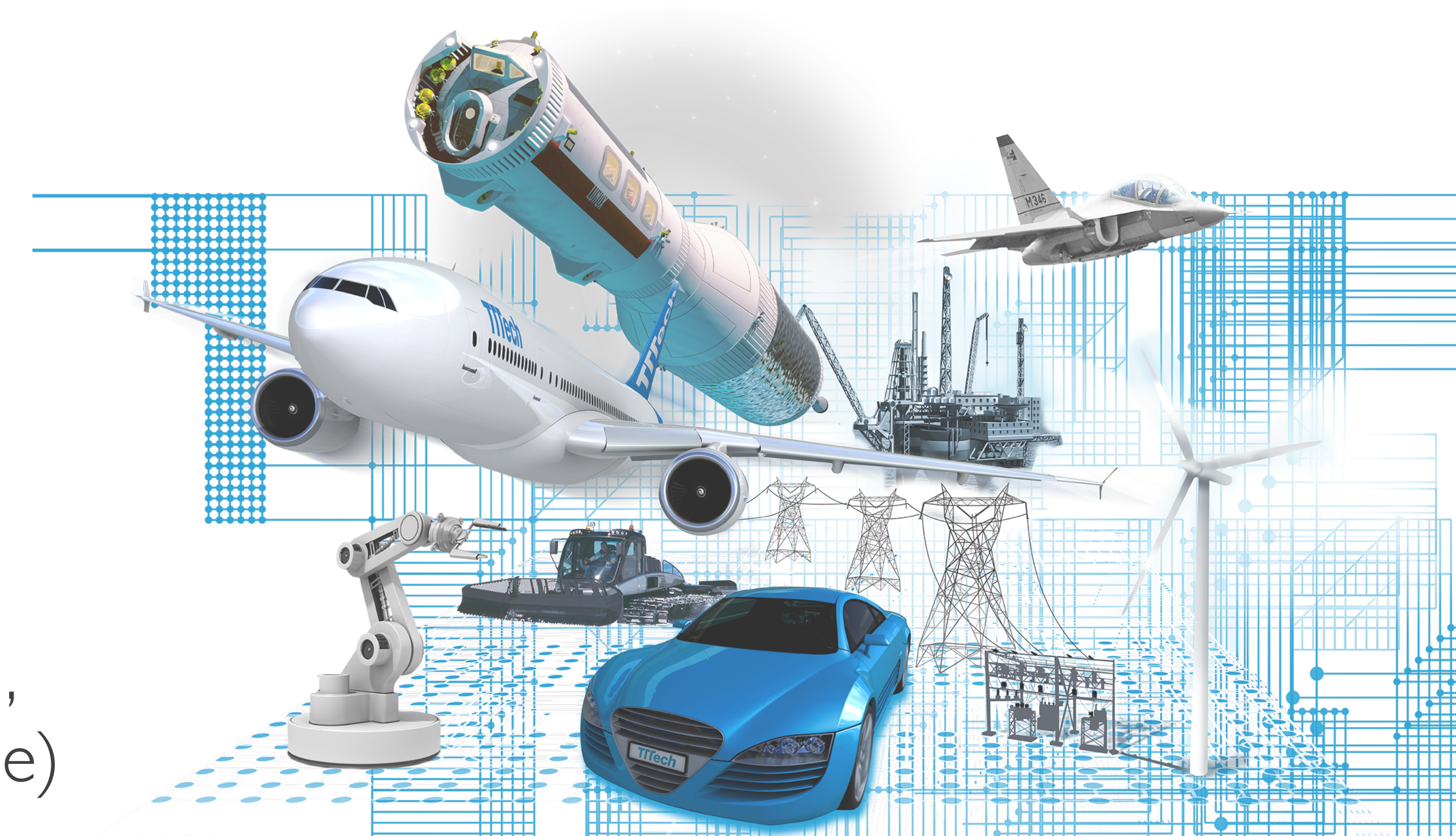
Ensuring Reliable Networks TTTech

SMT-based Schedule Synthesis for Time-Sensitive Networks

Silviu S. Craciunas
TTTech Computertechnik AG



ETR 2017 : École d'Été Temps Réel,
28 Aug. - 1 Sept. 2017, Paris (France)

