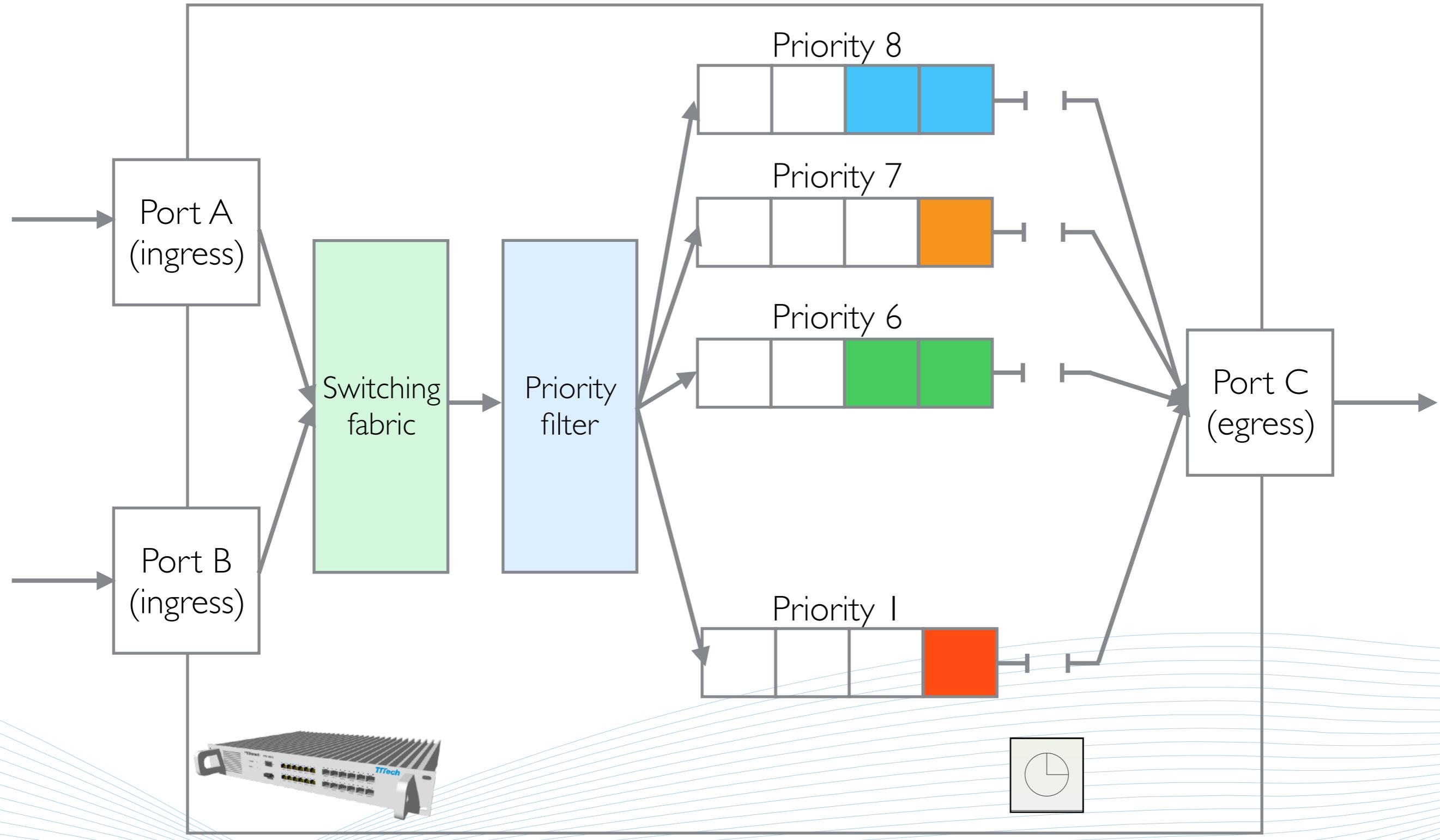
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Ensuring Reliable Networks

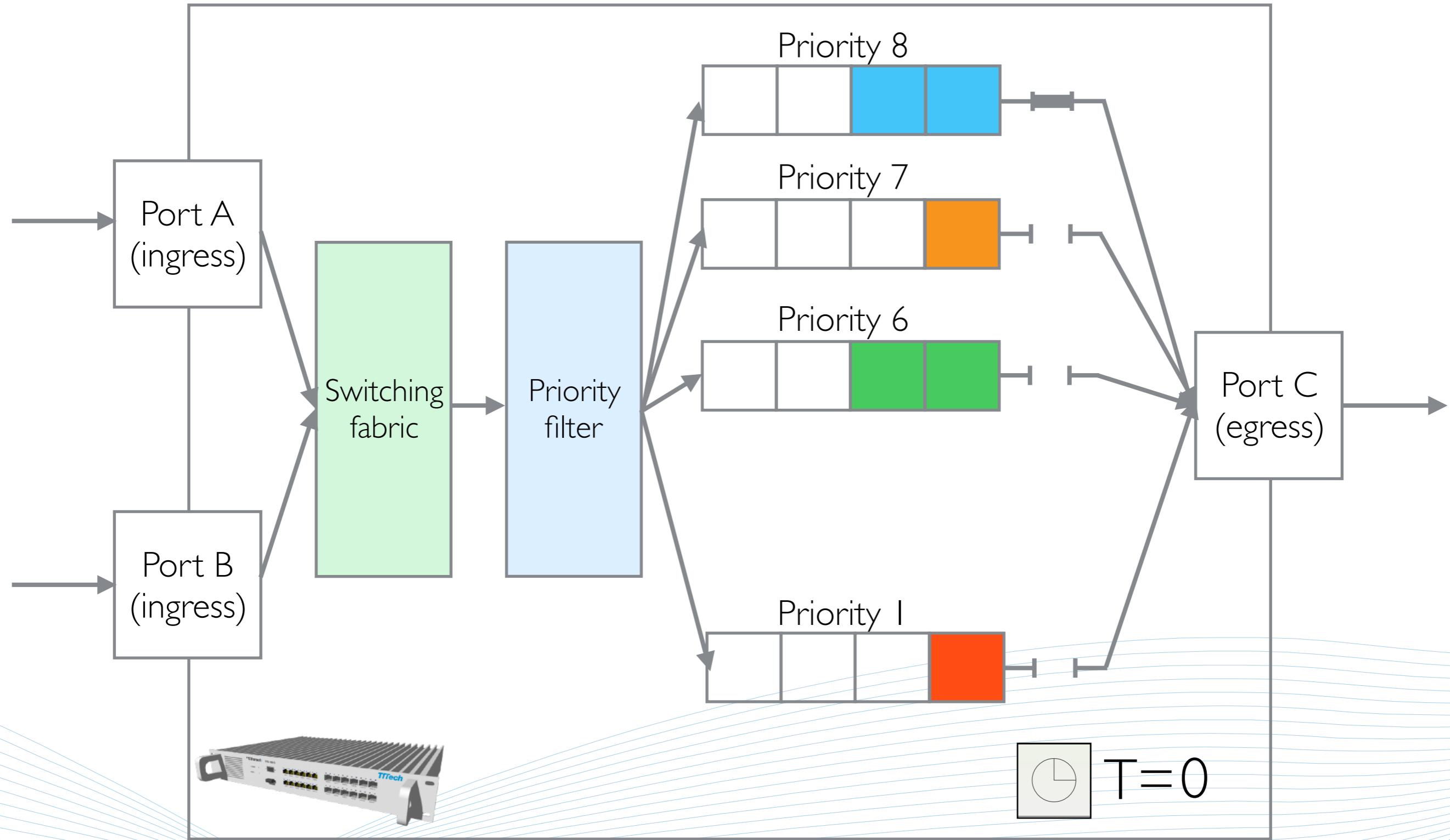
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Ensuring Reliable Networks

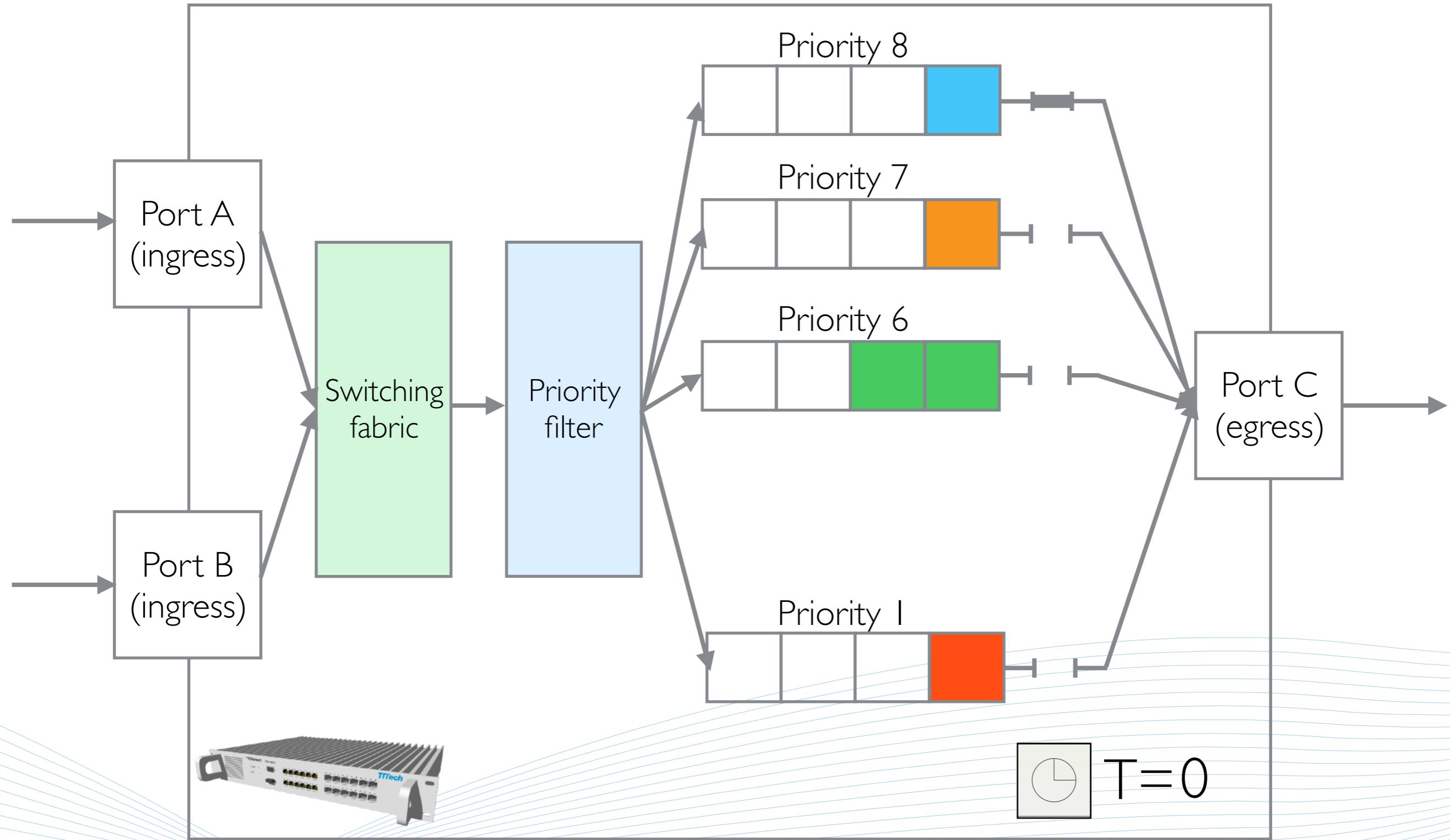
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Ensuring Reliable Networks