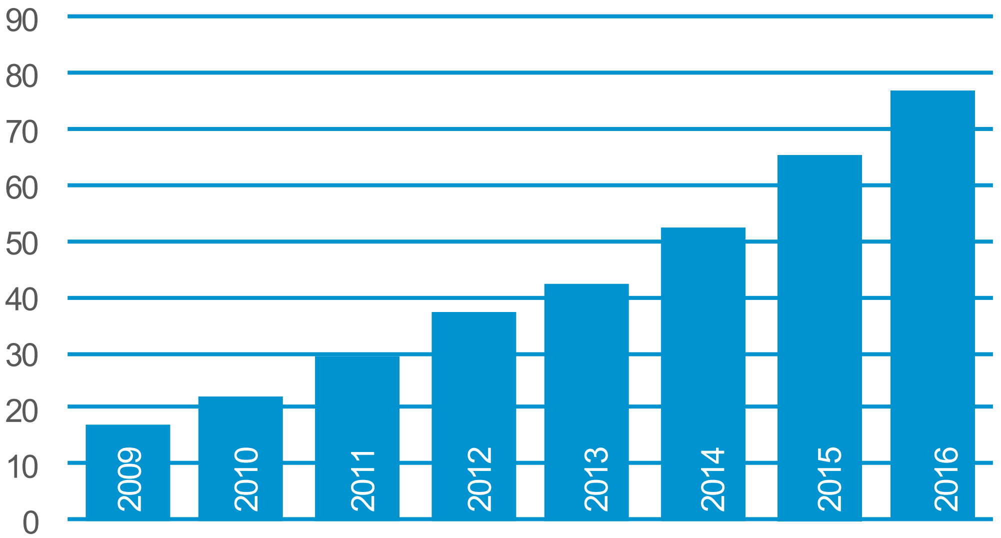
Company Key Facts

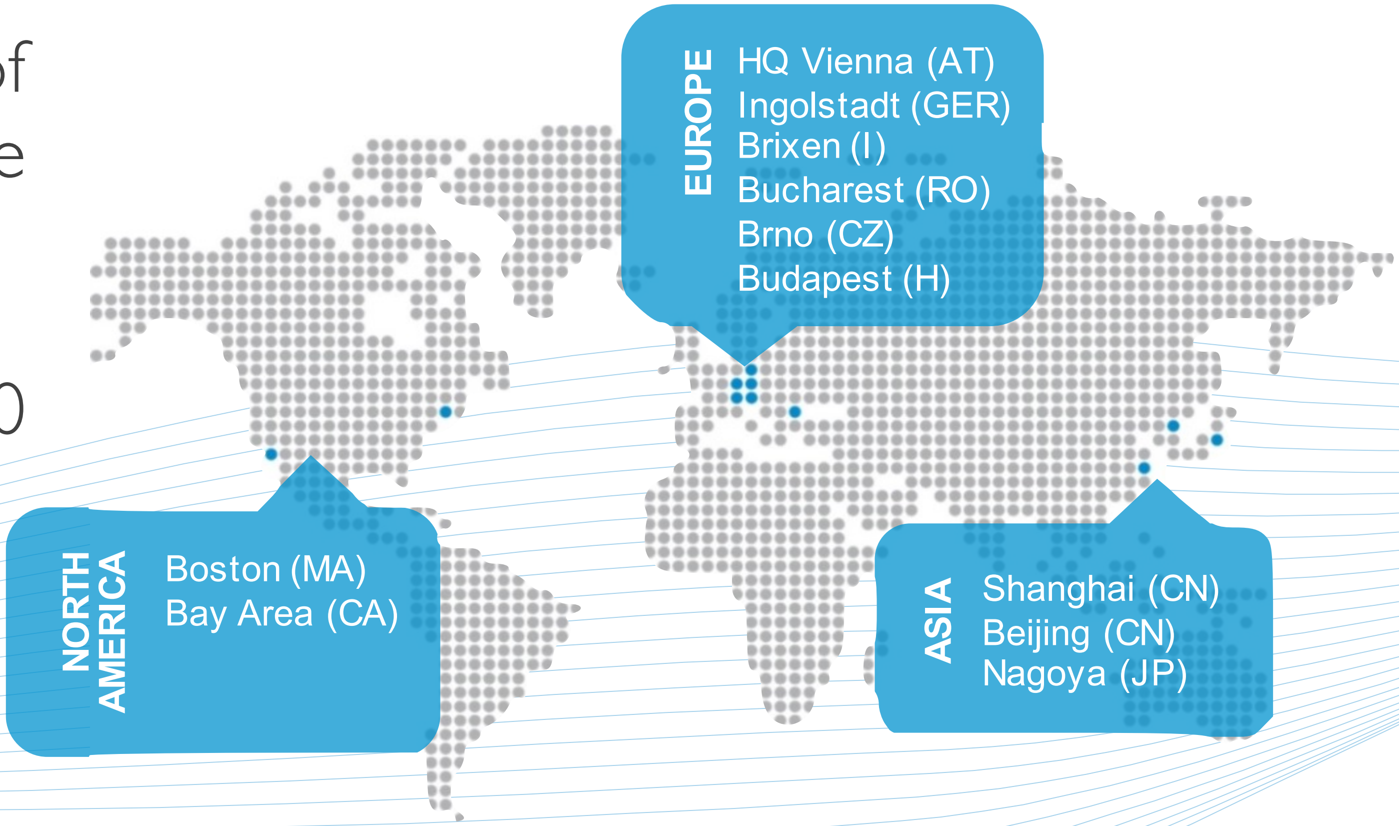
TTTech provides highly reliable and networked electronic systems with solutions based on time-triggered networking technology and modular building blocks for safety controllers

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

- 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 Currie 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

R&D Cooperation with Industry

- 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.

International Research Network

- EC-funded projects in ARTEMIS, DREAMS, ENABLE-S3, ECSEL, ITEA 1&2, Eurostars, Greencars, Cleansky, Marie Currie and other R&D Projects directly funded in FP5, FP6, FP7, H2020
- US programs: NASA, DARPA, NSF

R&D Cooperation with Universities & Research Organizations

- 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

Ensuring Reliable Networks TTTech

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

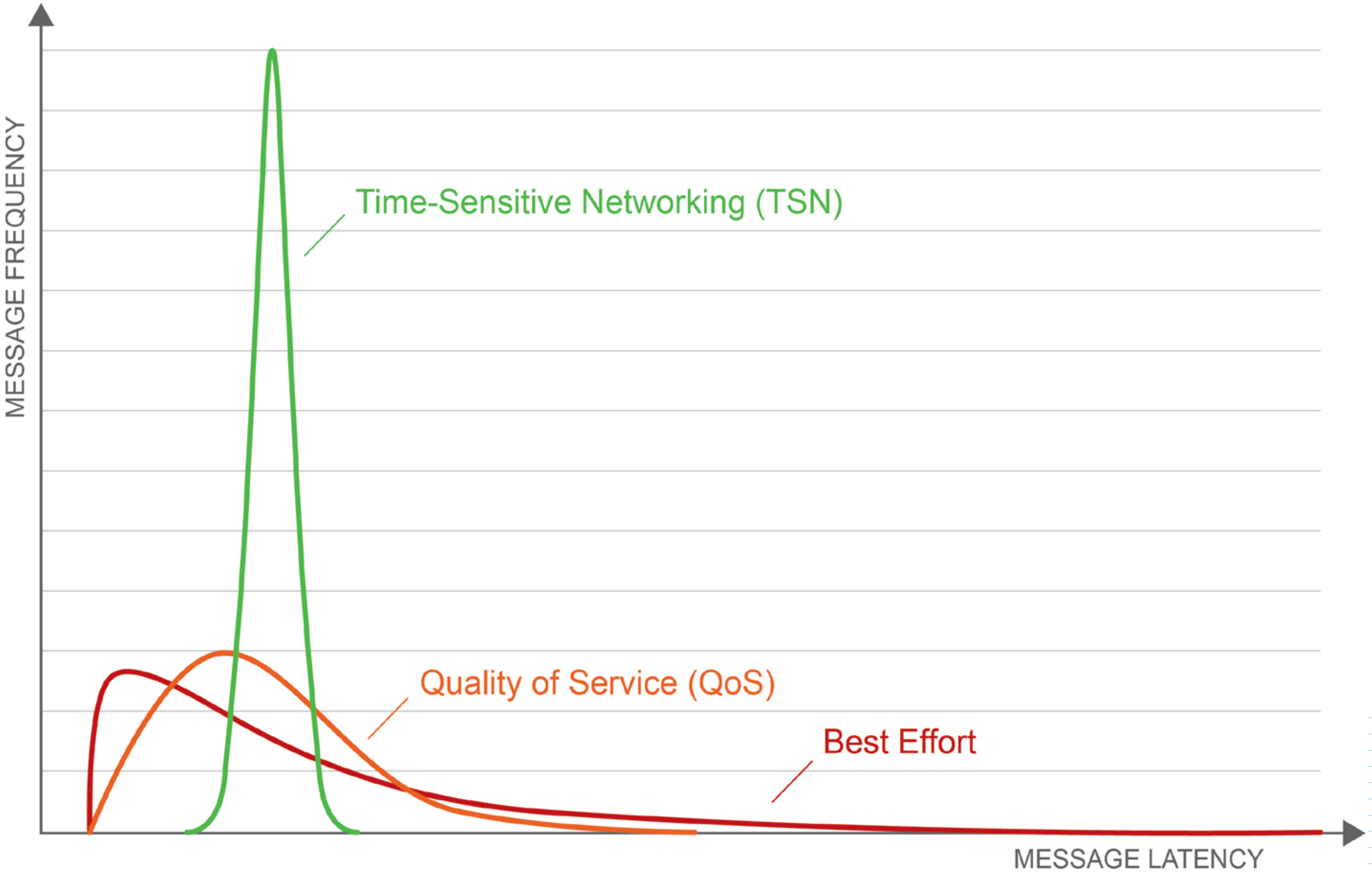
Embedded device will be safety relevant by 2020