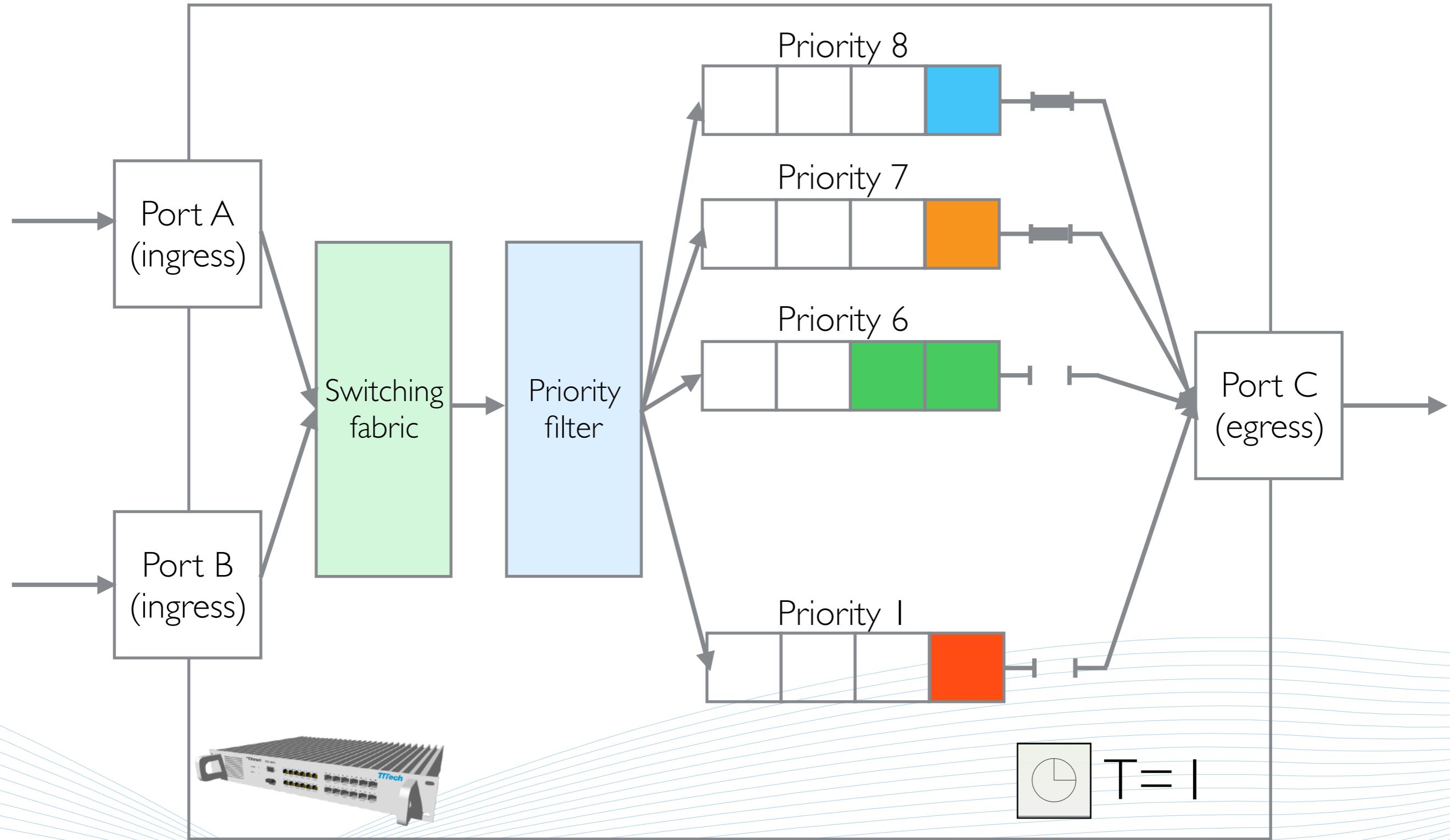
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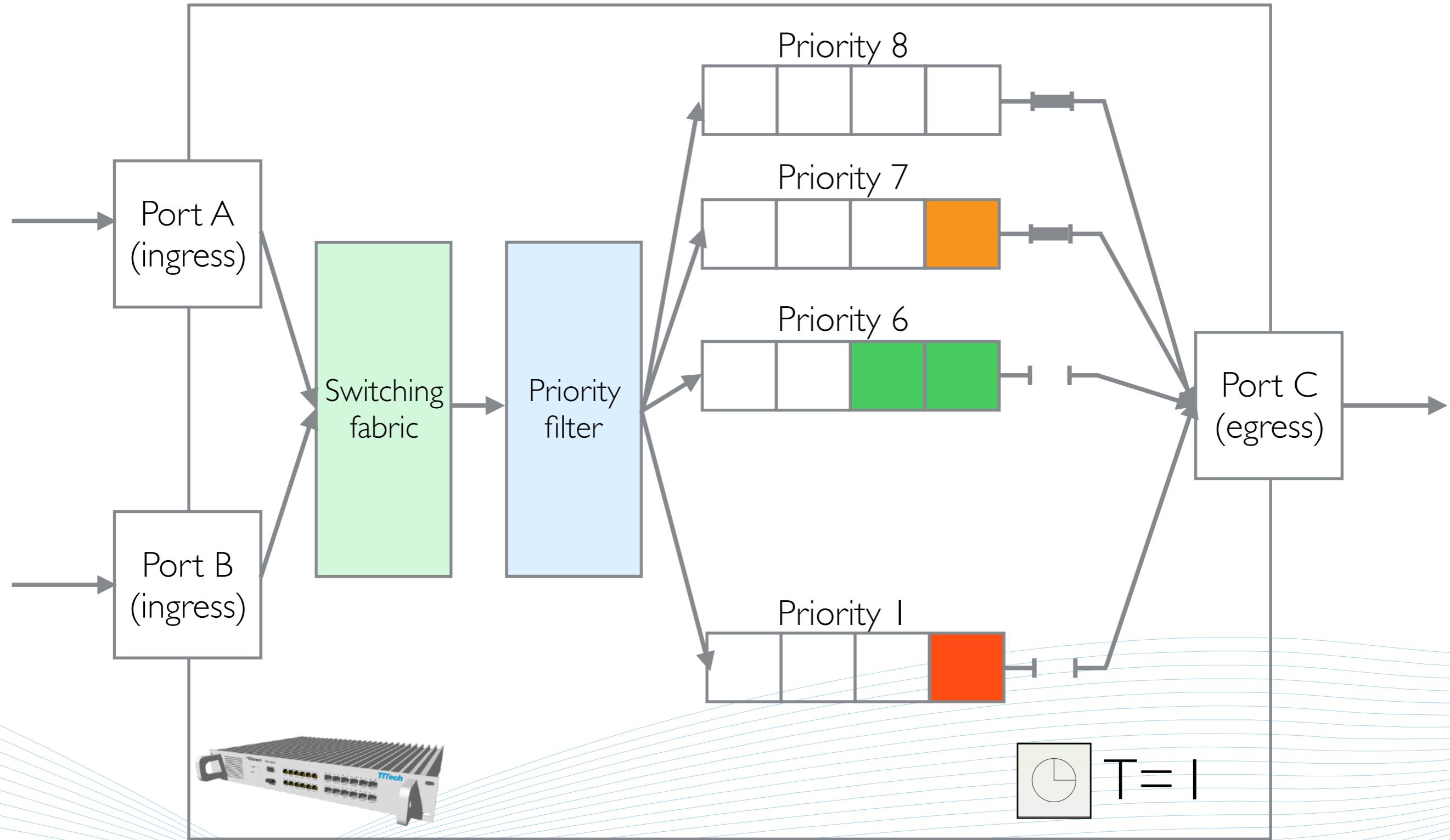
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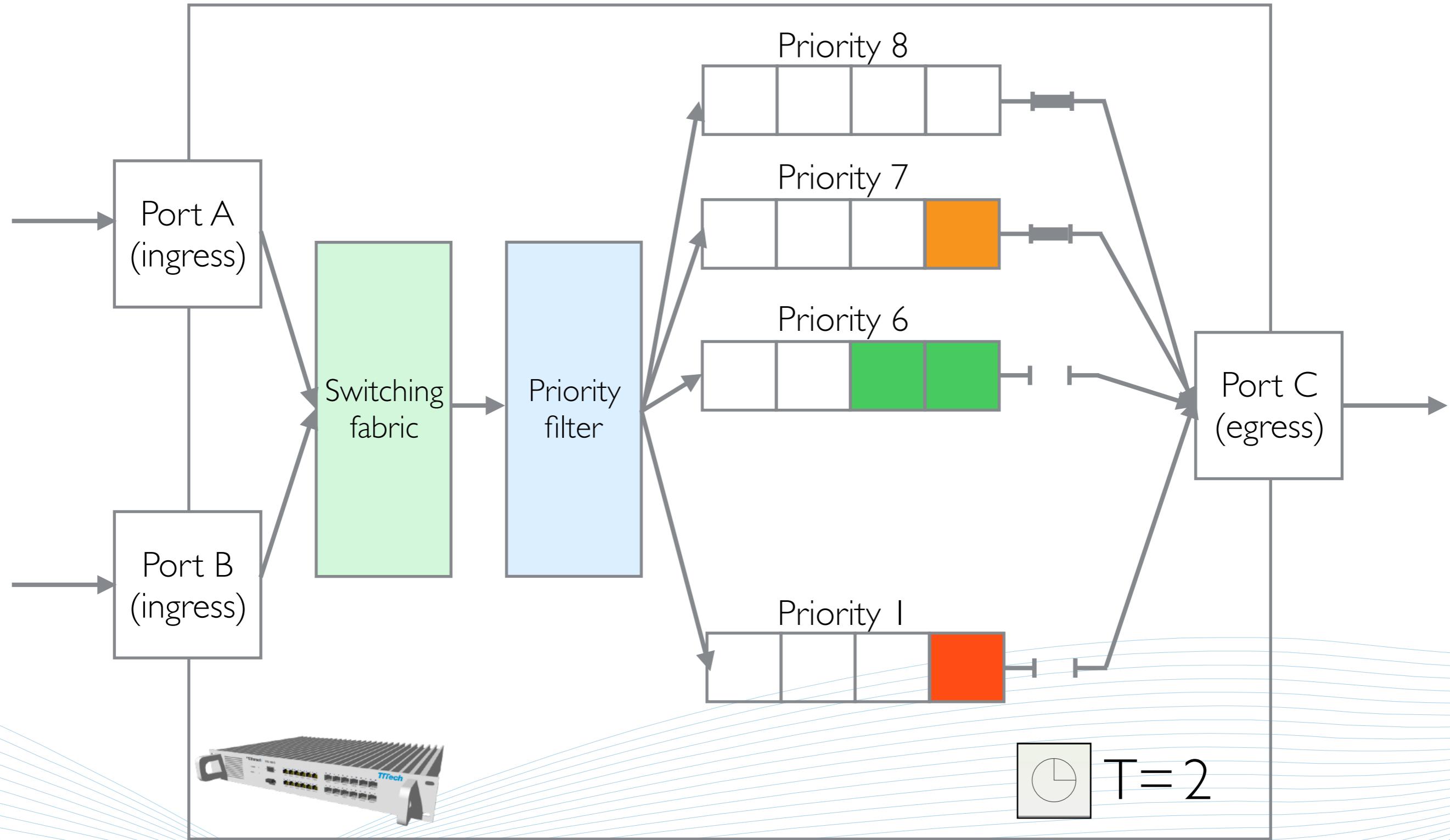
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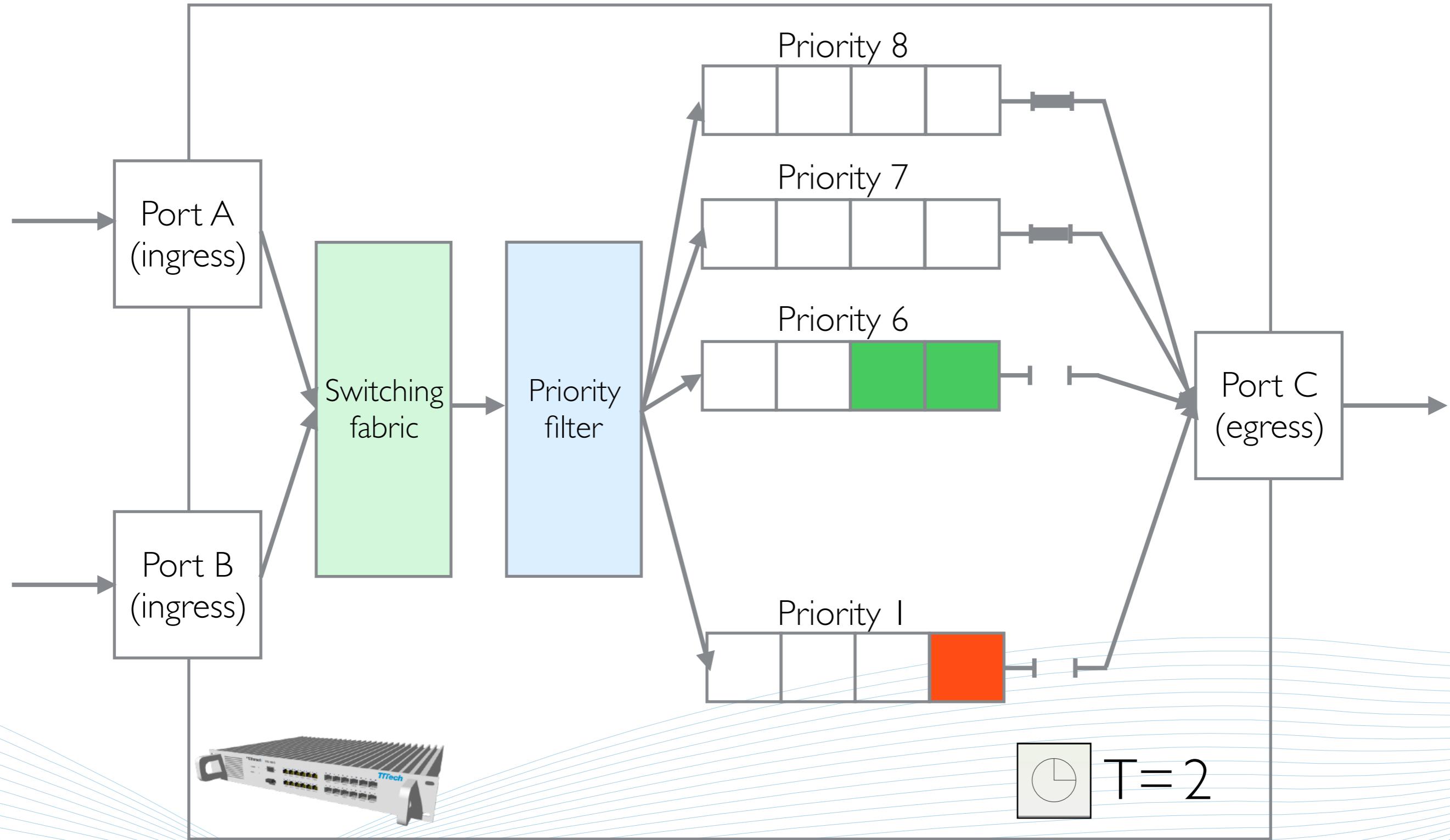
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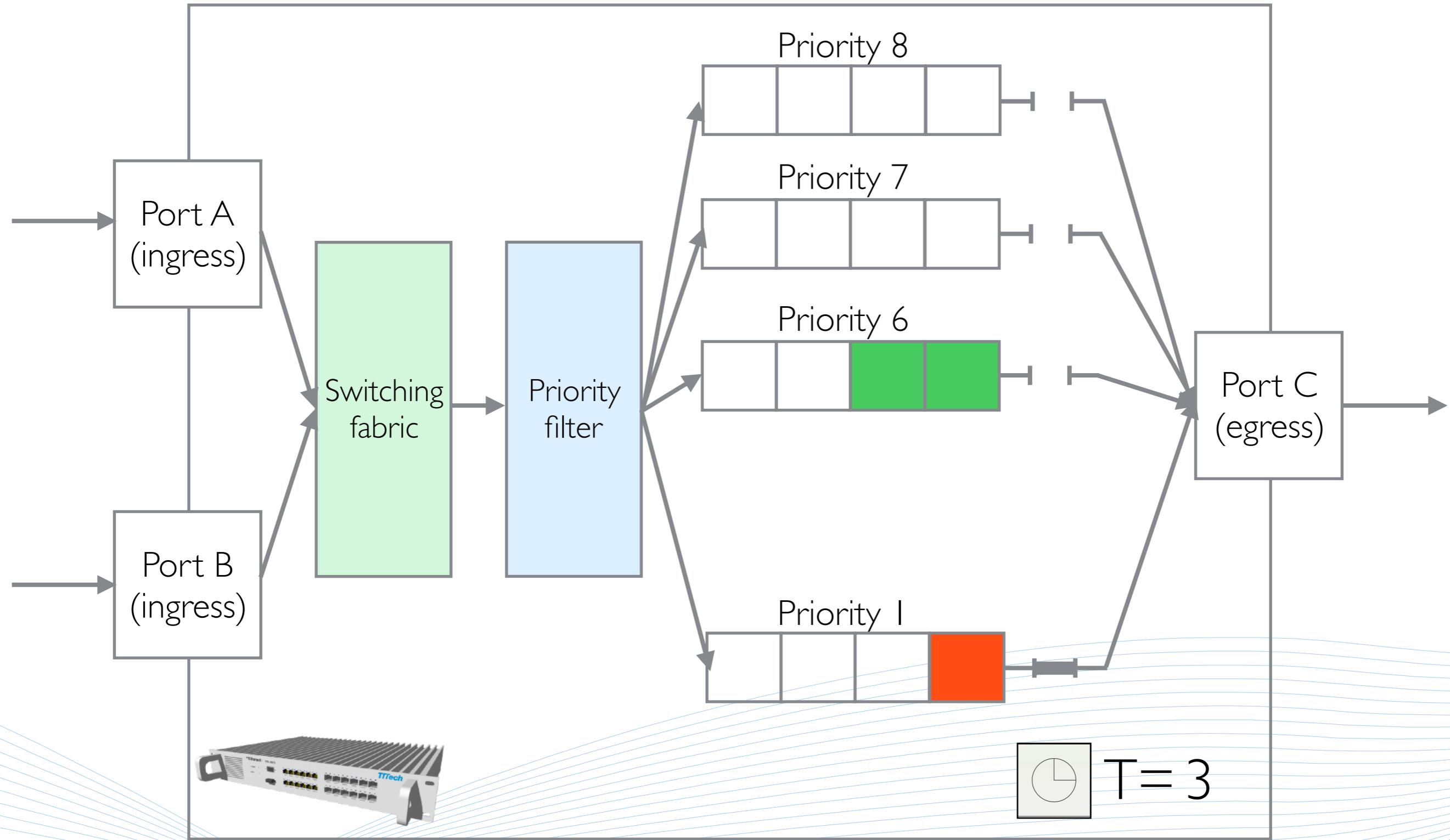
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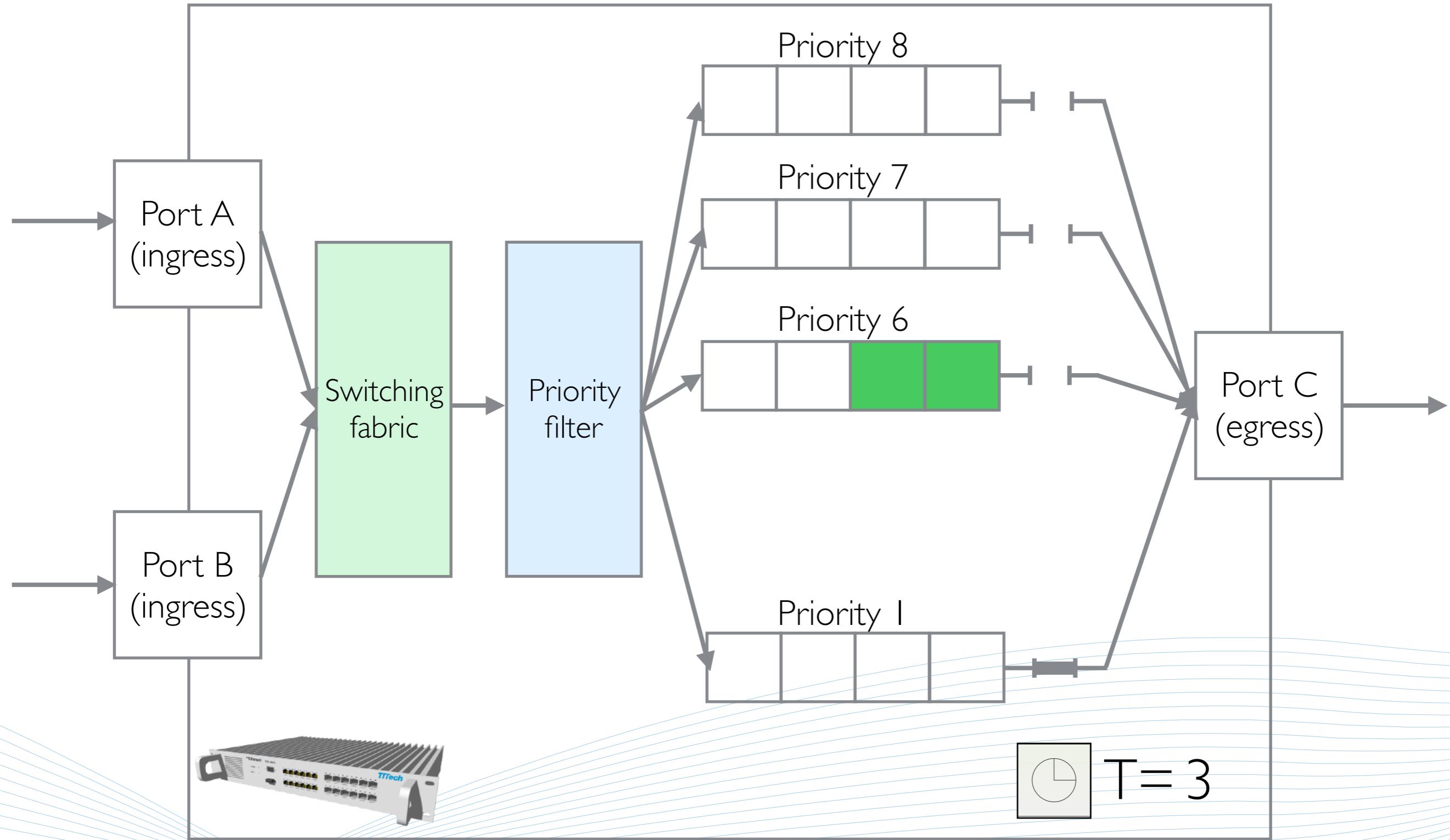
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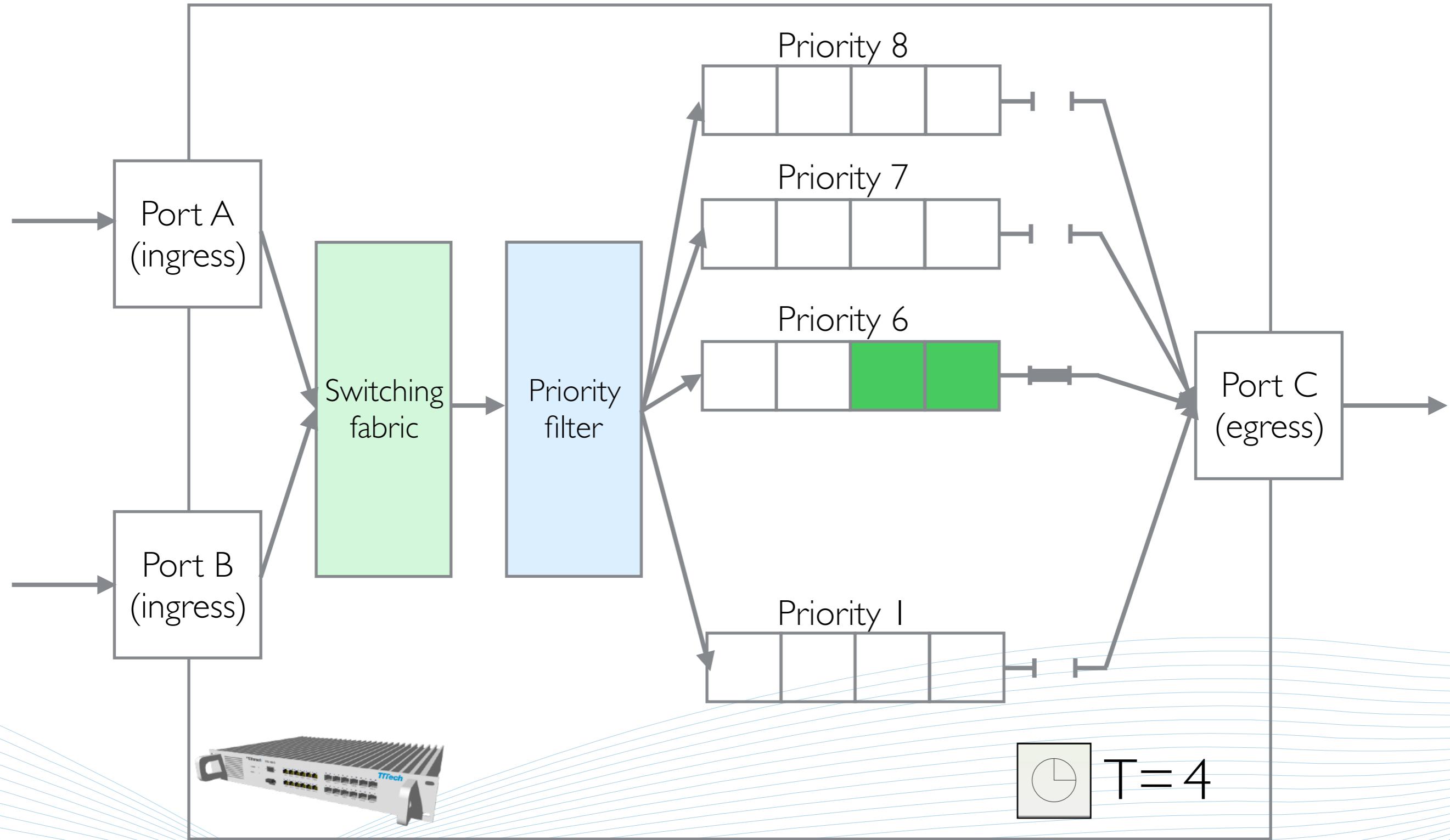
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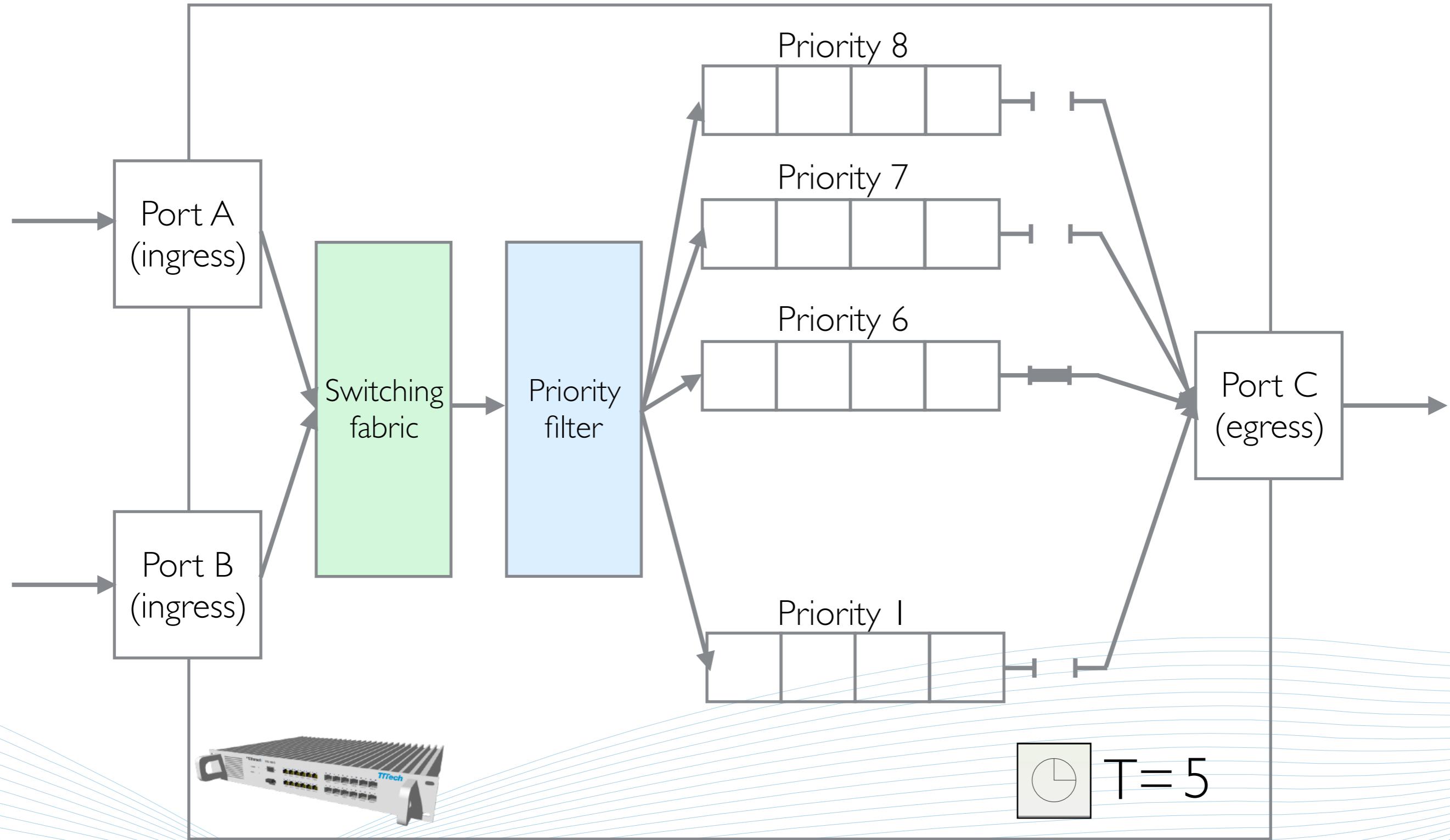
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# TSN switch

Ensuring Reliable Networks

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# Time-Sensitive Networks

Ensuring Reliable Networks



IEEE TSN task group - collection of sub-standards that enhance 802 Ethernet with real-time capabilities

Standard	Description
802.1ASrev	Timing & Synchronization
802.1Qbv	Enhancements for Scheduled Traffic (Timed Gates for Egress Queues)
802.1Qbu	Frame Preemption
802.1Qca	Path Control and Reservation
802.1Qcc	Central Configuration Management
802.1Qci	Per-Stream Time-based Ingress Filtering and Policing
802.1CB	Redundancy, Frame Replication & Elimination

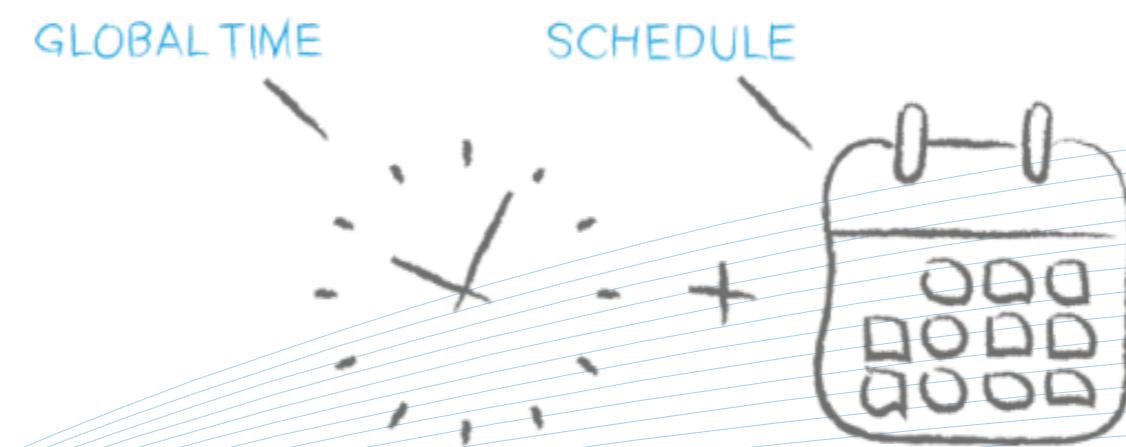
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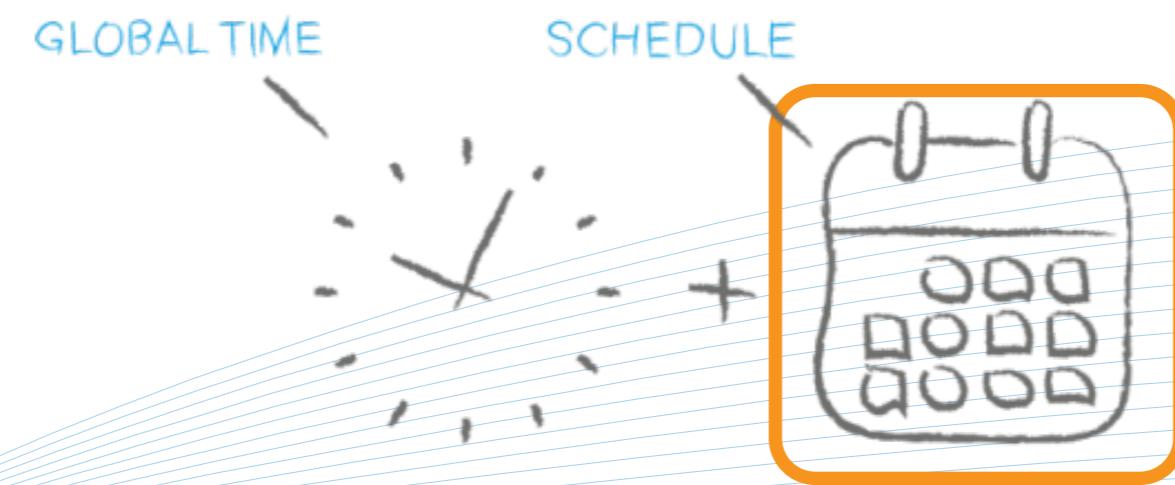
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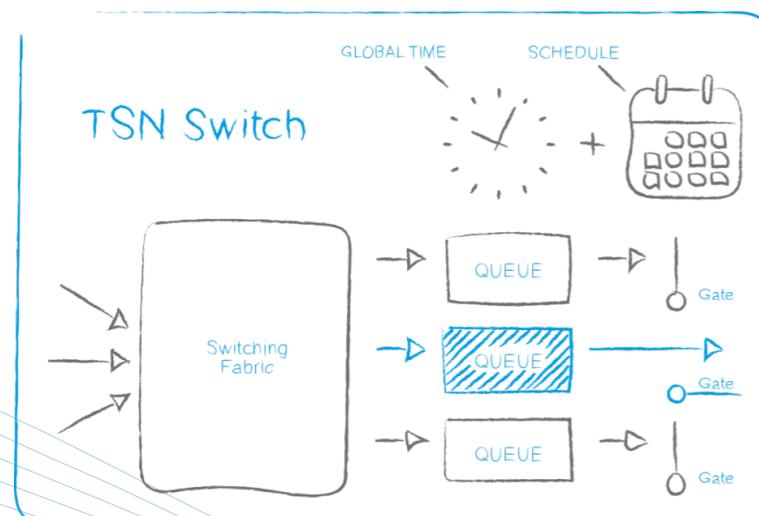
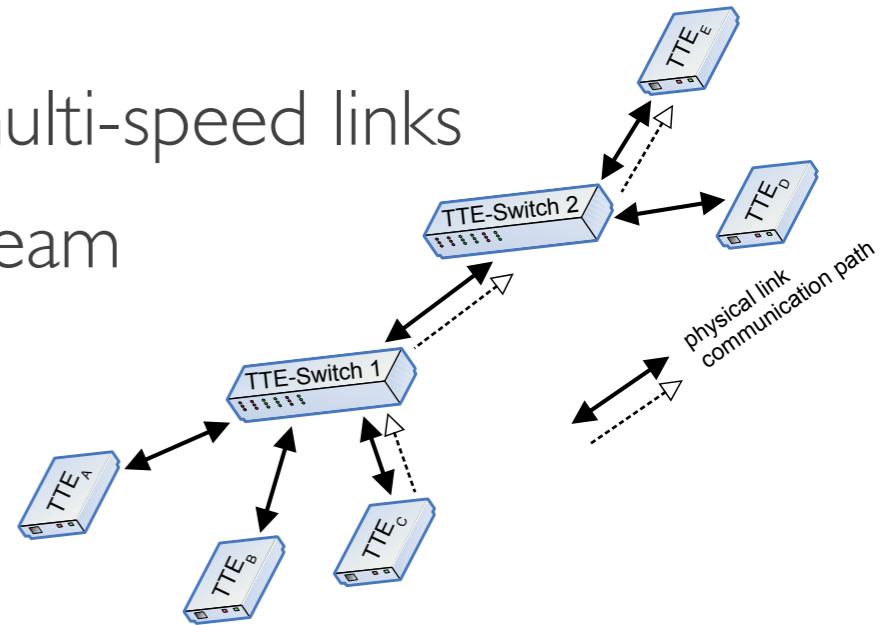


# Network & traffic model

Ensuring Reliable Networks

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- multi-hop layer 2 switched network via full-duplex multi-speed links
- (multicast) TSN streams with multiple frames per stream
- synchronised time (<1 usec precision)
- wire and device delays



- Scheduled 802.1Qbv-compatible devices (Sw + Es)
- Scheduled (mutually exclusive) & priority queues
- Guaranteed delivery of critical traffic with known latency, small & bounded jitter

# Functional parameters

$$\langle G(E), G(Q) \rangle$$

Device capabilities

$$G(E)$$

$$V_e$$

$$V_s$$

$$V_{e+s}$$

Scheduled Es

Scheduled Sw

Scheduled Es+Sw

Queue configuration

$$G(Q) = \langle \aleph, \aleph_{tt}, \aleph_{prio} \rangle$$

# Functional parameters

$$\langle G(E), G(Q) \rangle$$

Device capabilities

$$G(E)$$

$$\begin{array}{cc} V_e & V_s \\ \text{Scheduled Es} & \text{Scheduled Sw} \end{array}$$

Queue configuration

$$G(Q) = \langle \aleph, \aleph_{tt}, \aleph_{prio} \rangle$$

$$\boxed{V_{e+s}}$$

Scheduled Es+Sw

# Functional parameters

$$\langle G(E), G(Q) \rangle$$

Device capabilities

$$G(E)$$

$$\begin{array}{cc} V_e & V_s \\ \text{Scheduled Es} & \text{Scheduled Sw} \end{array}$$

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$$\aleph_{tt} \geq 1$$

# Functional parameters

$$\langle G(E), G(Q) \rangle$$

Device capabilities

$$G(E)$$

$$\begin{array}{ccc} V_e & V_s & V_{e+s} \\ \text{Scheduled Es} & \text{Scheduled Sw} & \text{Scheduled Es+Sw} \end{array}$$

Queue configuration

$$G(Q) = \langle \aleph, \aleph_{tt}, \aleph_{prio} \rangle$$

$$\aleph_{tt} \geq 1$$

- Critical traffic assigned to the scheduled queues
- Non-critical traffic assigned to priority queues (post-analysis through network calculus [[Frances@ERTS06](#)])
- Isolation: non-critical streams may interfere with each other in priority queues, but not with critical streams (isolated in the scheduled queues)

# 802.1Qbv configurations

$\{V_{e+s}, \langle 1|1|0 \rangle\}$

Only critical traffic (serialized similar to bus systems)

$\{V_{e+s}, \langle n|1|n-1 \rangle\}$

Legacy AVB systems that require a few additional high-criticality flows [Specht@ECRTS16]

$\{V_{e+s}, \langle n|n|0 \rangle\}$

Maximize solution space for critical traffic, non-critical traffic can be scheduled by inverting the cumulated schedule of scheduled queues

$\{V_{e+s}, \langle n|m|n-m \rangle\}$

High-criticality applications that feature both scheduled and non-scheduled traffic, trade-off between schedulability of critical traffic and timeliness properties and flexibility for non-scheduled traffic

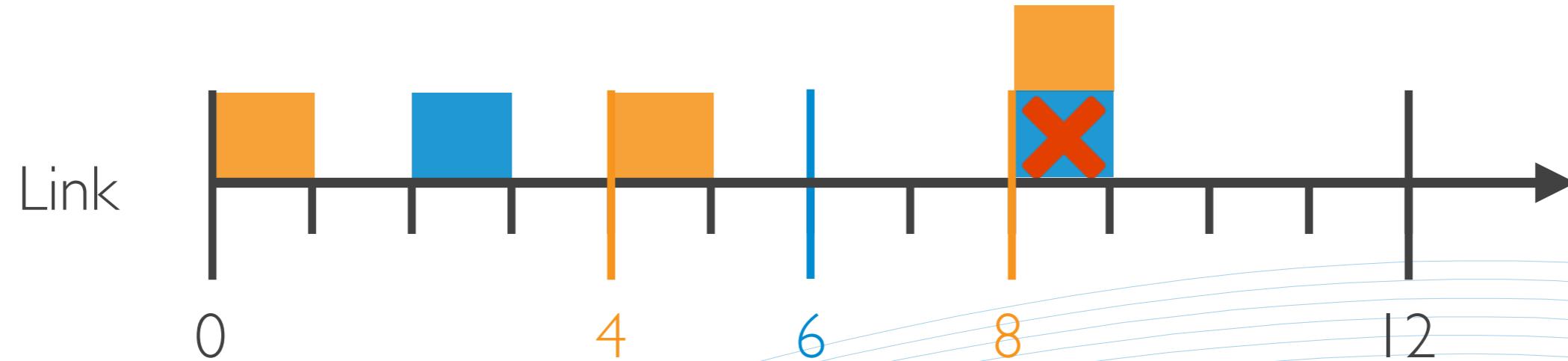
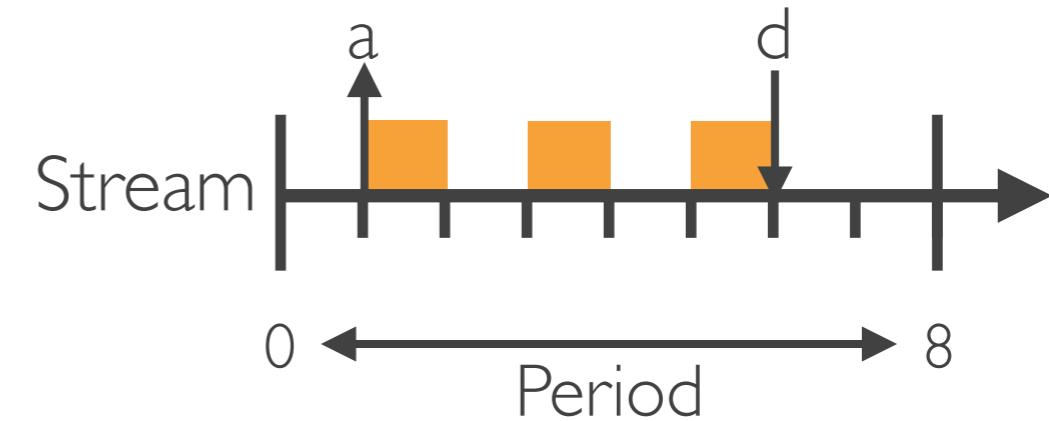
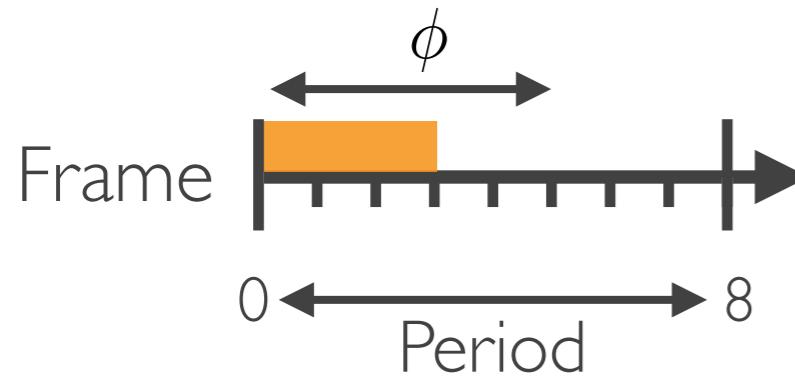
$\{V_{e+s}, \langle n|0|n \rangle\}$

Standard AVB (IEEE 802.1BA) network in which flows are serviced according to the priority

# Deterministic Ethernet Constraints

Ensuring Reliable Networks

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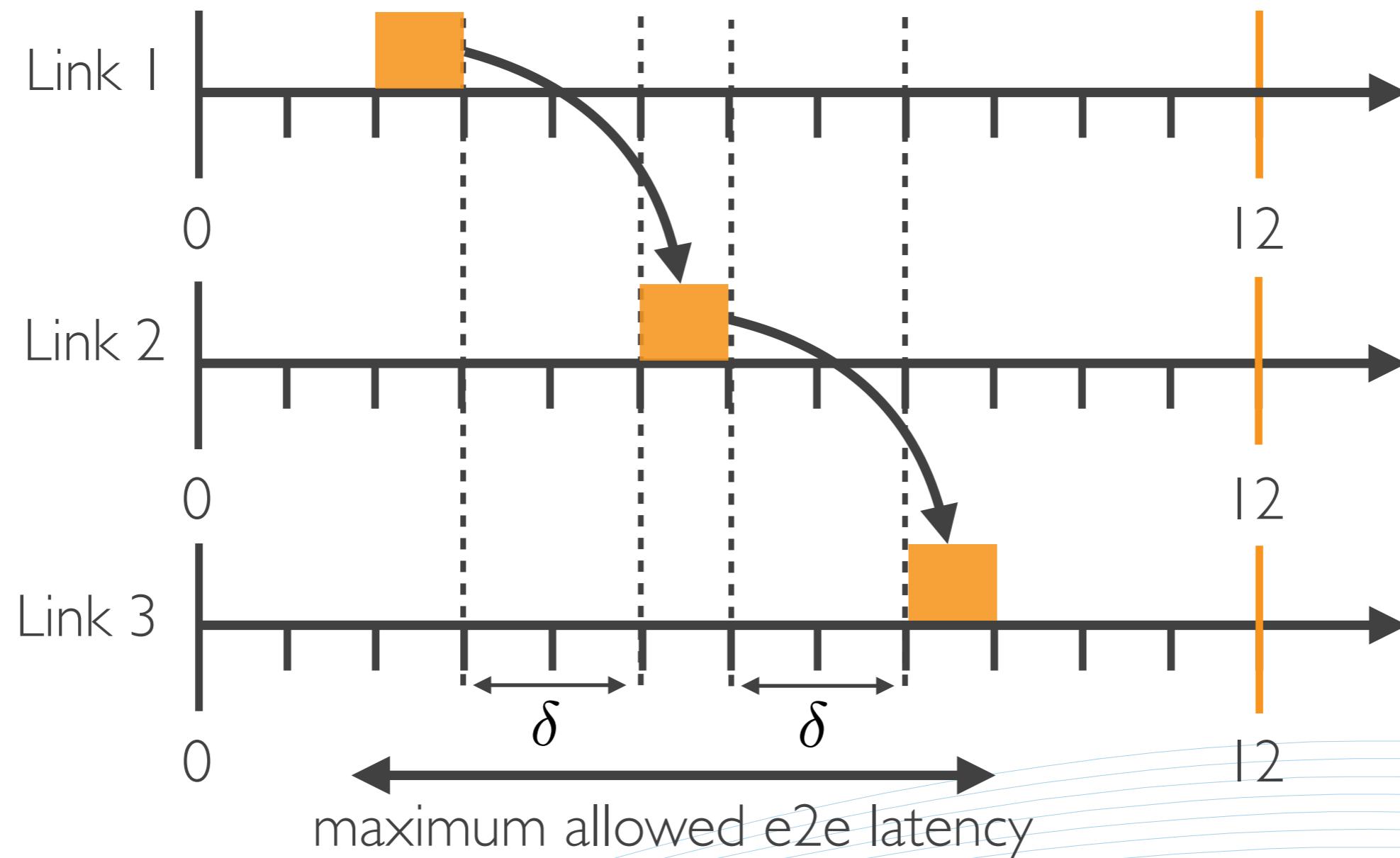


see also [[Steiner@RTSS10](#)] or [[Craciunas@RTNSI4](#)]

# Stream and e2e latency constraints

Ensuring Reliable Networks

**TTTech**

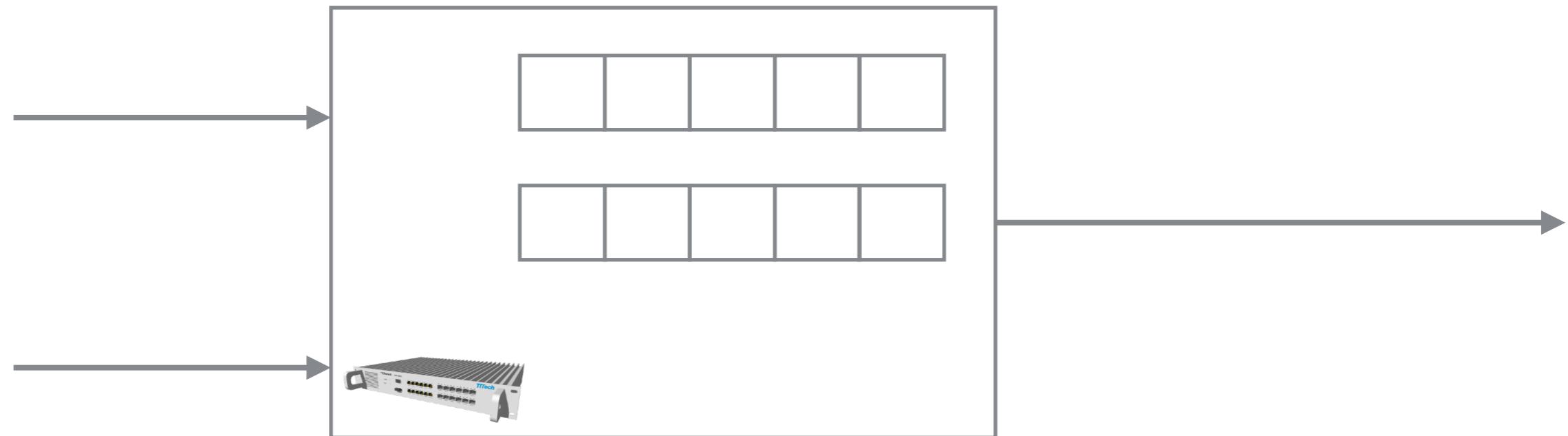


see also [[Steiner@RTSS10](#)] or [[Craciunas@RTNSI14](#)]

# Queue Interleaving

Ensuring Reliable Networks

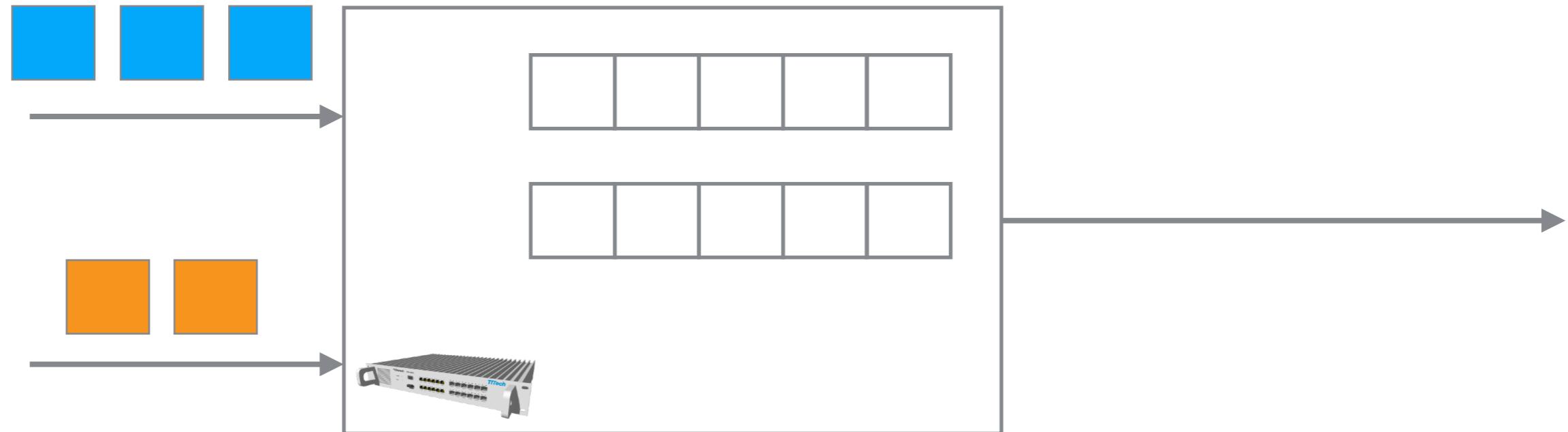
**TTTech**



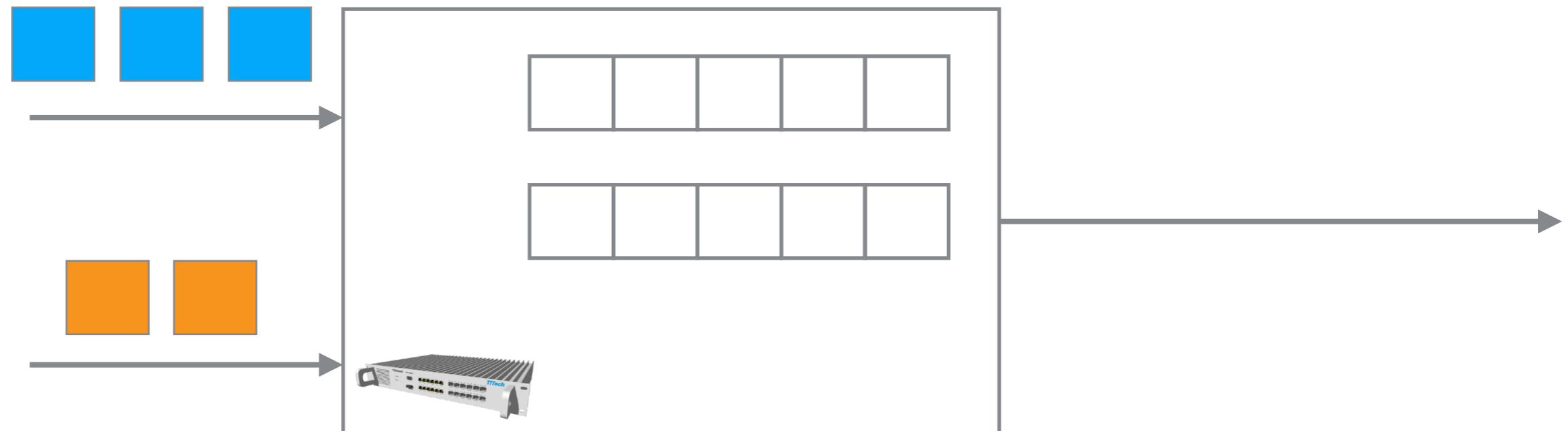
# Queue Interleaving

Ensuring Reliable Networks

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# Queue Interleaving

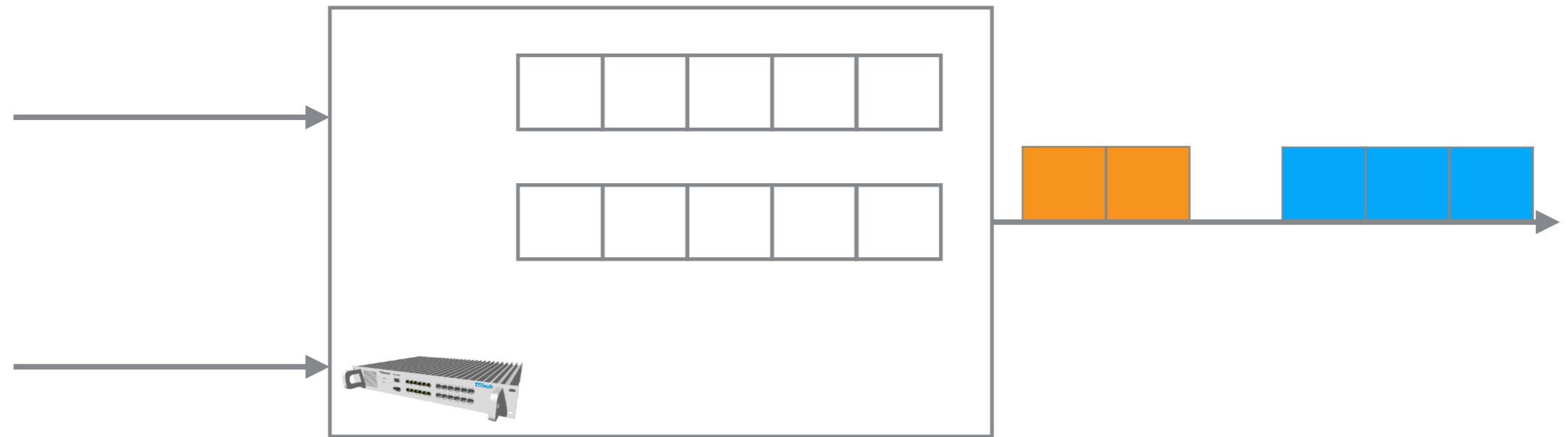


In order to maintain jitter and latency requirements we expect at each device a certain timely order of frames