Safety & Reliability

Time-sensitive domains

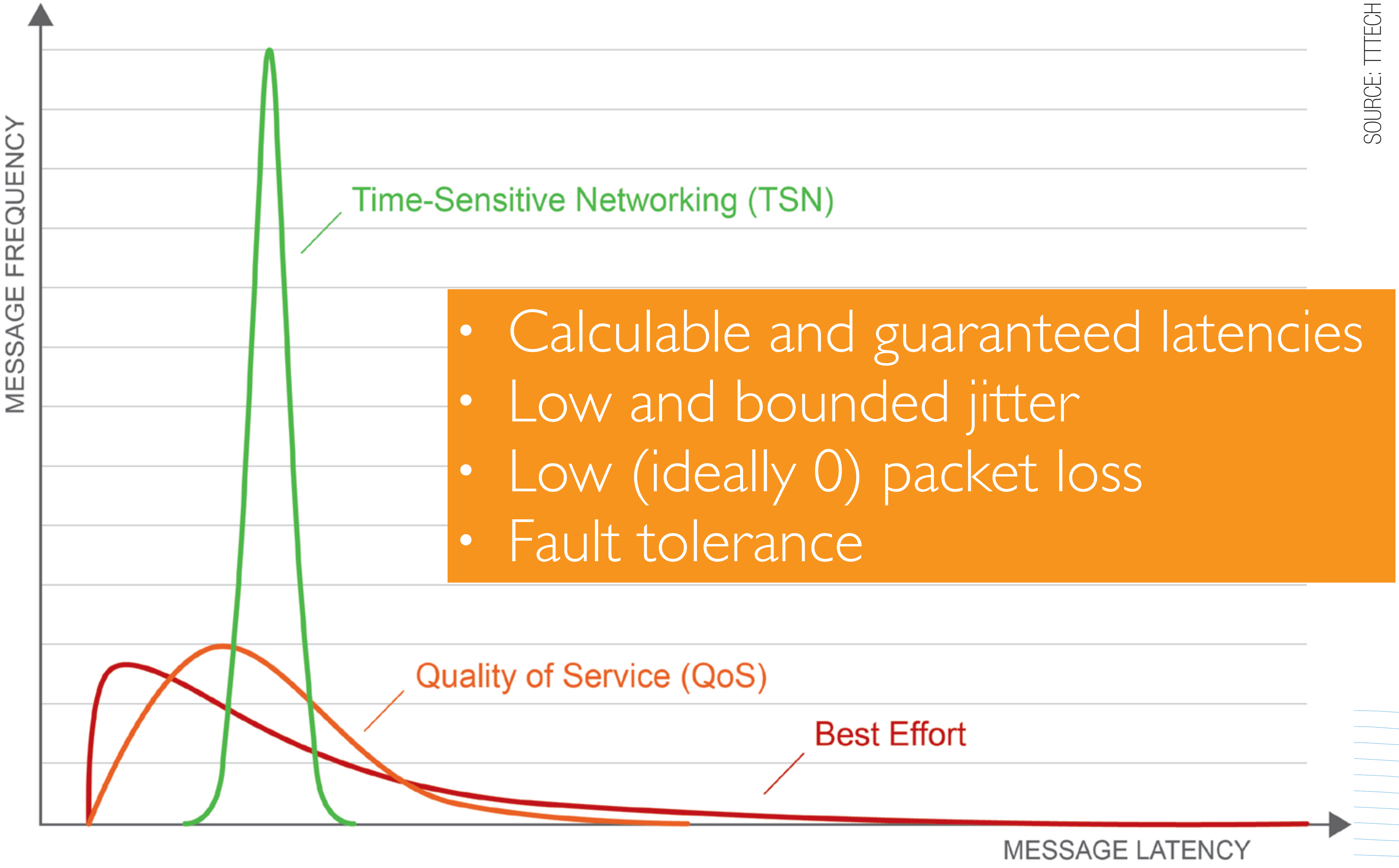
Time-sensitive networking

Ensuring Reliable Networks TTTech



SOURCE: TTTECH

Time-sensitive networking

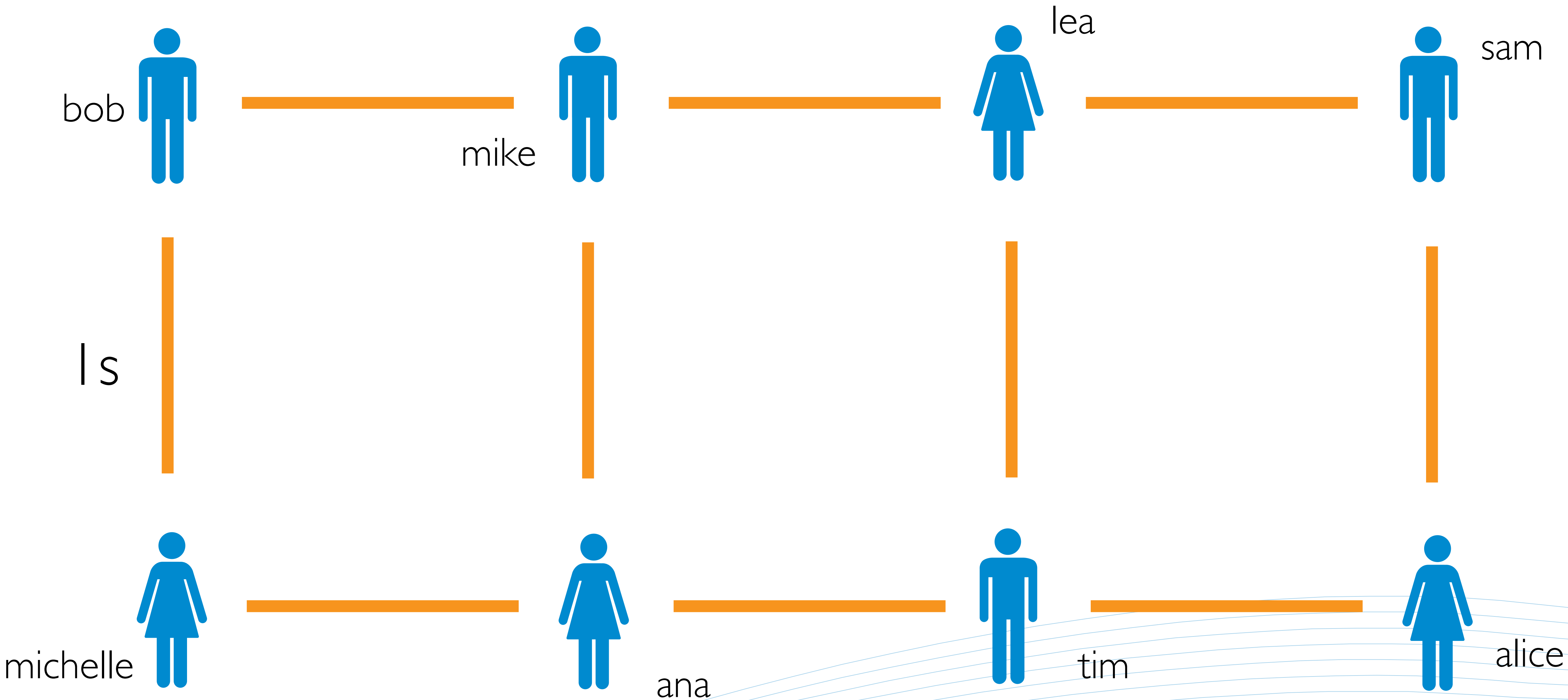


SOURCE: TTTECH

- Calculable and guaranteed latencies
- Low and bounded jitter
- Low (ideally 0) packet loss
- Fault tolerance