# Queue Interleaving

Ensuring Reliable Networks

**TTTech**

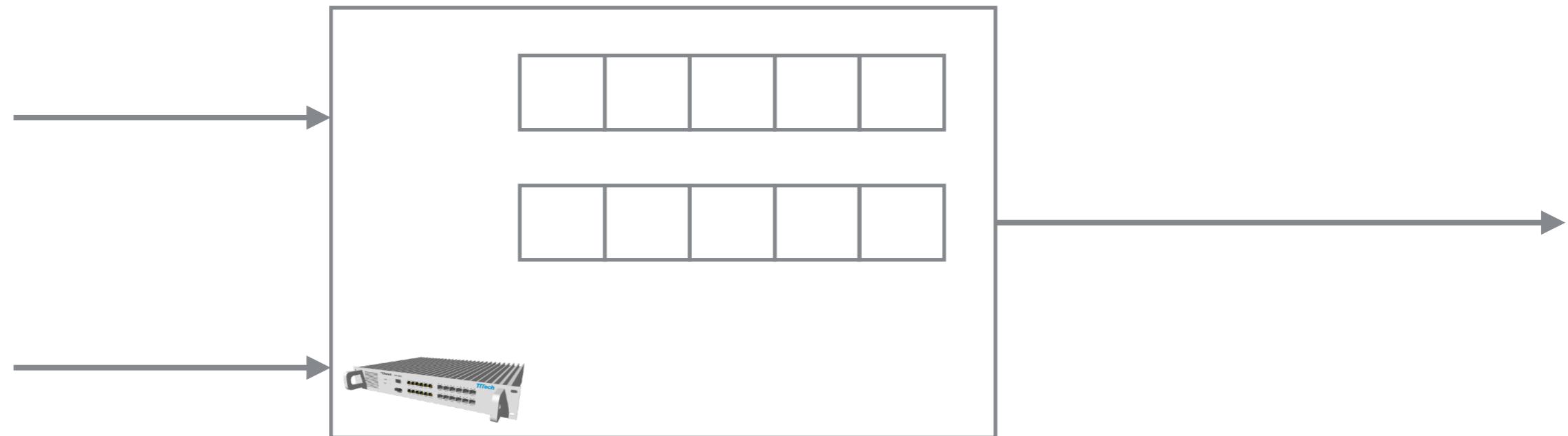


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Ensuring Reliable Networks

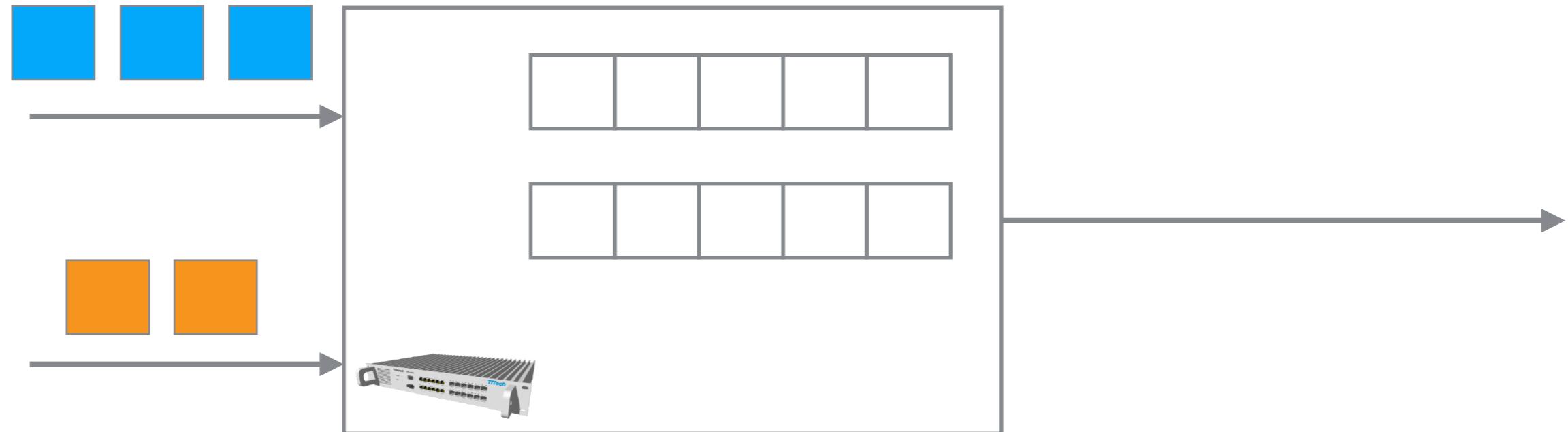
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# Queue Interleaving

Ensuring Reliable Networks

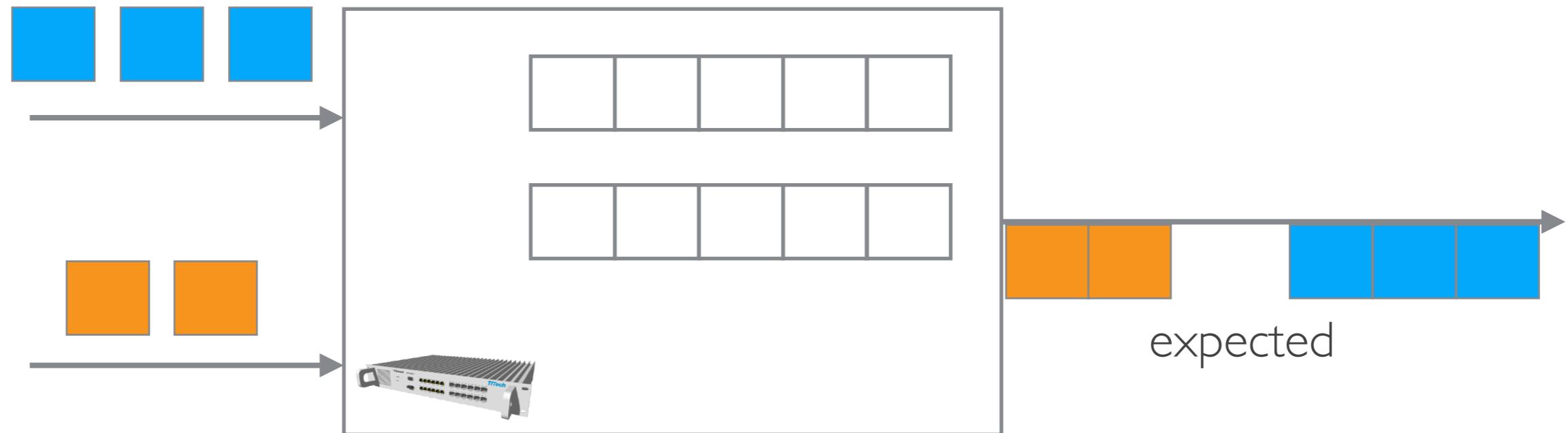
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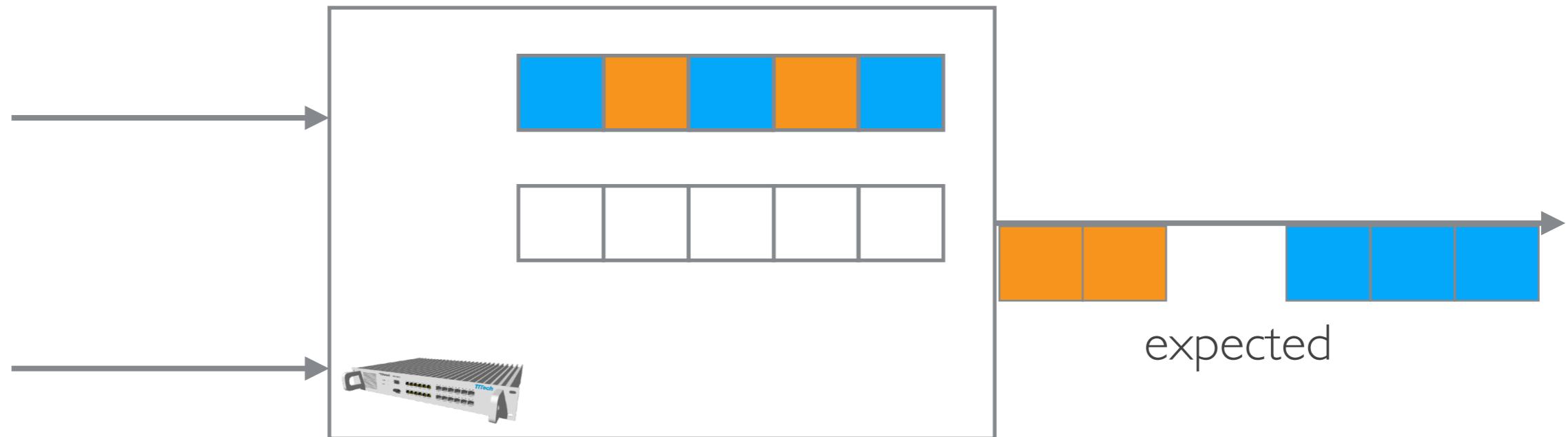
# Queue Interleaving

Ensuring Reliable Networks

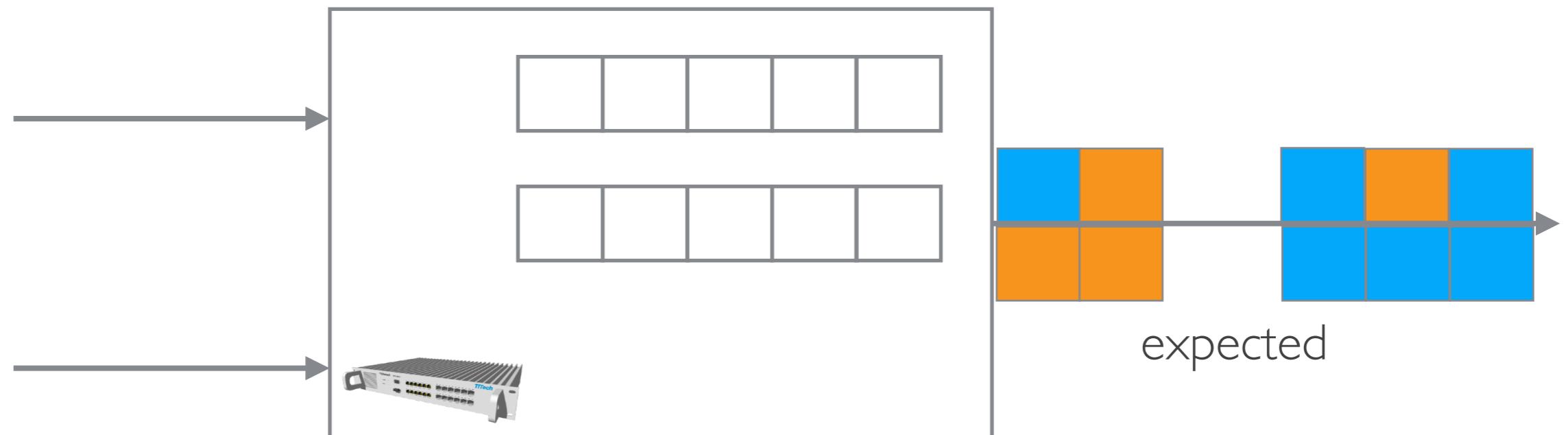
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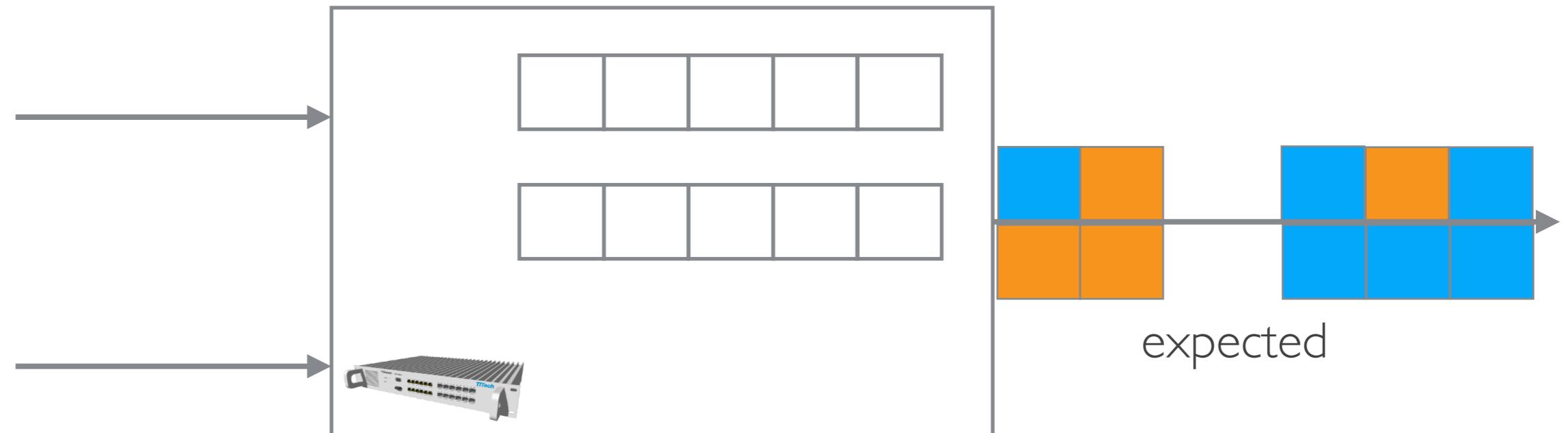
# Queue Interleaving



# Queue Interleaving



# Queue Interleaving



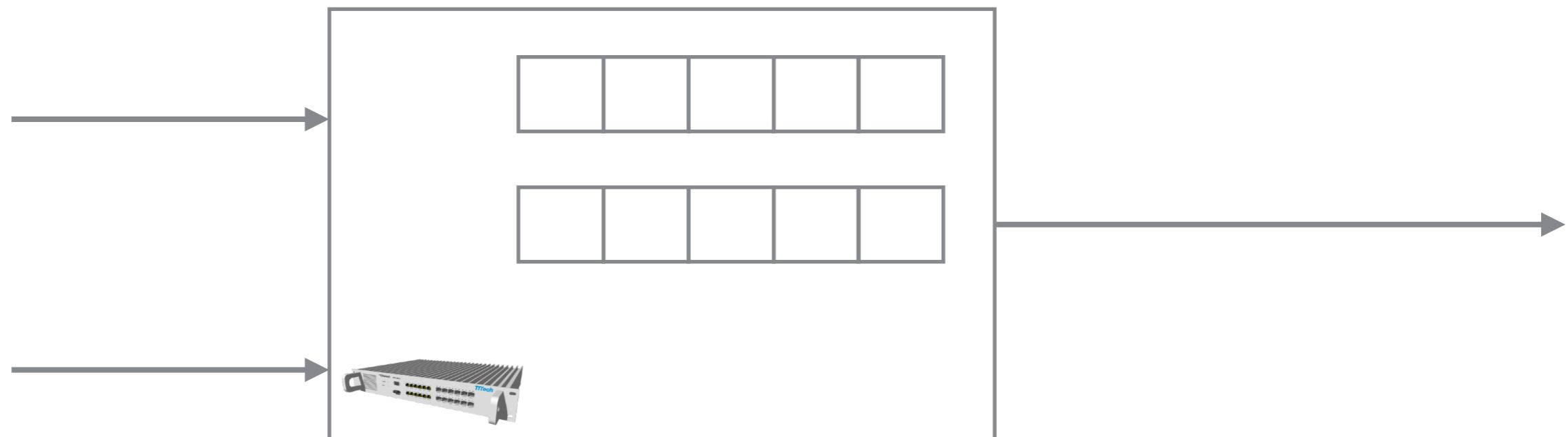
- synchronization errors, frame loss, time-based ingress policing (e.g. IEEE 802.1 Qci) may lead to non-deterministic placement in queues during runtime
- timed gates control events on the egress port, not the order of frames in the queue
- placing of frames in the scheduled queues at runtime may be non-deterministic

**Timely behaviour of streams may oscillate, accumulating jitter for the overall end-to-end transmission**

# Queue Isolation

Ensuring Reliable Networks

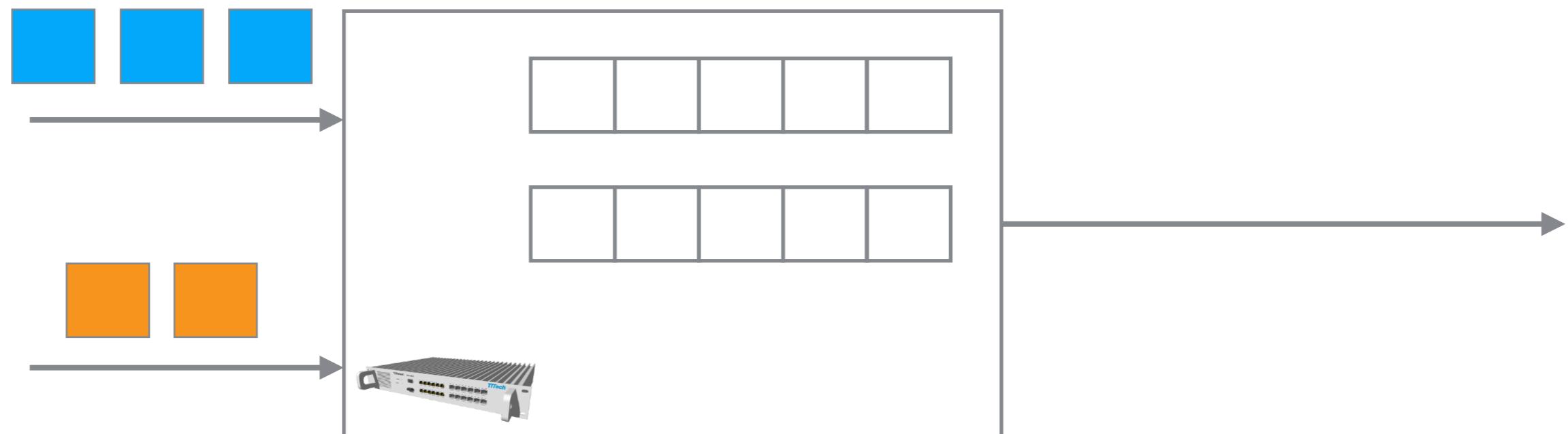
**TTTech**



# Queue Isolation

Ensuring Reliable Networks

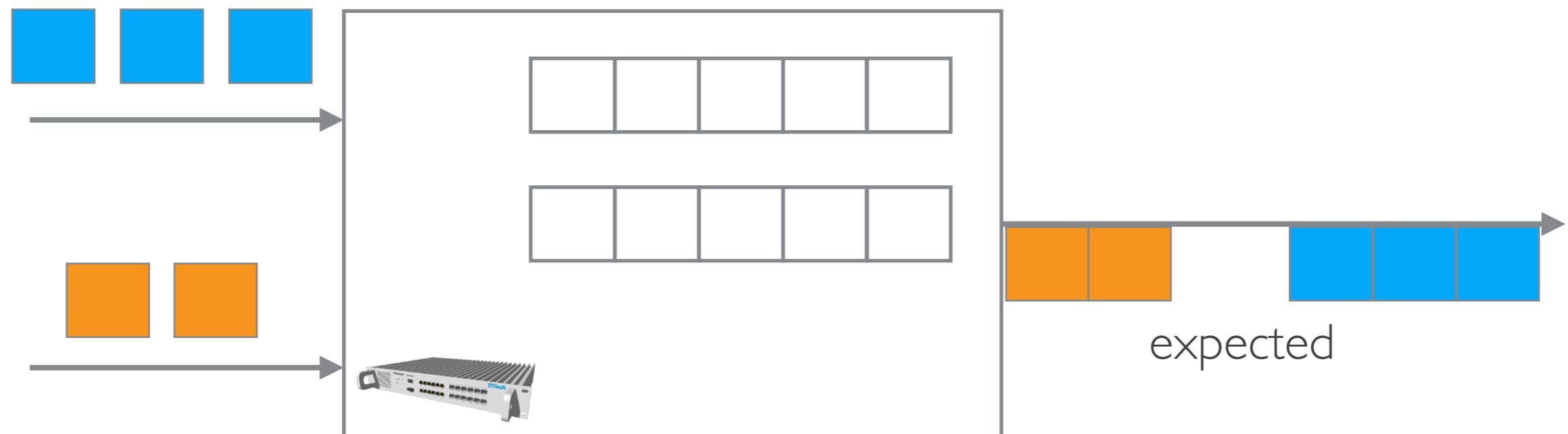
**TTTech**



# Queue Isolation

Ensuring Reliable Networks

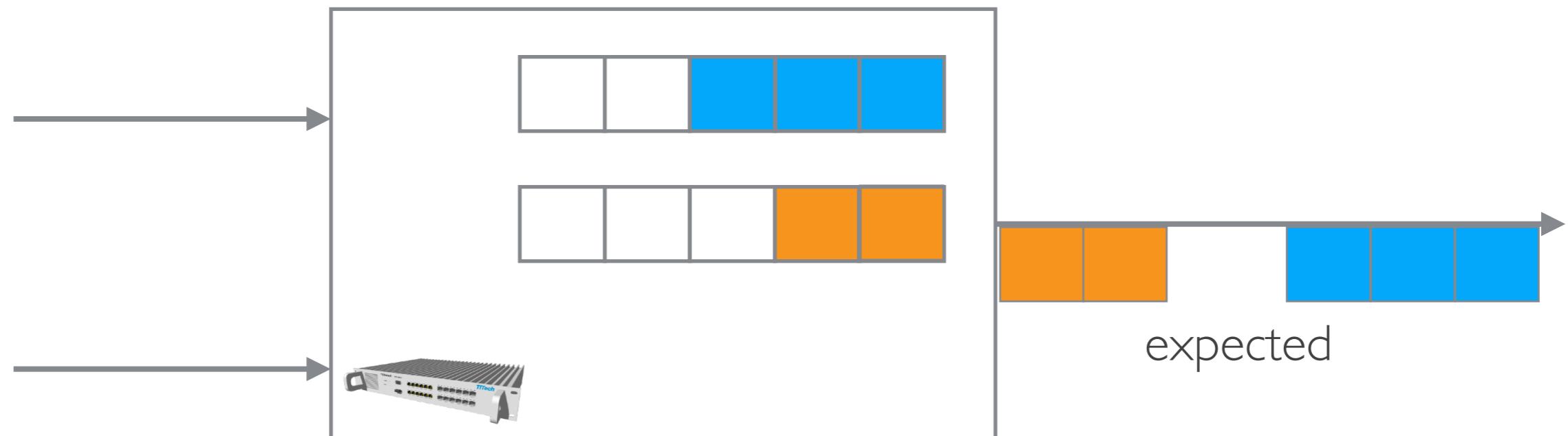
**TTTech**



# Queue Isolation

Ensuring Reliable Networks

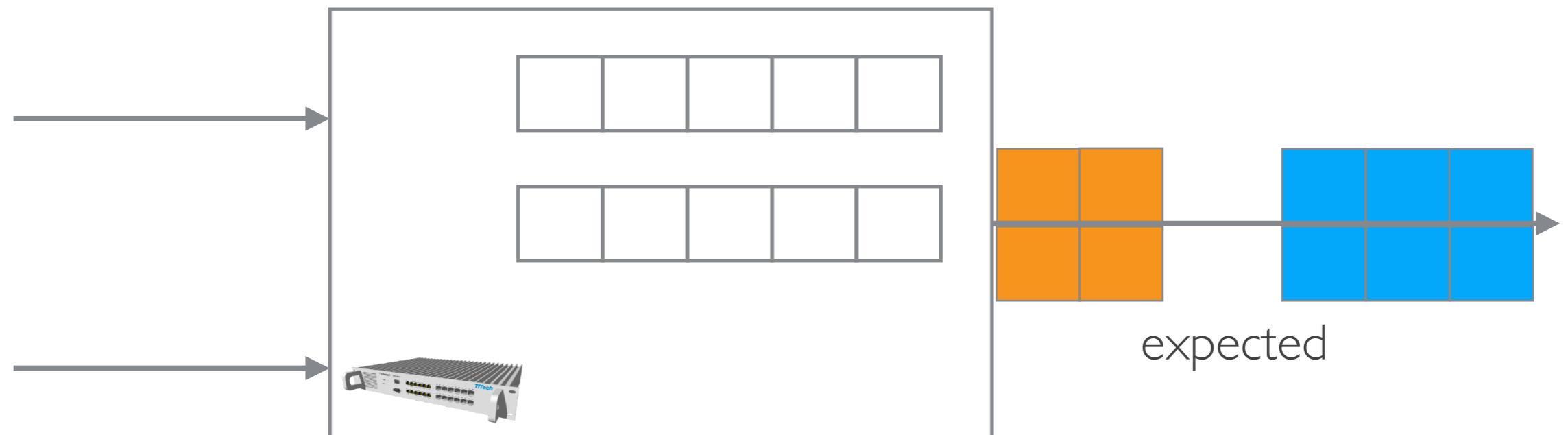
**TTTech**



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Ensuring Reliable Networks

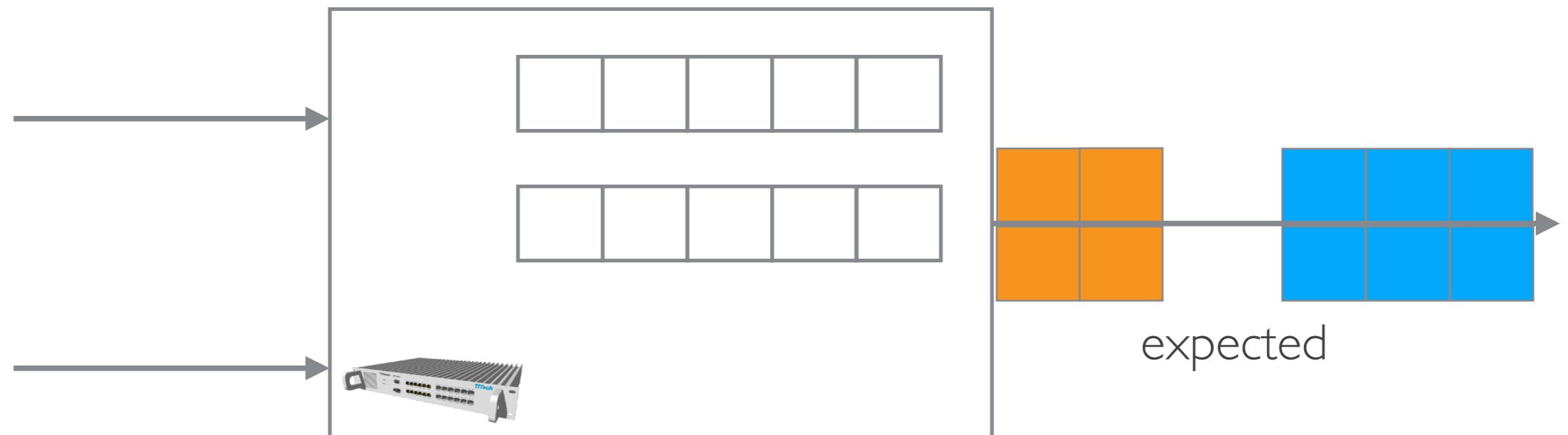
**TTTech**



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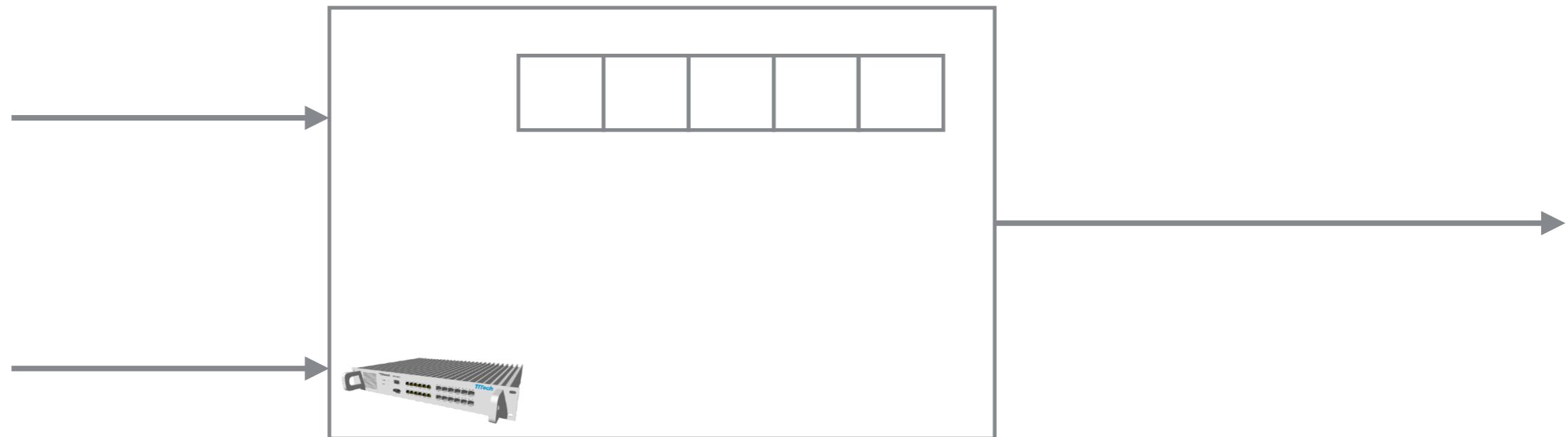
Ensuring Reliable Networks

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Solves the non-determinism problem but  
reduces the solution space

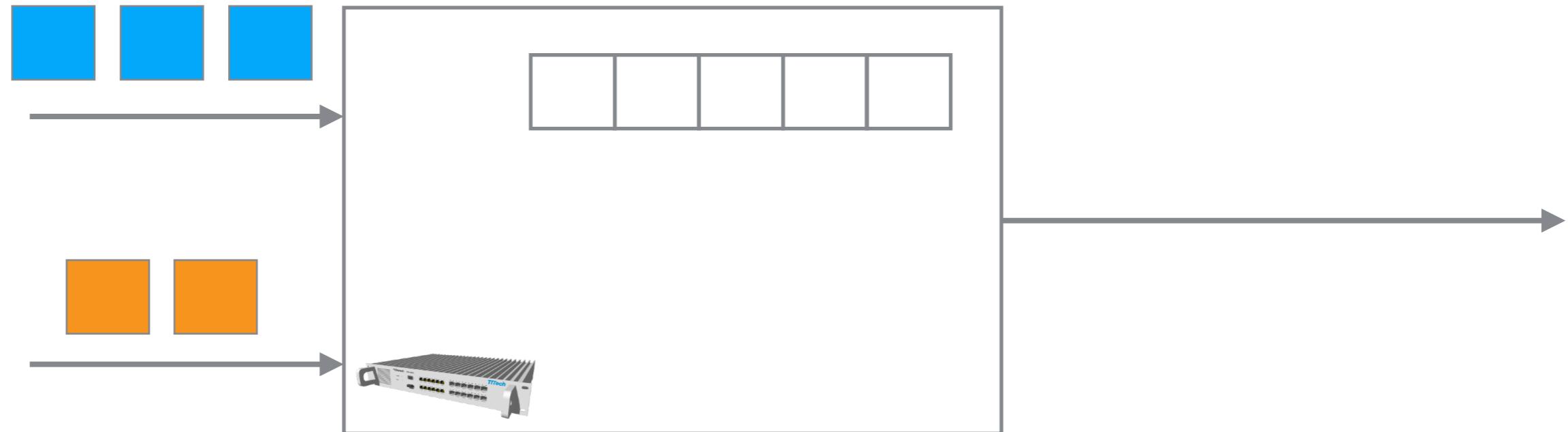
# Stream (Flow) isolation



# Stream (Flow) isolation

Ensuring Reliable Networks

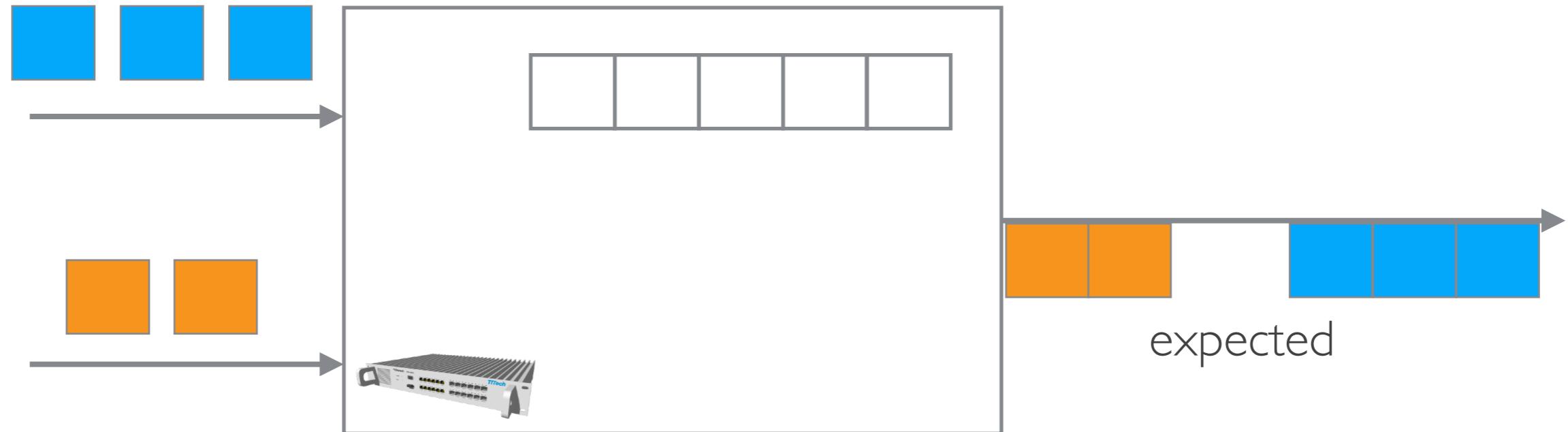
**TTTech**



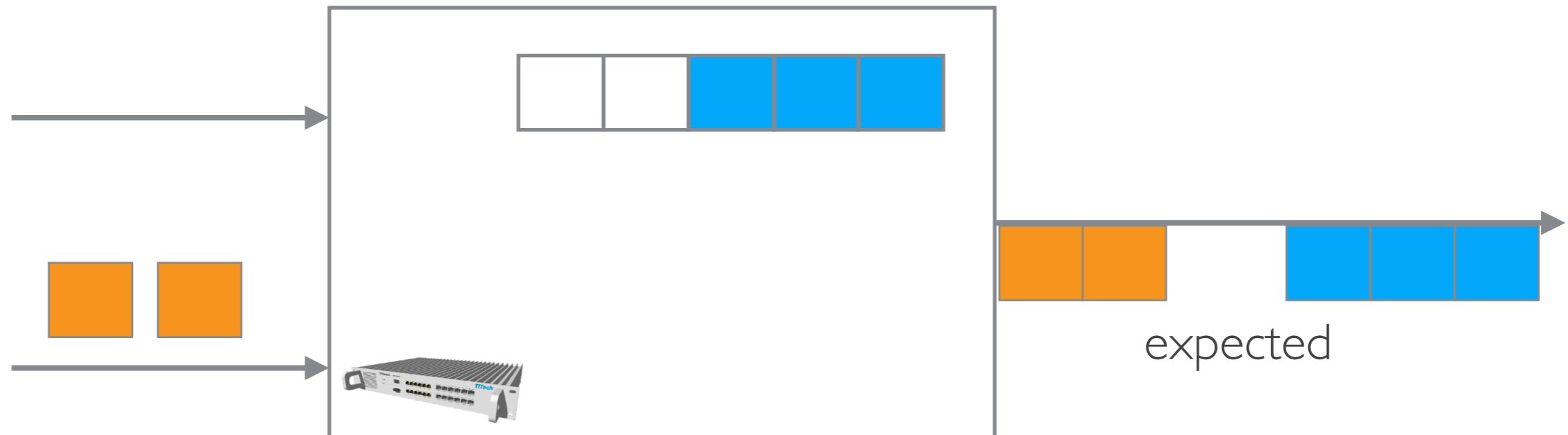
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Ensuring Reliable Networks

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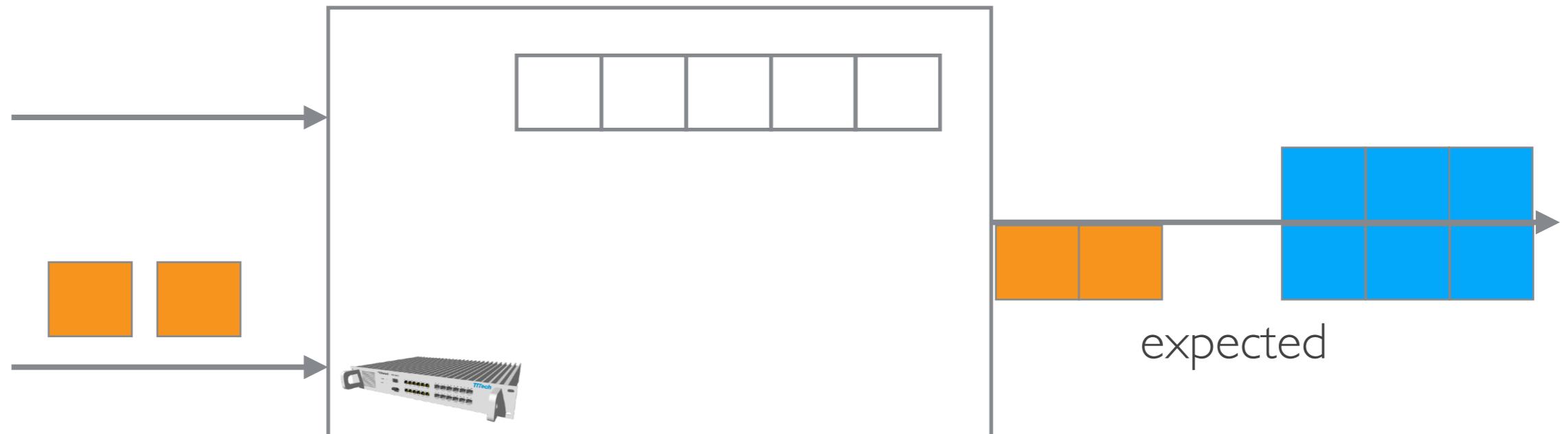
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Ensuring Reliable Networks

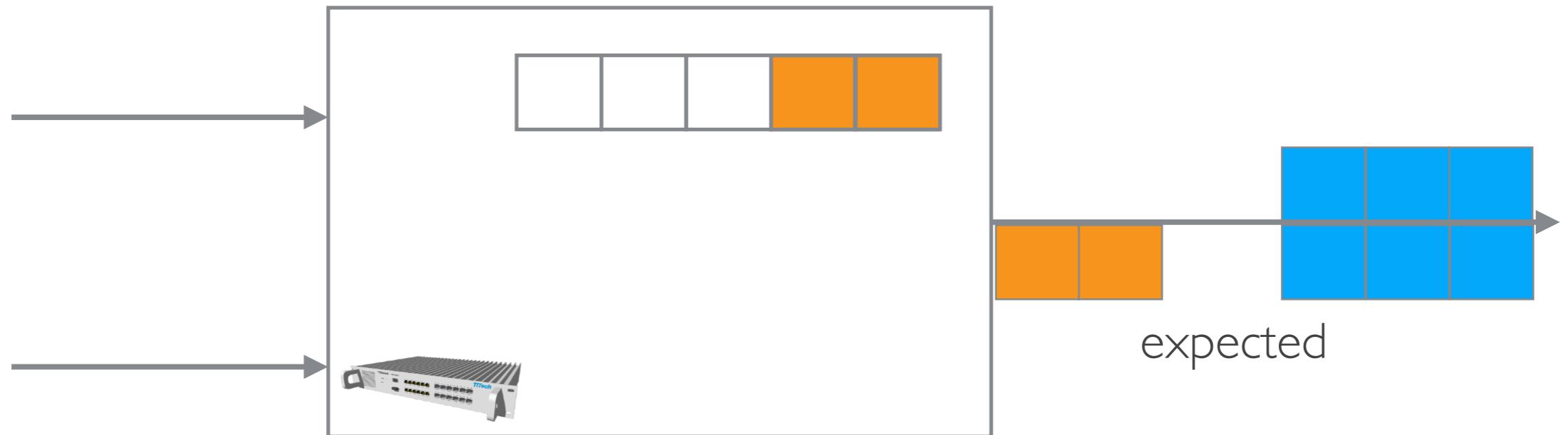
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Ensuring Reliable Networks

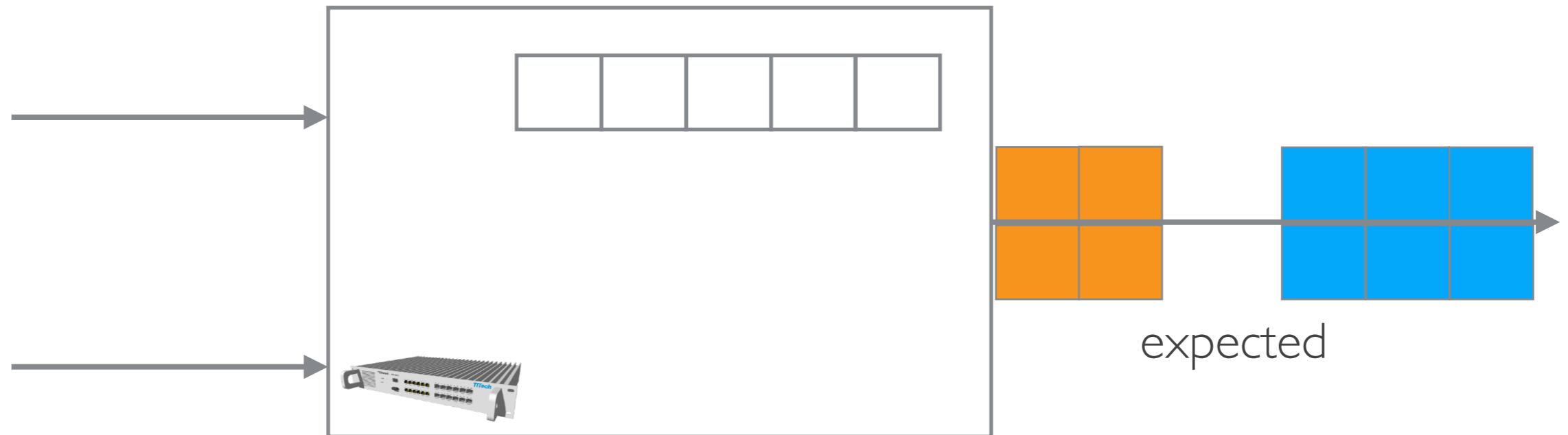
**TTTech**



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Ensuring Reliable Networks

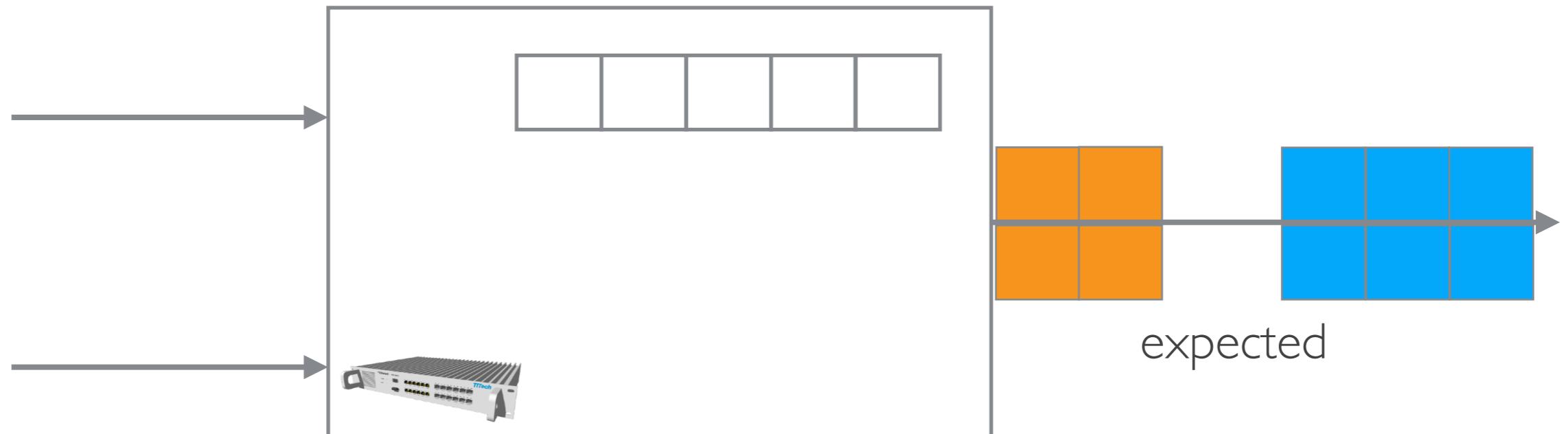
**TTTech**



# Stream (Flow) isolation

Ensuring Reliable Networks

**TTTech**

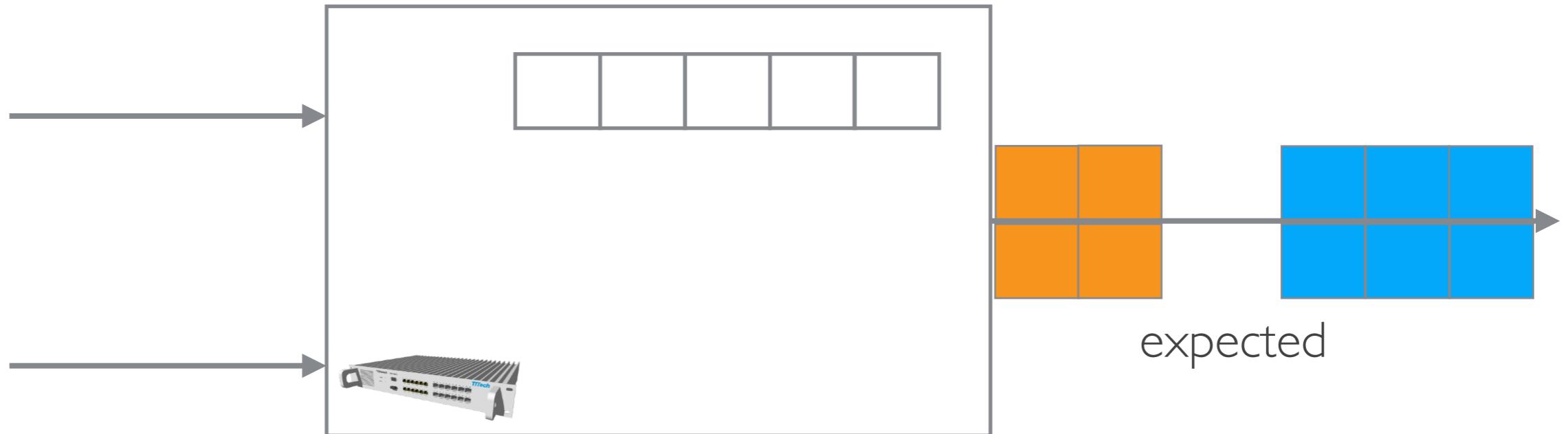


- Once a flow has arrived, no other flow can arrive in the same queue until the first flow has been completely sent
- Better than queue isolation but still restrictive

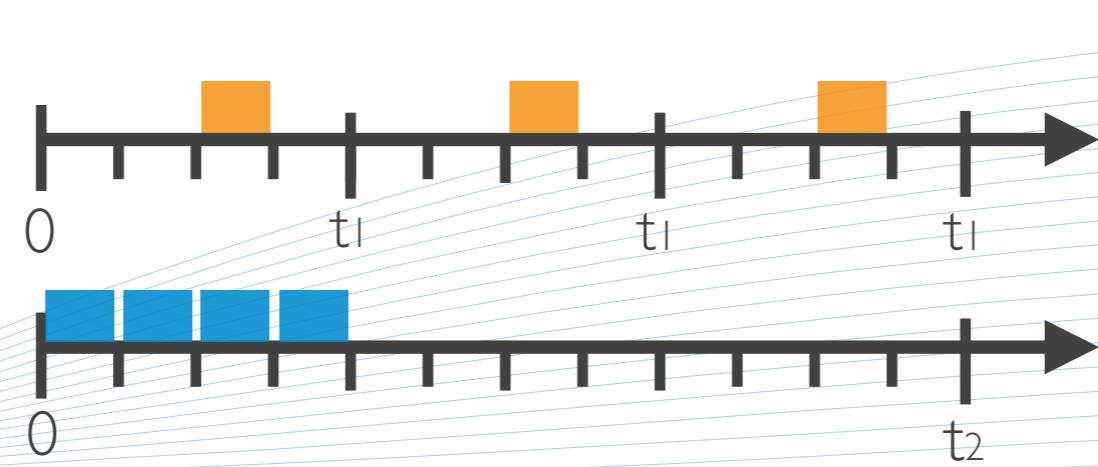
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Ensuring Reliable Networks