Experiment

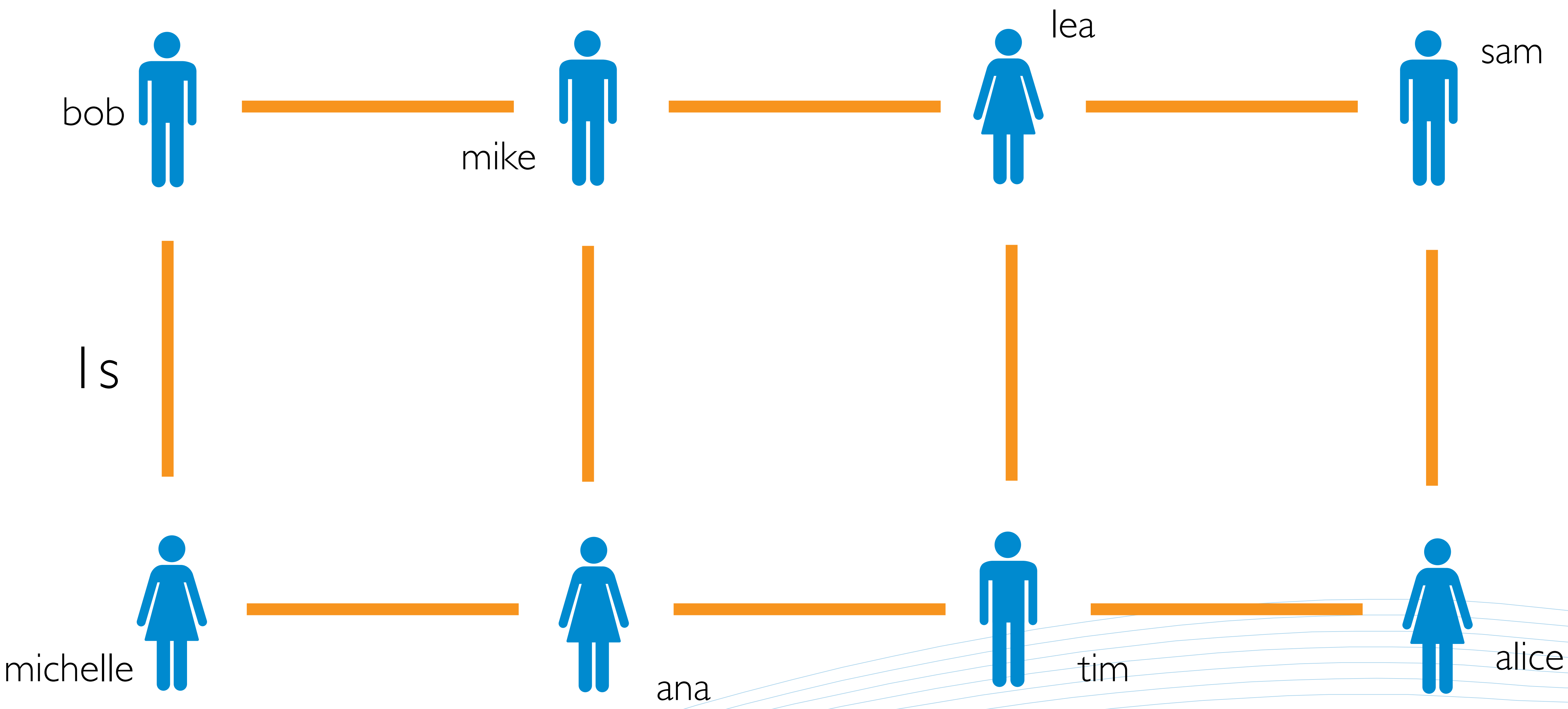
t=



maximum latency = 4s

Experiment

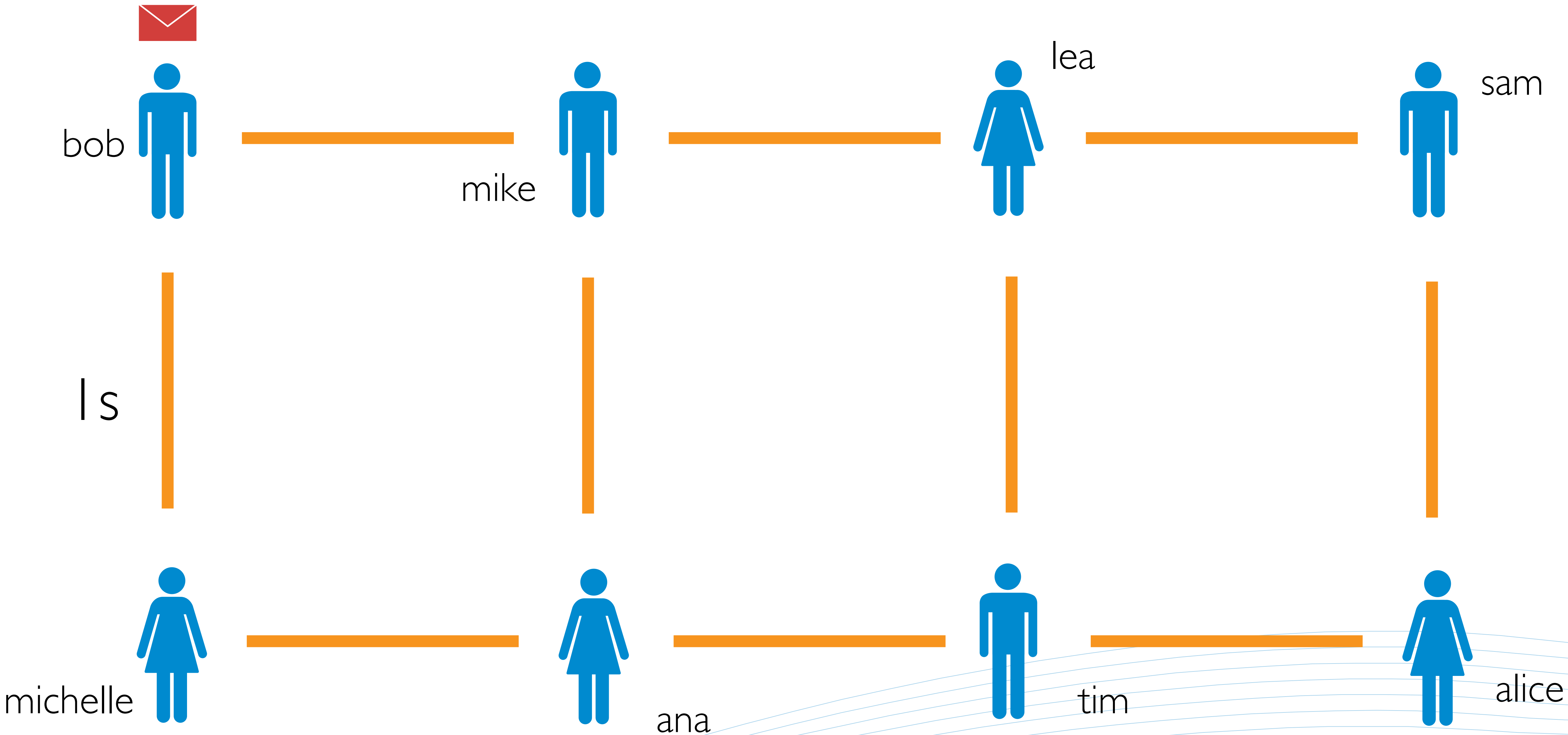
t= 0



maximum latency = 4s