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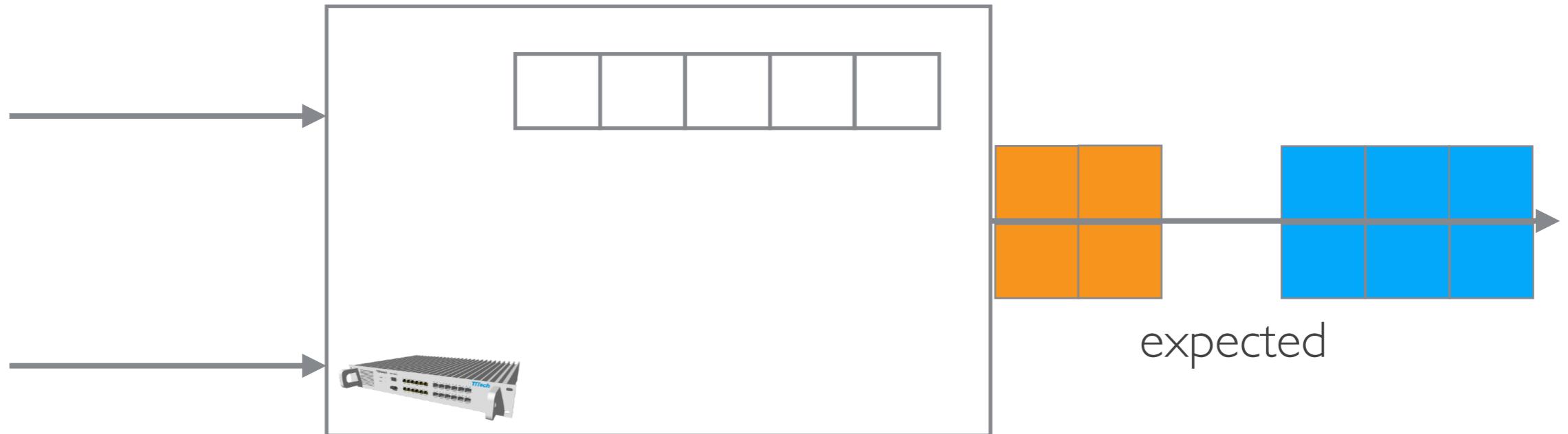
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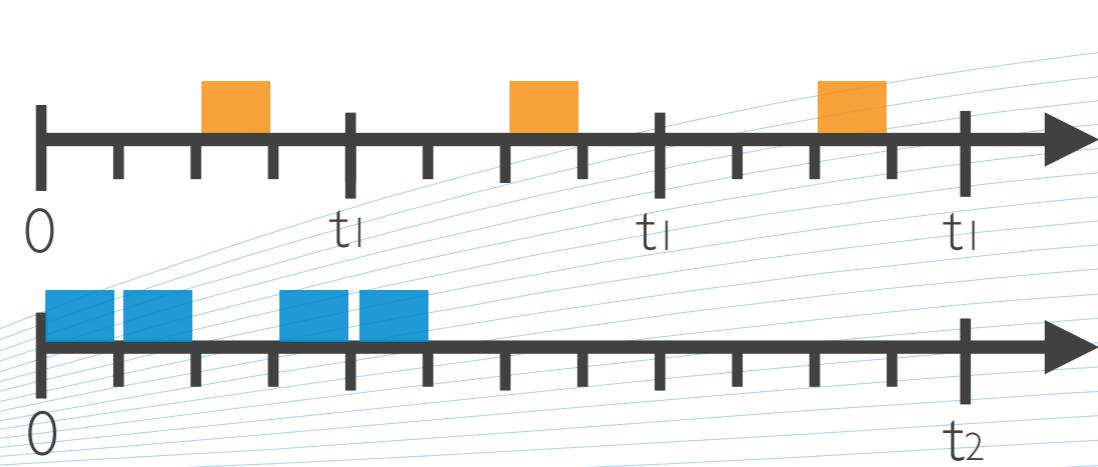
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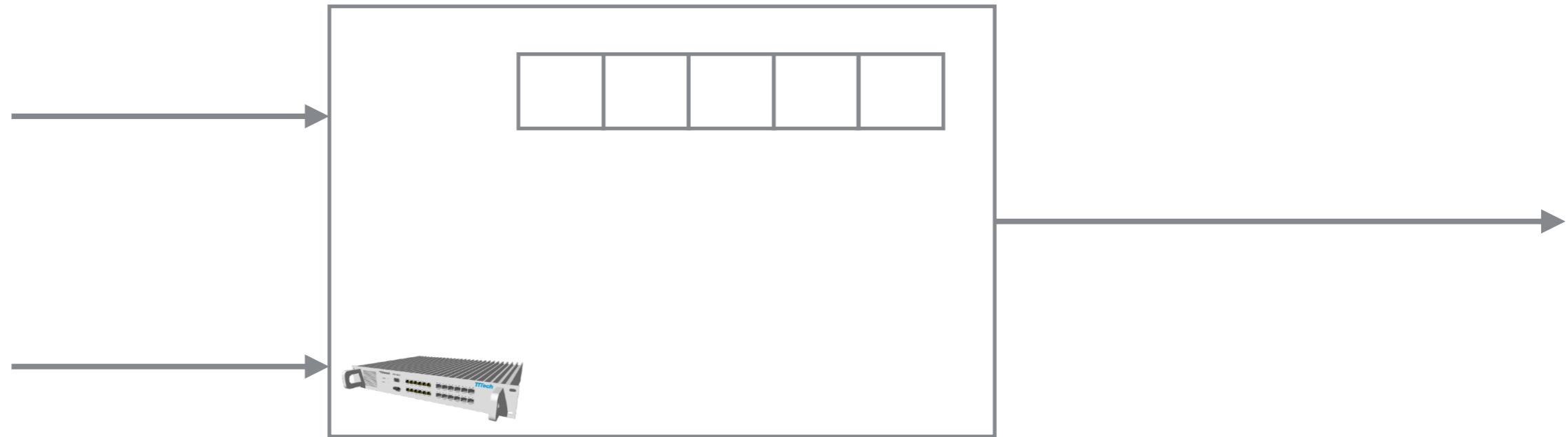
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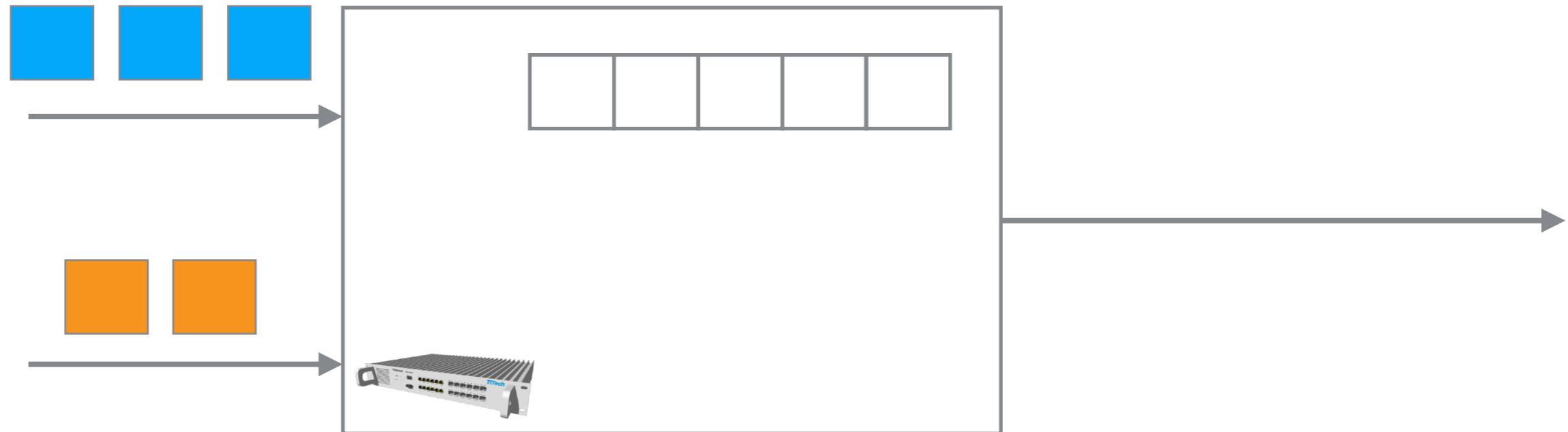
# Frame isolation



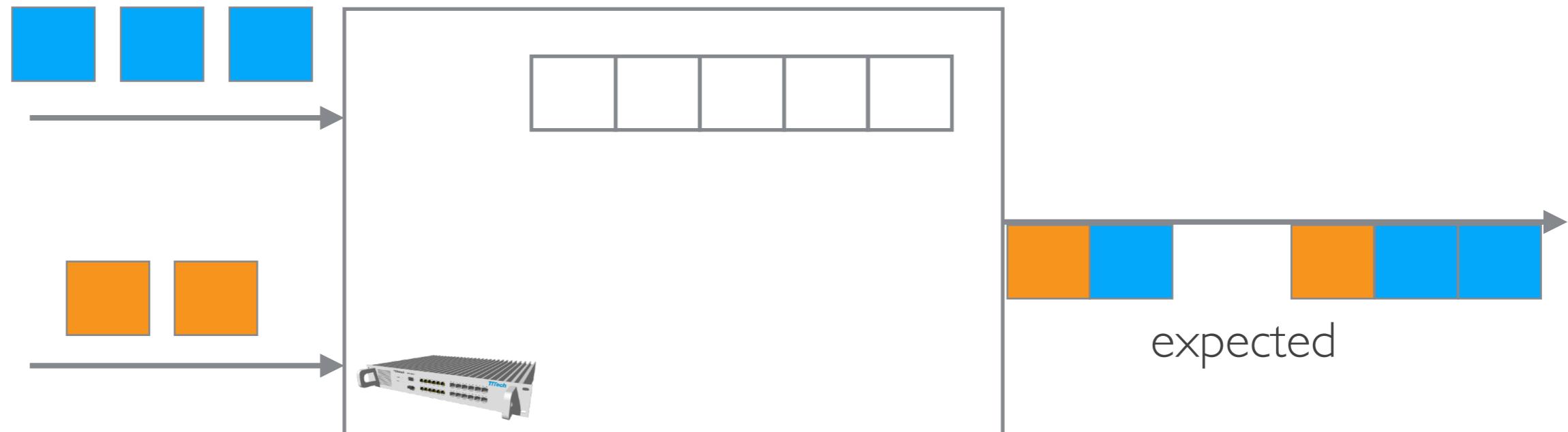
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Ensuring Reliable Networks