Experiment

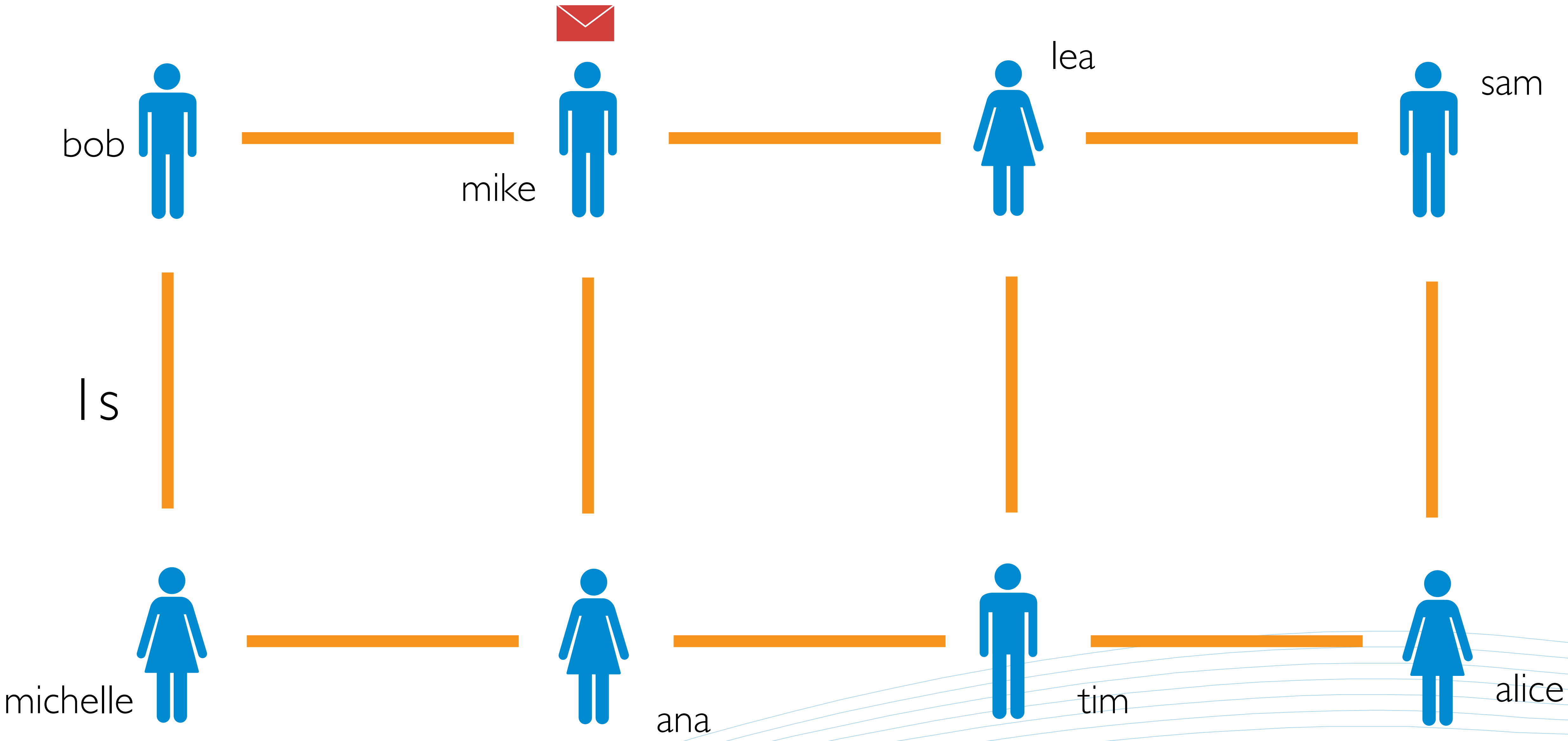
t= 0



maximum latency = 4s

Experiment

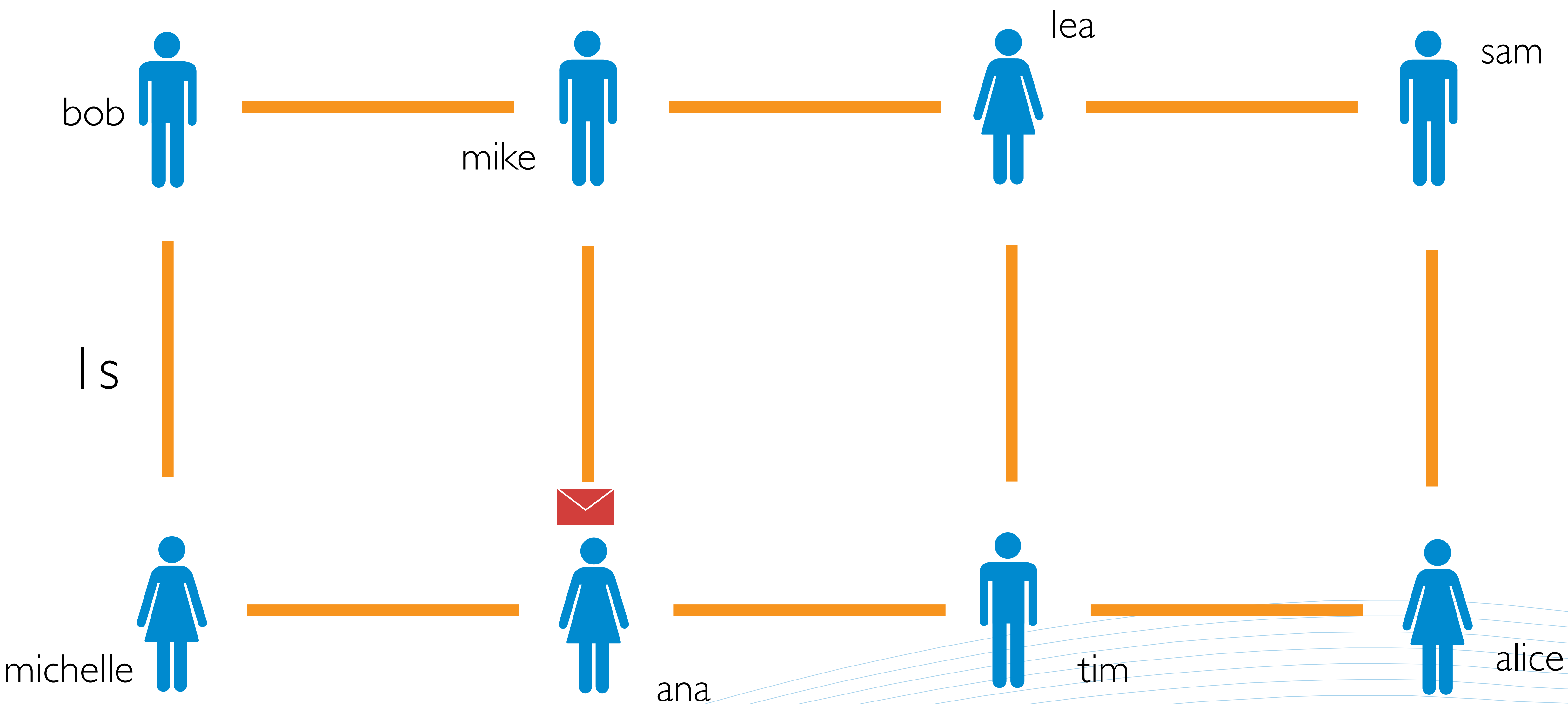
t= 0



maximum latency = 4s

Experiment

t= 0

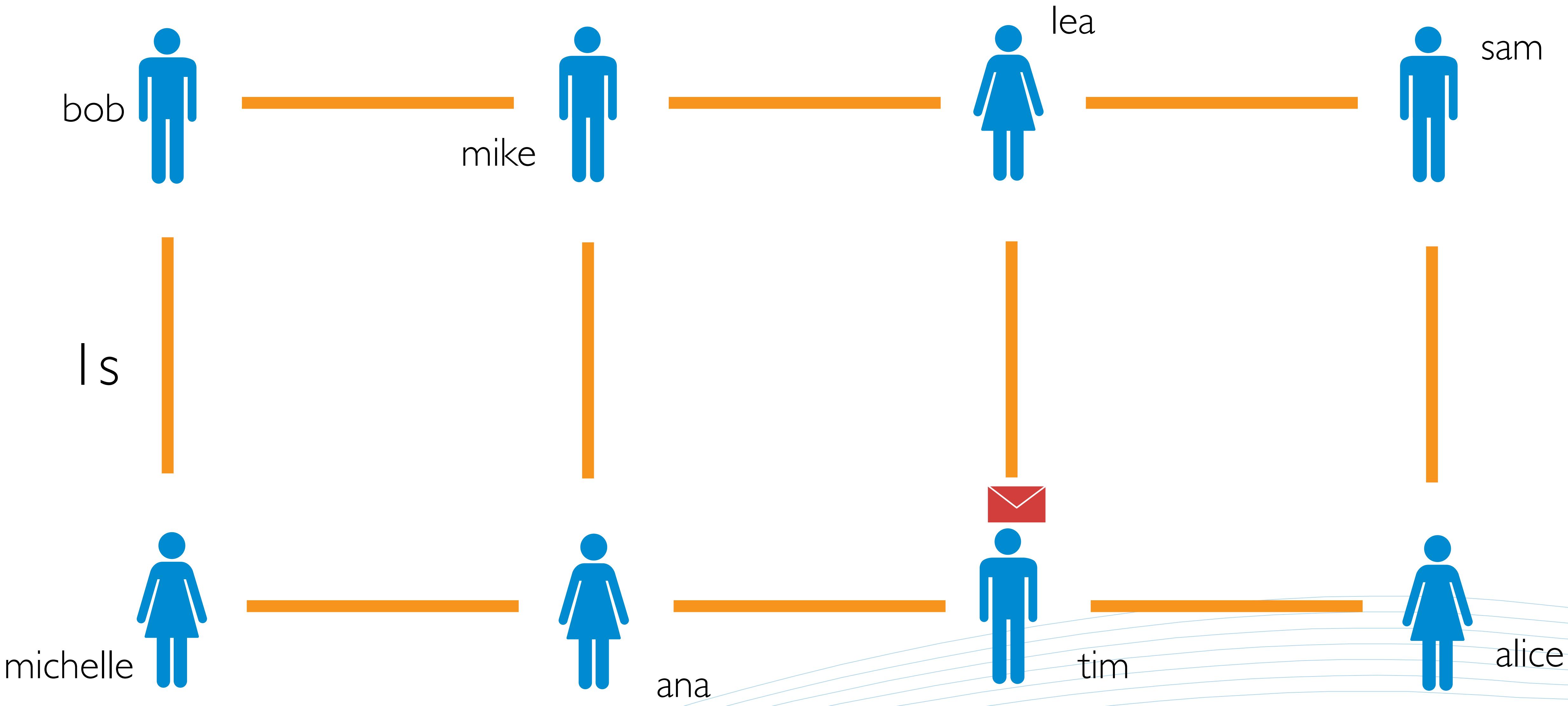


maximum latency = 4s

Experiment

Ensuring Reliable Networks TTTech

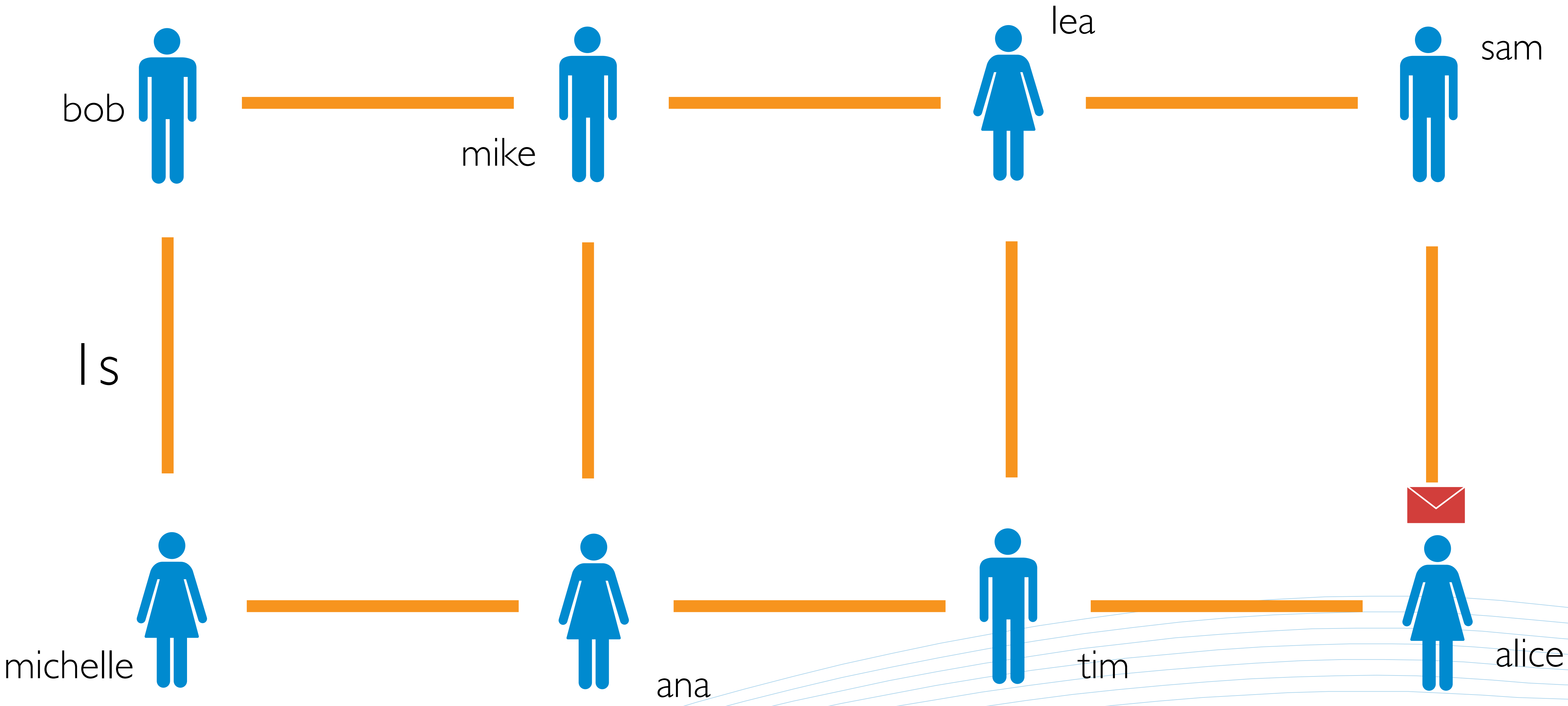