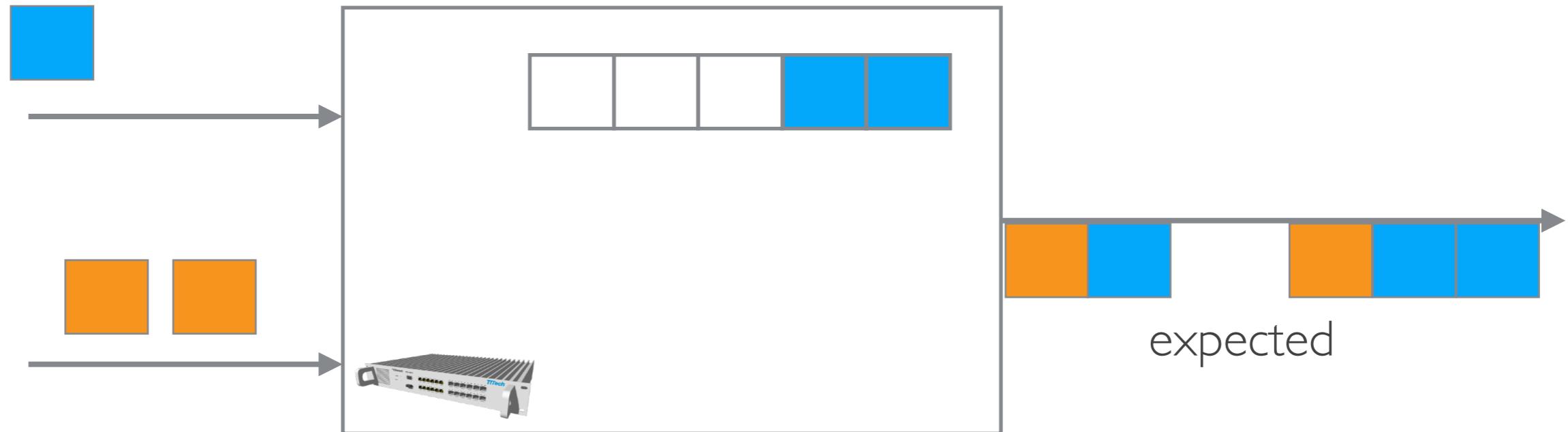
**TTTech**



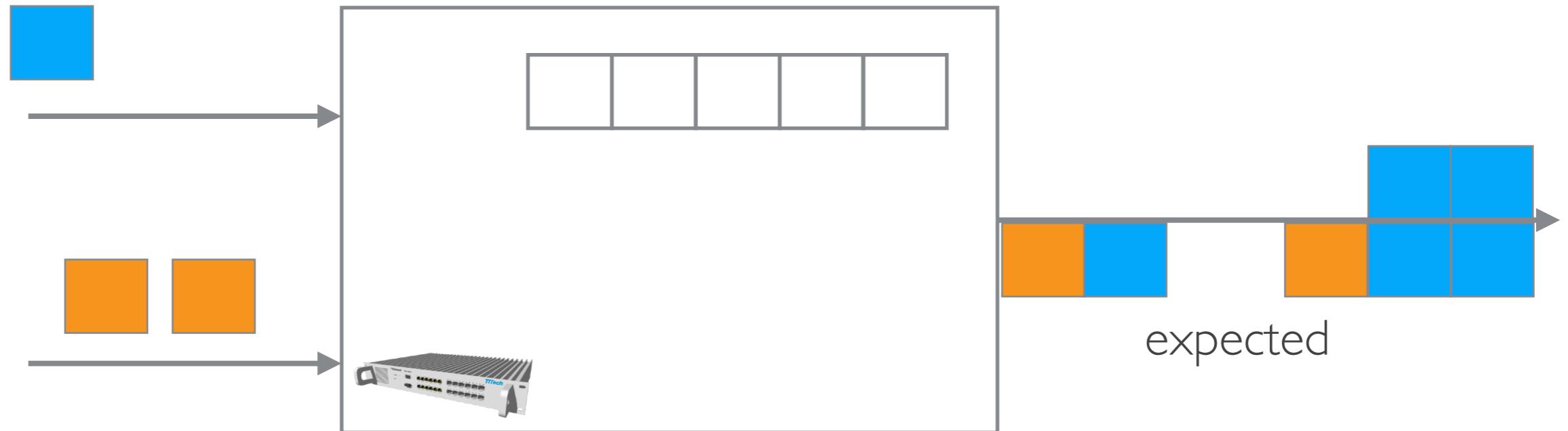
# Frame isolation



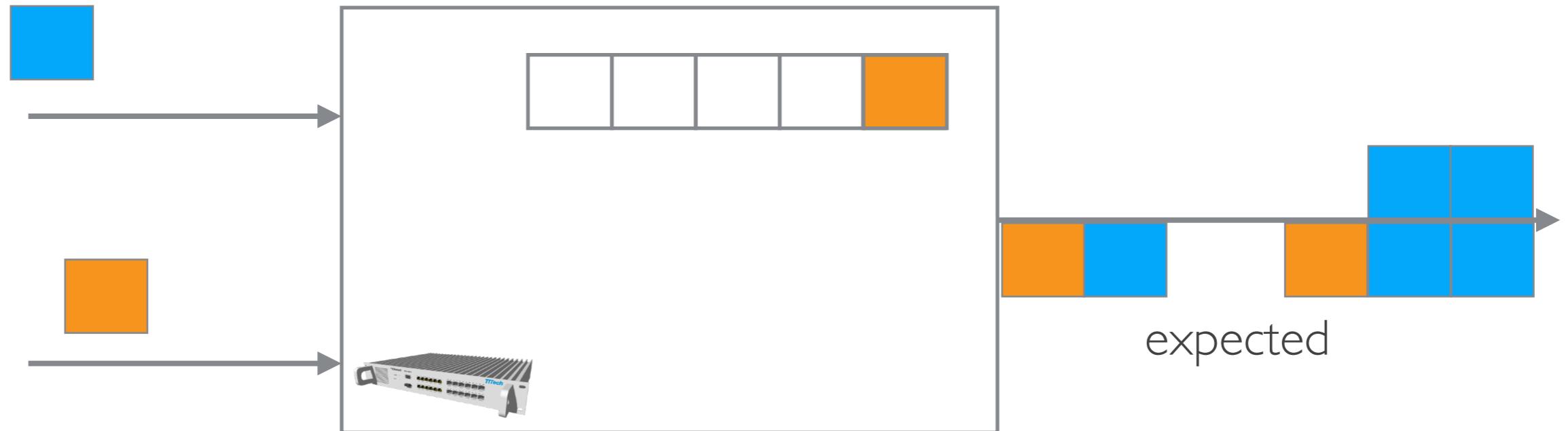
# Frame isolation



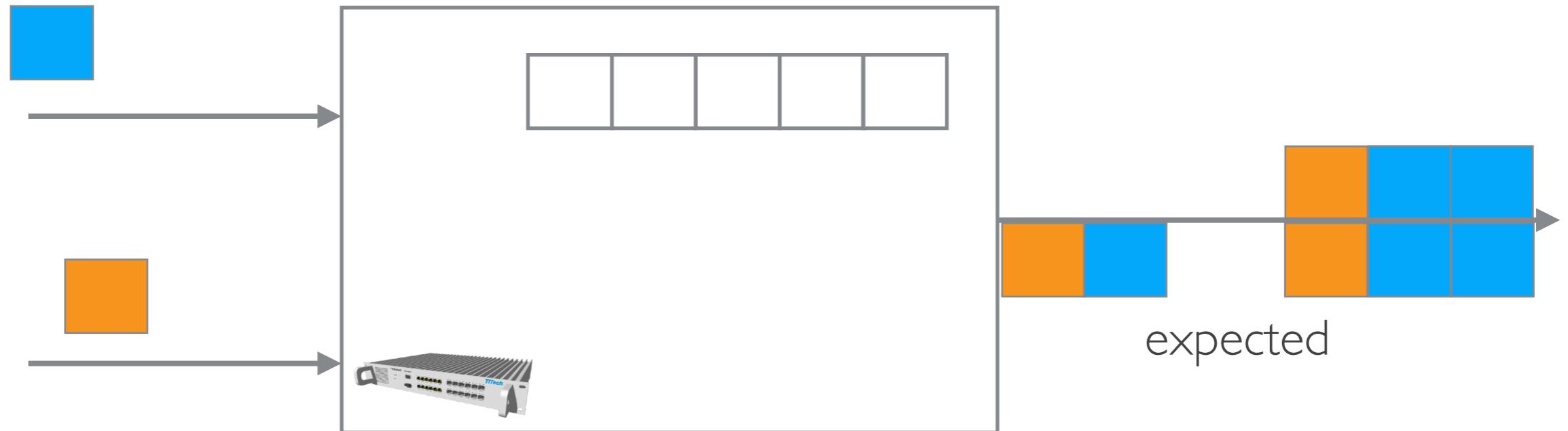
# Frame isolation



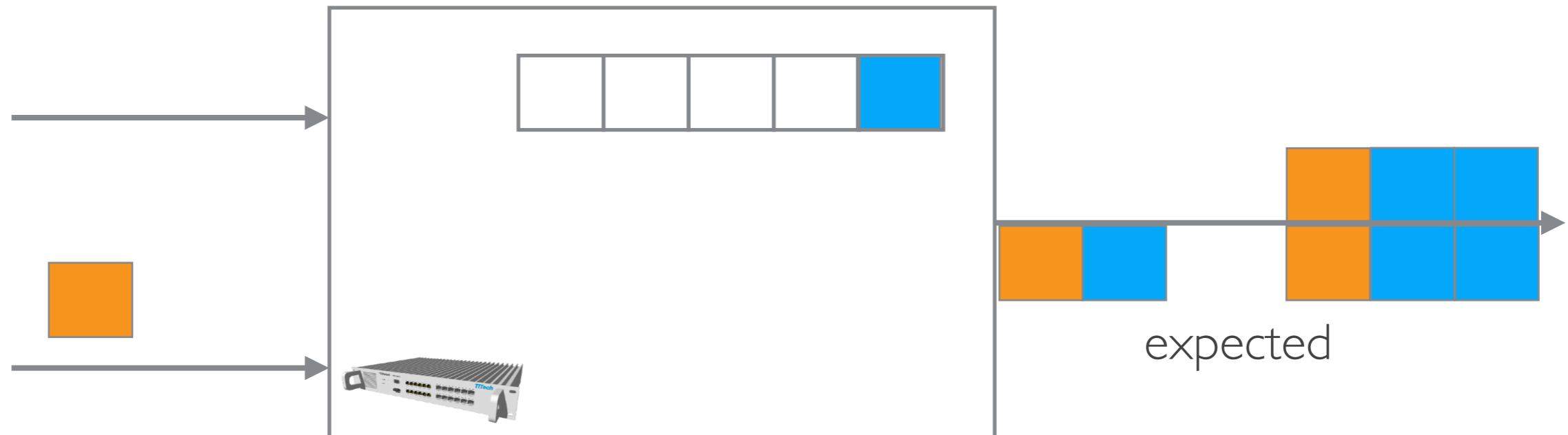
# Frame isolation



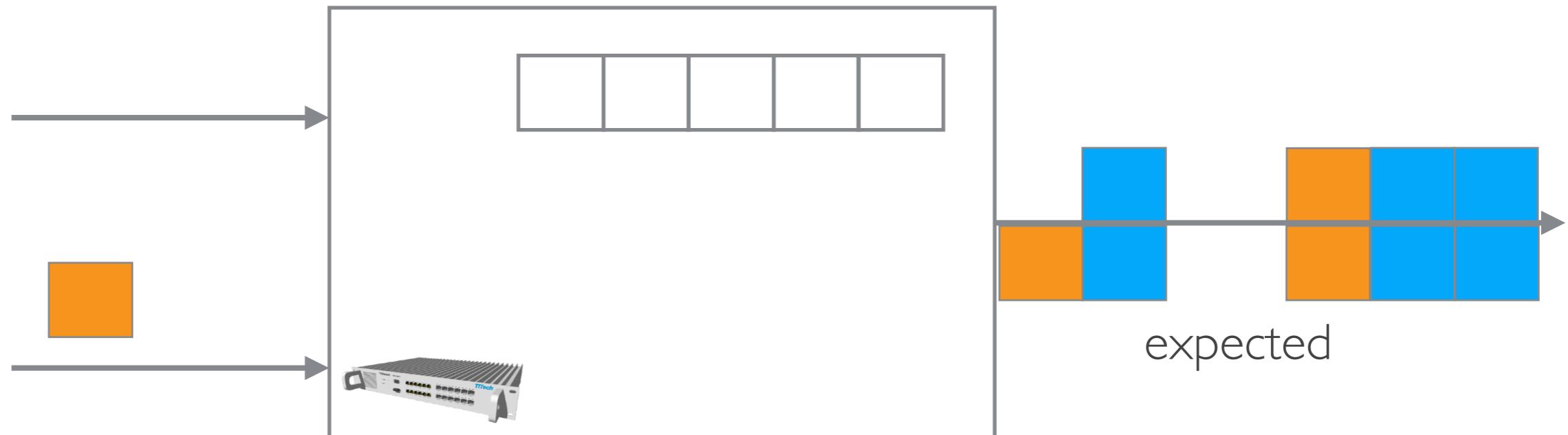
# Frame isolation



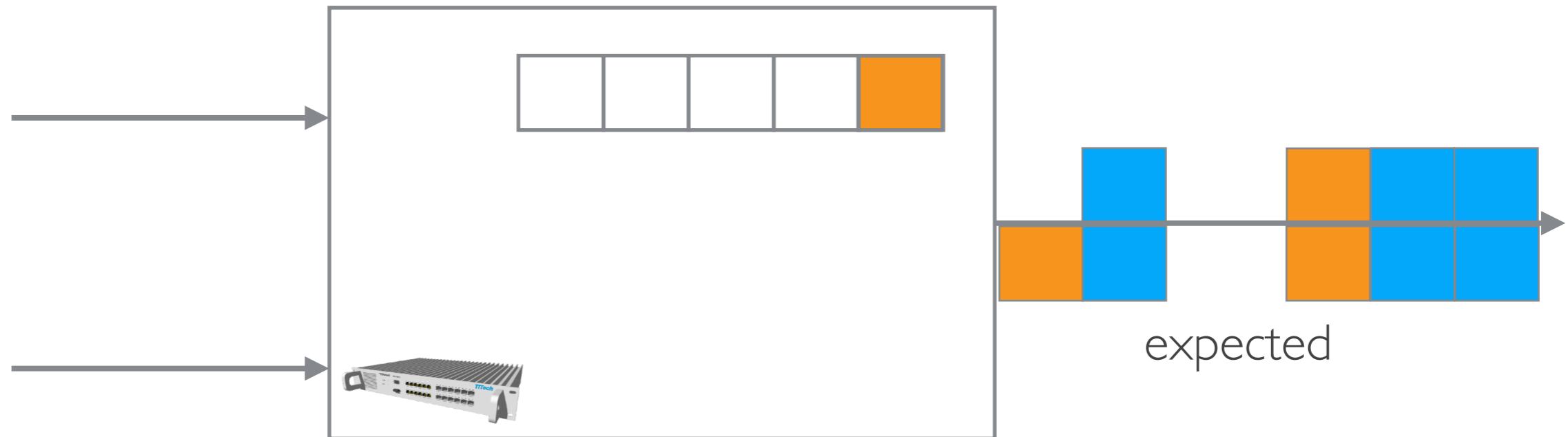
# Frame isolation



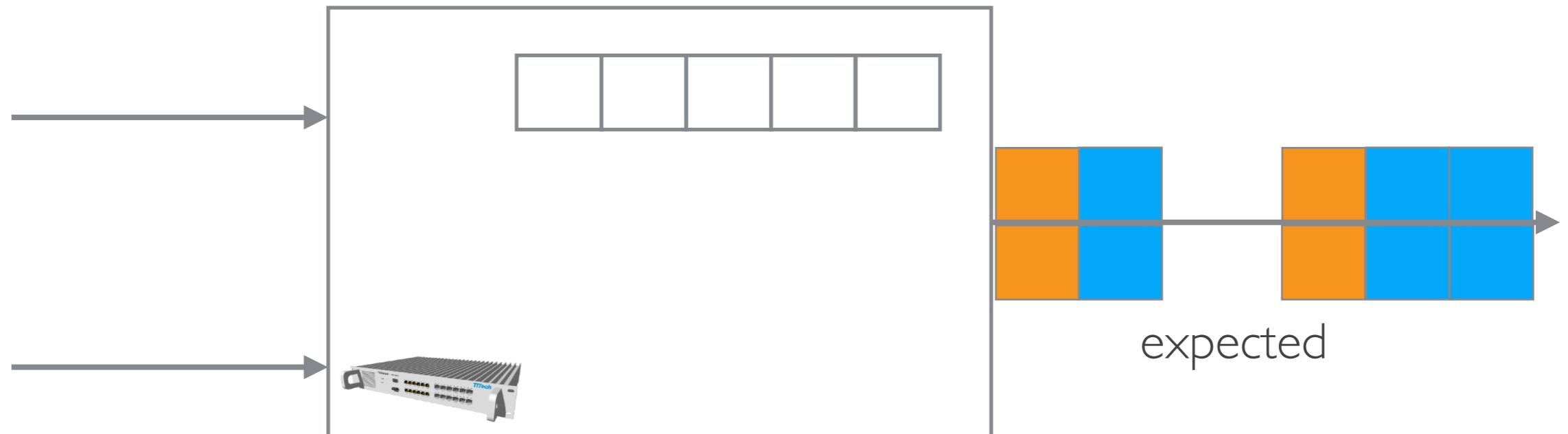
# Frame isolation



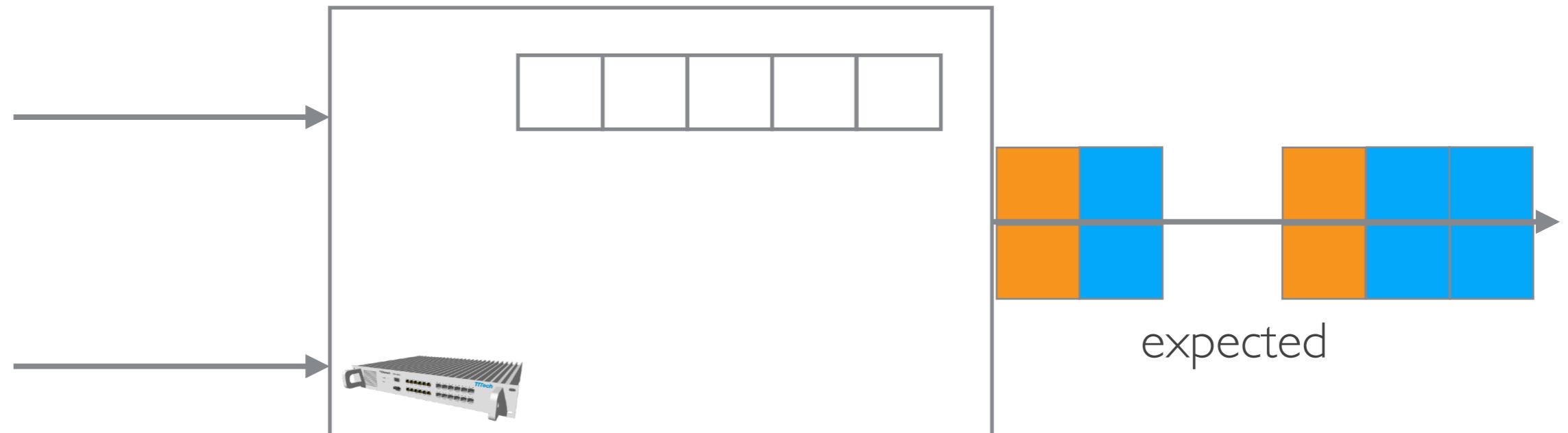
# Frame isolation



# Frame isolation



# Frame isolation



- Ensure that there are only frames of one flow in the queue at a time
- Frames from another flow may only enter the queue if the already queued frames of the initial flow have been serviced
- Less performant than stream isolation since the solver has to consider all frame interleavings

# 802.1 Qbv scheduling constraint

Ensuring Reliable Networks



The constraint for minimum jitter scheduling of critical traffic for 802.1 Qbv networks is:

isolate framesstreams in the **time domain**

OR

isolate streams in **different queues**

# Scheduling problem



# Scheduling problem

Find **offsets** and **queue assignments** for individual frames of TSN streams along the route that conform to the constraints

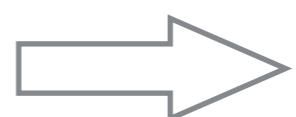


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Reduces to finding a solution for a set of inequalities resulting from

- frame constraints
- link constraints
- stream constraints
- end-to-end latency constraints
- **stream or frame isolation constraints**



802.1 Qbv

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802.1 Qbv

NP-complete

# Satisfiability Modulo Theories

Ensuring Reliable Networks



satisfiability of logical formulas in first-order formulation

background theories

$\mathcal{LA}(\mathbb{Z})$   $\mathcal{BV}$

variables  $x_1, x_2, \dots, x_n$

logical symbols  $\vee, \wedge, \neg, (, )$

non-logical symbols  $+, =, \%, \leq$

quantifiers  $\exists, \forall$

optimization (OMT) [[Bjørner@TACAS15](#)]

A lot of solvers and a very active community

OpenSMT [[Bruttomesso@TACAS10](#)]

Yices [[Dutertre@CAV14](#)]

CVC4 [[Barrett@CAV11](#)]

Z3 [[de Moura@TACAS08](#)]

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Ensuring Reliable Networks



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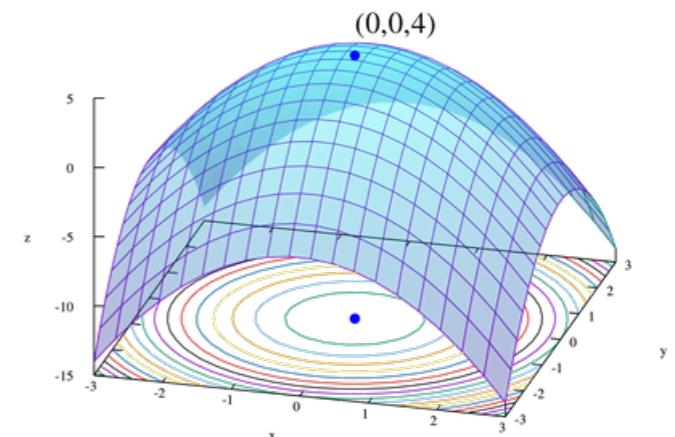
Z3 [[de Moura@TACAS08](mailto:de Moura@TACAS08)]

# Optimization

Optimize schedule with respect to certain properties of the system (e.g. minimize end-to-end latency of selected streams)

802.1Qbv-specific optimizations:

- **QoS properties:** minimize required scheduled queues in order to increase QoS properties of non-critical traffic
- **Design space exploration** in case of infeasible use-cases, i.e. find the minimal number of queues required for scheduled traffic such that a schedule is found



Many more optimization opportunities in combination with other TSN sub-standards (e.g. frame preemption)

# Experiments

- **Z3** v4.4.1 solver (64bit) (Yices v2.4.2 with quantifier-free linear integer arithmetic)
- 64bit 4-core **3.40GHz** Intel Core-i7 PC with 4GB memory
- 3 predefined topologies ranging from 3 end-systems connected to one switch to 7 end-systems connected through 5 switches via **1Gbit/s** links with a **1usec** macrotick granularity (generate **high utilization** on the links)
- Time-out value for a run to **5 hours**
- System configuration:  $\{V_{e+s}, \langle 8,8,0 \rangle\}$

A decorative graphic at the bottom of the slide consists of numerous thin, light blue lines that converge towards the bottom center, creating a fan-like or wave-like effect.

Scalability and schedulability experiments

# Evaluation



# Evaluation

time

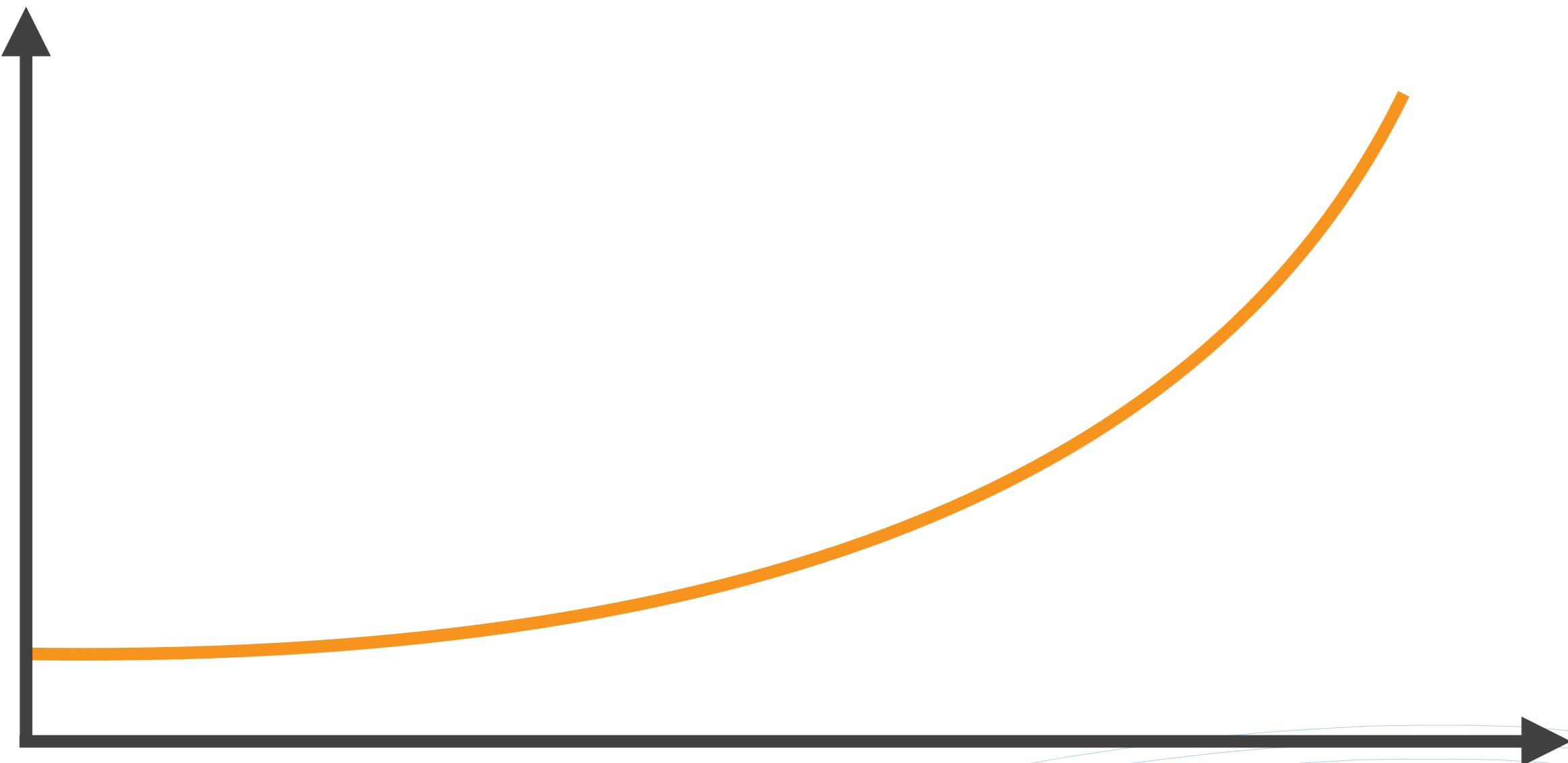


# Evaluation

Ensuring Reliable Networks

**TTTech**

time

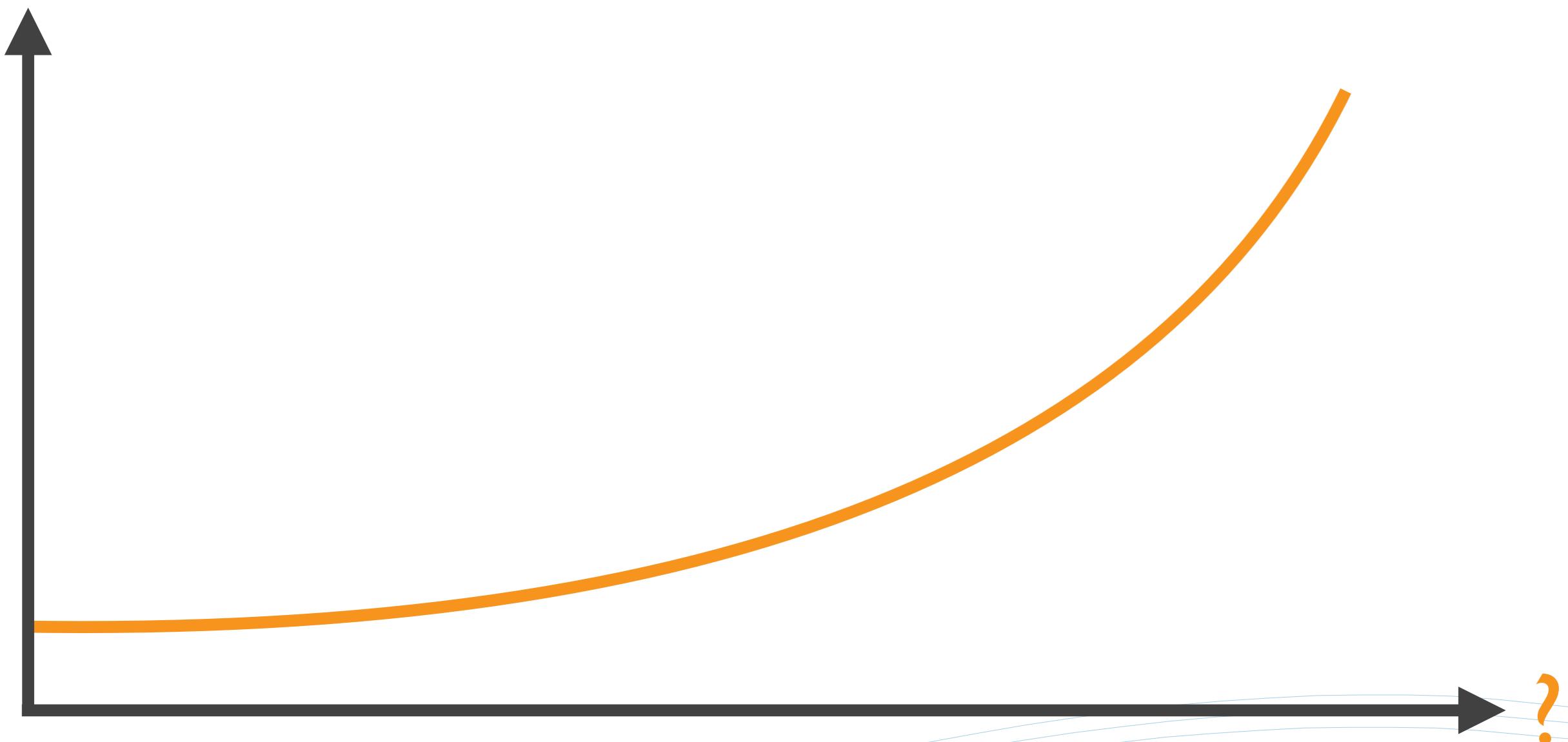


# Evaluation

Ensuring Reliable Networks

**TTTech**

time

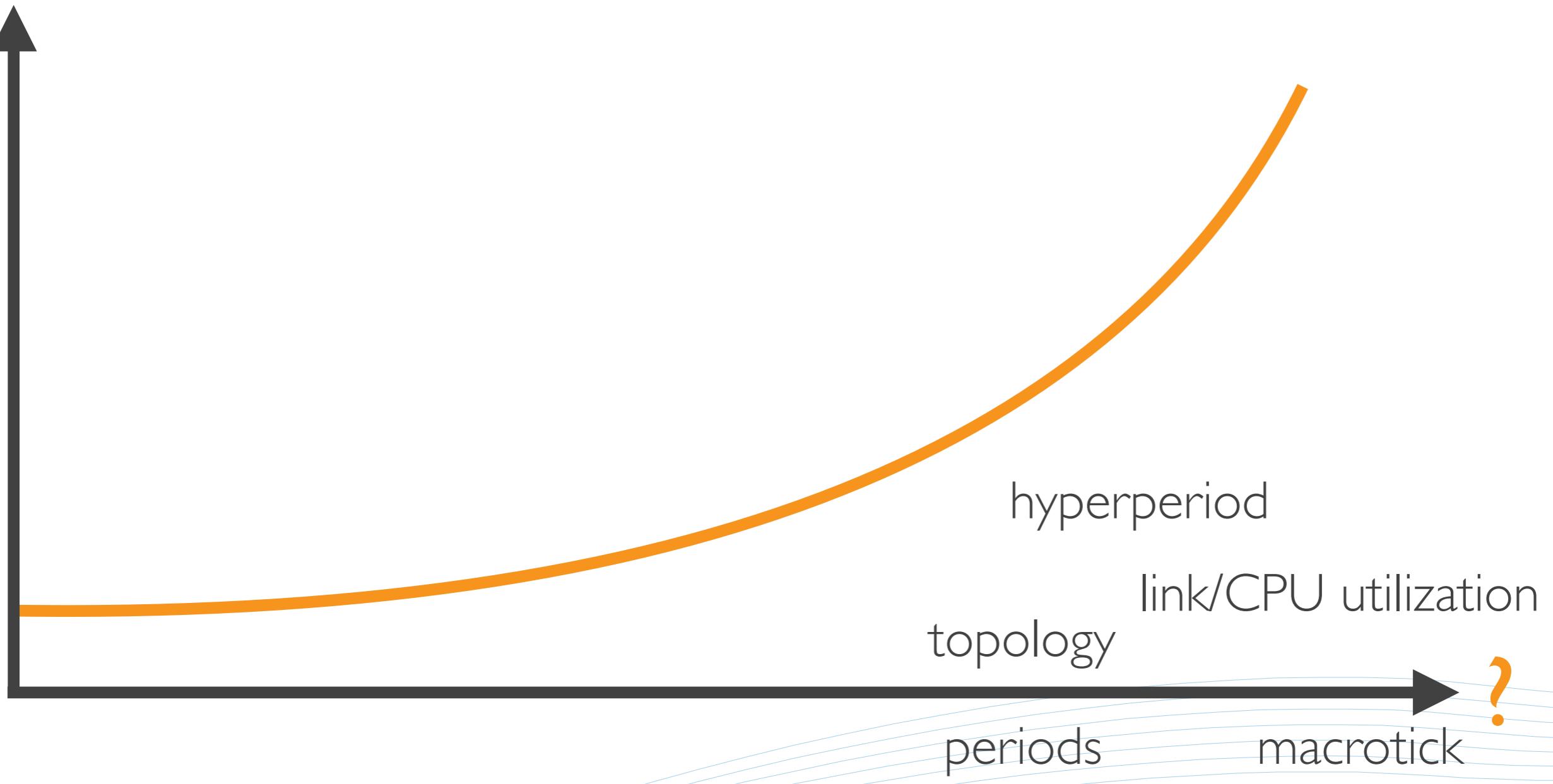


# Evaluation

Ensuring Reliable Networks

**TTTech**

time



# Scalability Experiments

Ensuring Reliable Networks

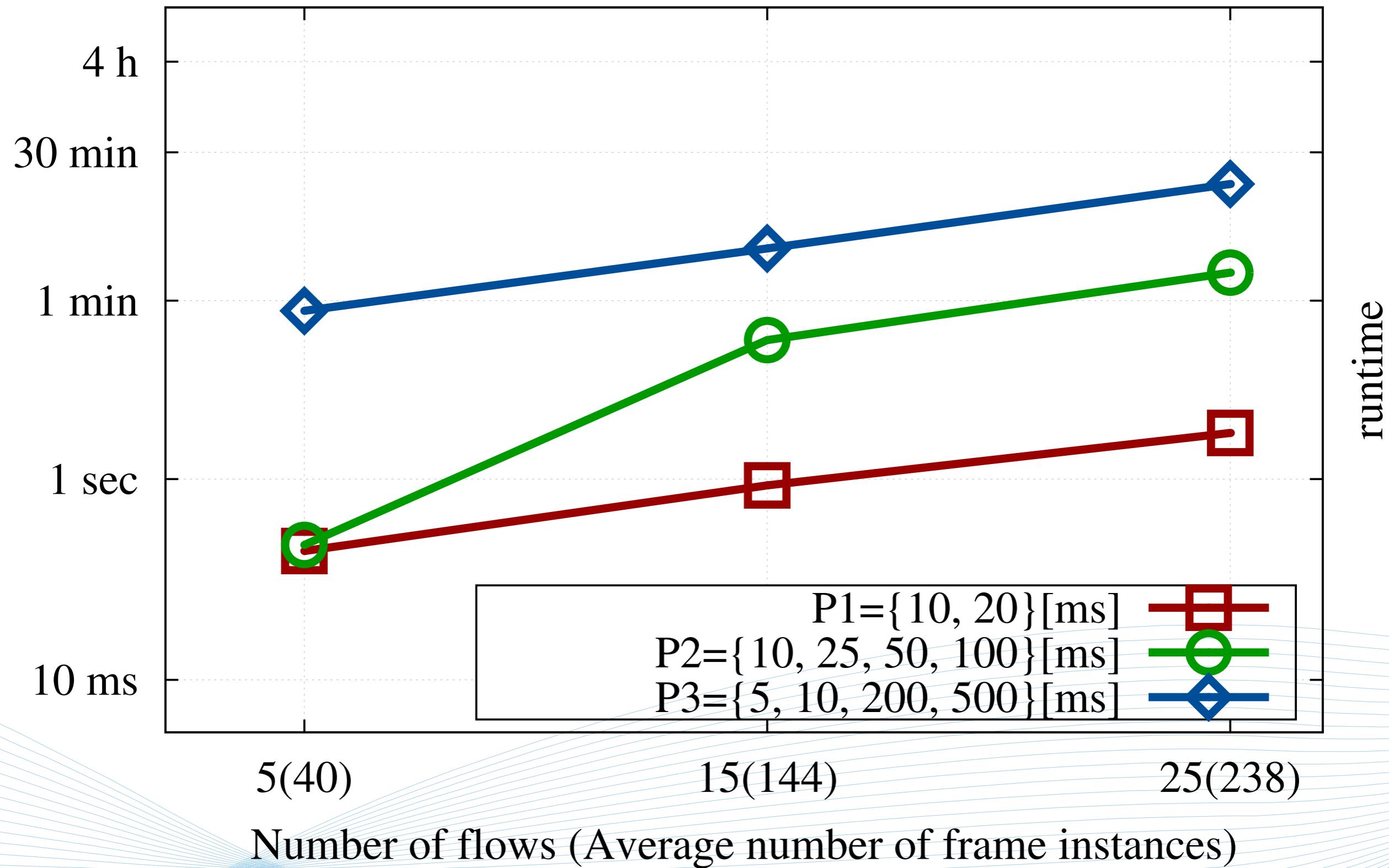


- **Frame isolation** method (using an incremental backtracking algorithm with step size of 1)
- Vary the problem set in **3 dimensions**:
  1. topology size,
  2. number of flows,
  3. flow periods (chosen randomly from 3 sets of predefined periods)
- Data size uniformly between **2** and **8 MTU**-sized frames
- Senders and receivers are chosen **randomly**

# Scalability Experiments

Ensuring Reliable Networks

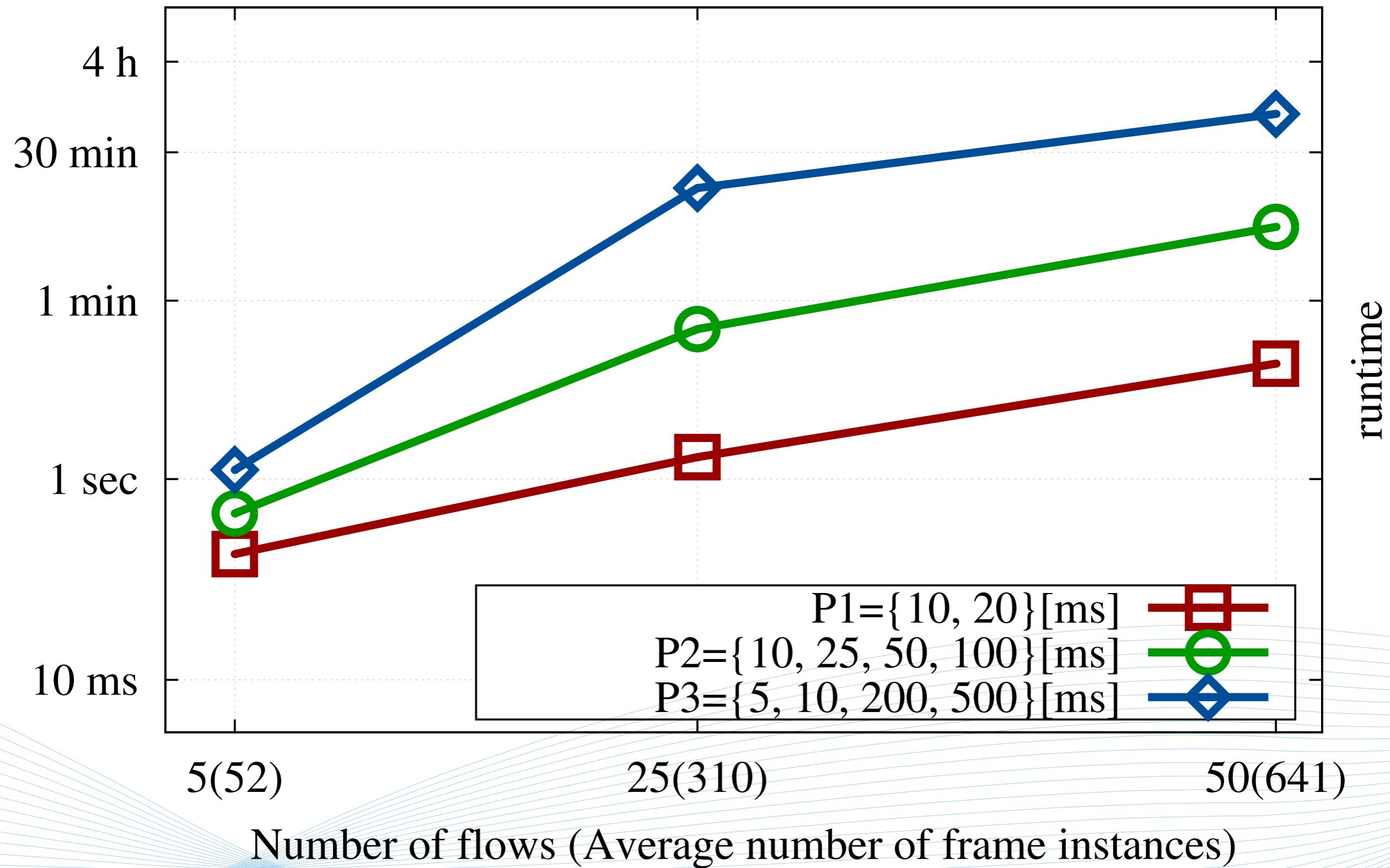
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# Scalability Experiments

Ensuring Reliable Networks

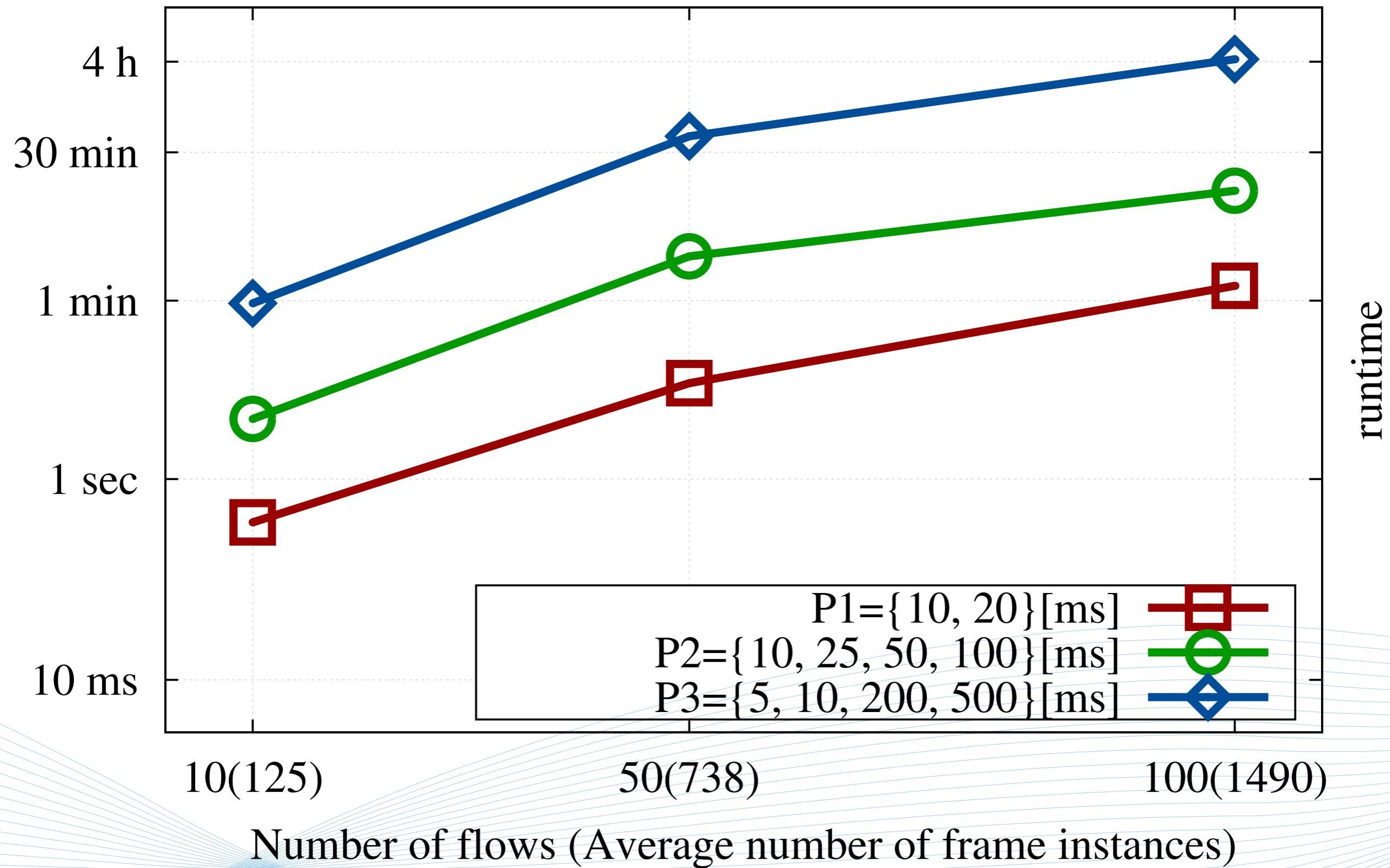
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# Scalability Experiments

Ensuring Reliable Networks

**TTTech**

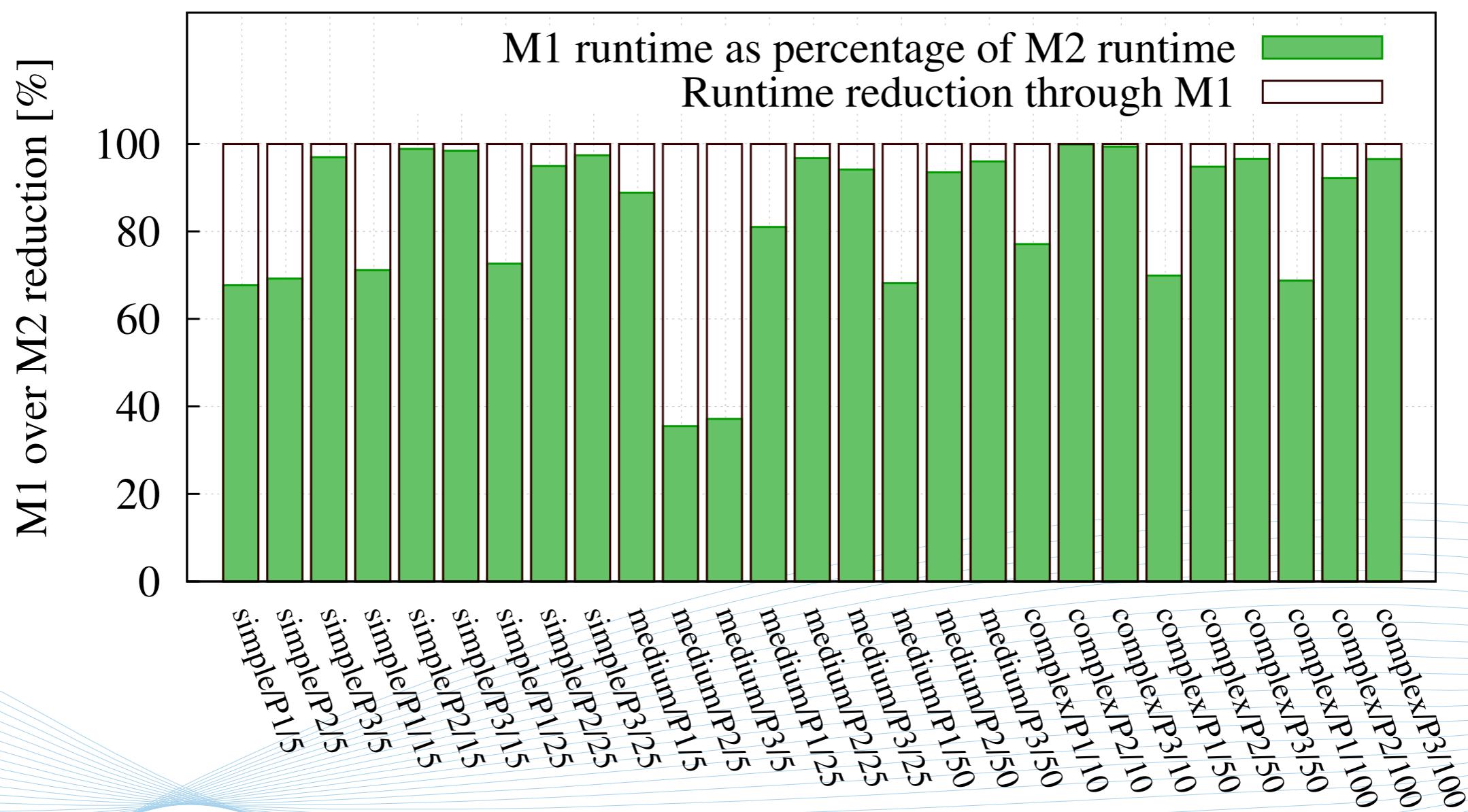


# Frame vs. Stream Isolation

Ensuring Reliable Networks

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- 381 randomly generated test cases with up to 1000 streams
- 17 reached the **time-out**
- Stream isolation was on average 13% faster with a median of 8.03%
- 36.7h for stream isolation and 59h for frame isolation - 30.73% improvement



# Schedulability Experiments

Ensuring Reliable Networks

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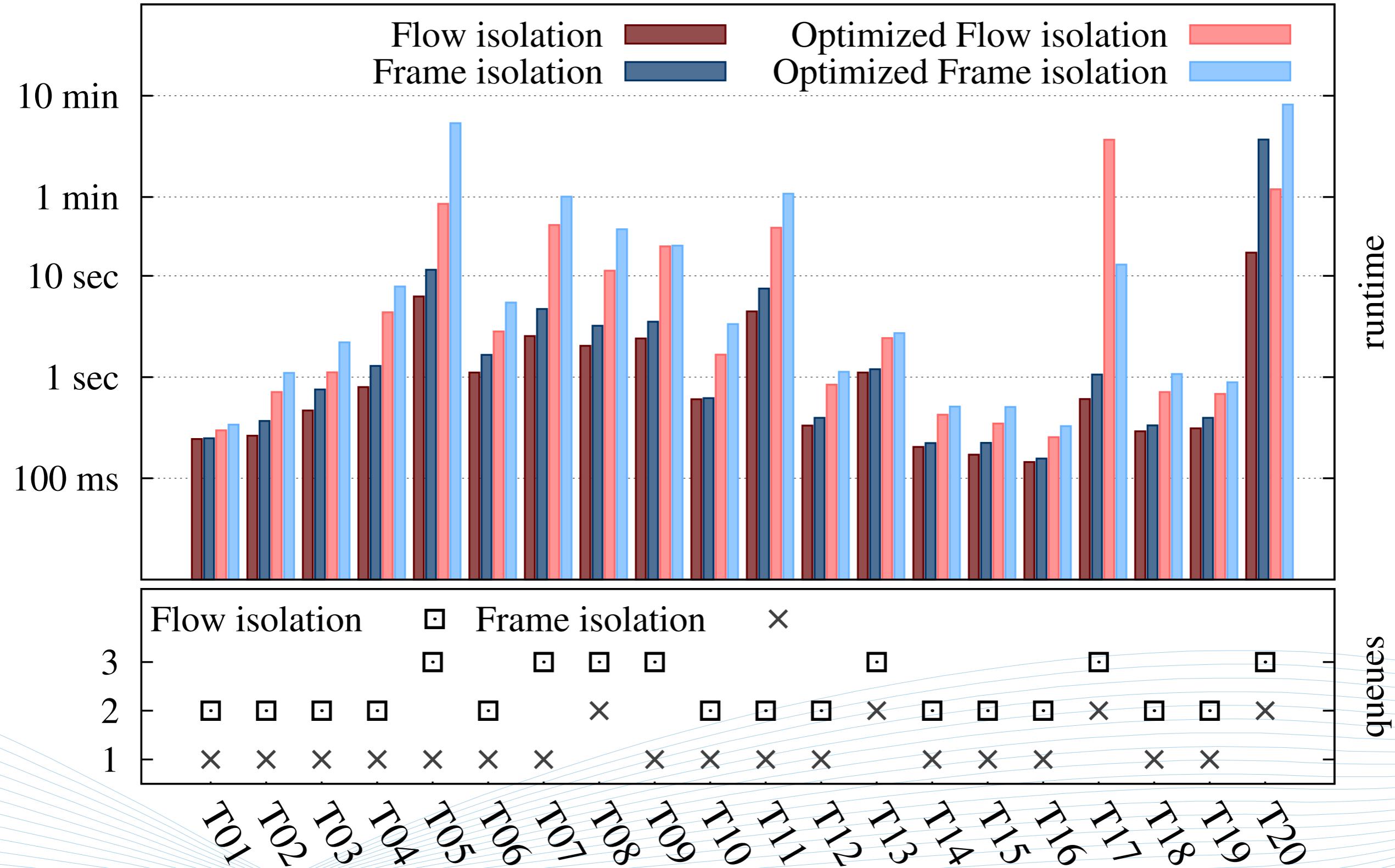
- Generated inputs that force streams to **interleave** if scheduled in the same egress queue
- Runs **w/ and w/o optimization** objectives using both stream and frame isolation methods
- Minimize **accrued sum** of the number of **queues** used per egress port
- No incremental steps for optimization runs



# Schedulability Experiments

Ensuring Reliable Networks

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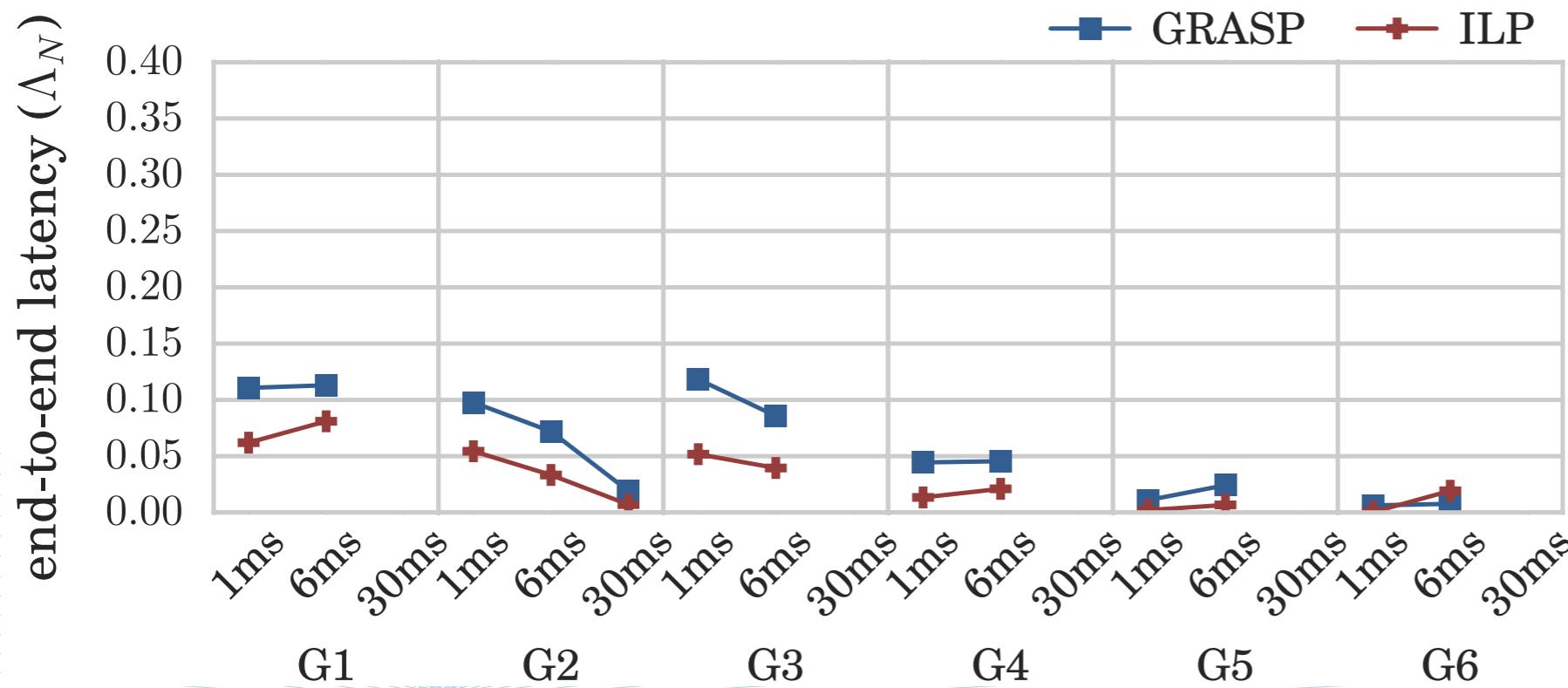
# Heuristics

For large networks we have to use heuristics,  
e.g:

Greedy Randomized Adaptive Search Procedure  
(GRASP)-based metaheuristic together with M.  
L. Raagaard and P. Pop (c.f. [2])

ID	running time (s)			queue usage			
	ILP	OMT	GRASP	$K$	$\underline{K}$	$\bar{K}$	$K_N$
T01	0.66	0.81	0.32	2	2	5	0
T04	2.49	2.46	0.21	2	2	5	0
T05	3.73	3.43	0.34	2	2	3	0
T10	4.70	5.12	0.72	4	4	8	0
T11	16.54	12.94	0.84	3	3	7	0
T12	210.03	34.33	0.69	5	5	9	0
T14	39.06	22.87	0.84	2	2	3	0
T18	10.98	7.17	0.56	2	2	5	0

**Table 2: Comparison of ILP, OMT, and GRASP**



# Conclusions



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Scheduling problem arising from the IEEE 802.1 Qbv extension on multi-hop fully switched TSN networks



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# References and further reading

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IEEE 802.1 Time Sensitive Networking (TSN) task group - <http://www.ieee802.org/1/pages/tsn.html>

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