t= 0



maximum latency = 4s

Experiment

t= 0

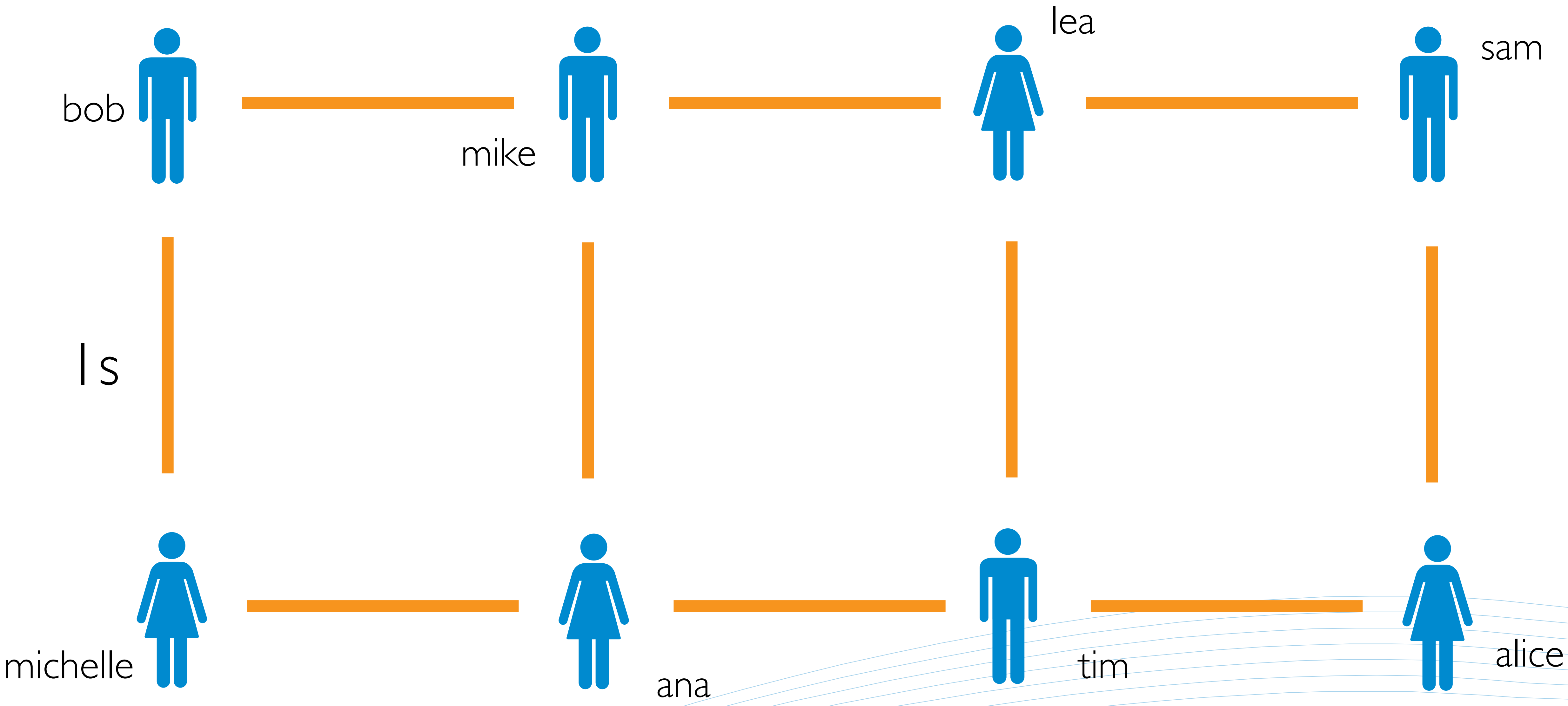


maximum latency = 4s

Experiment

Ensuring Reliable Networks TTTech

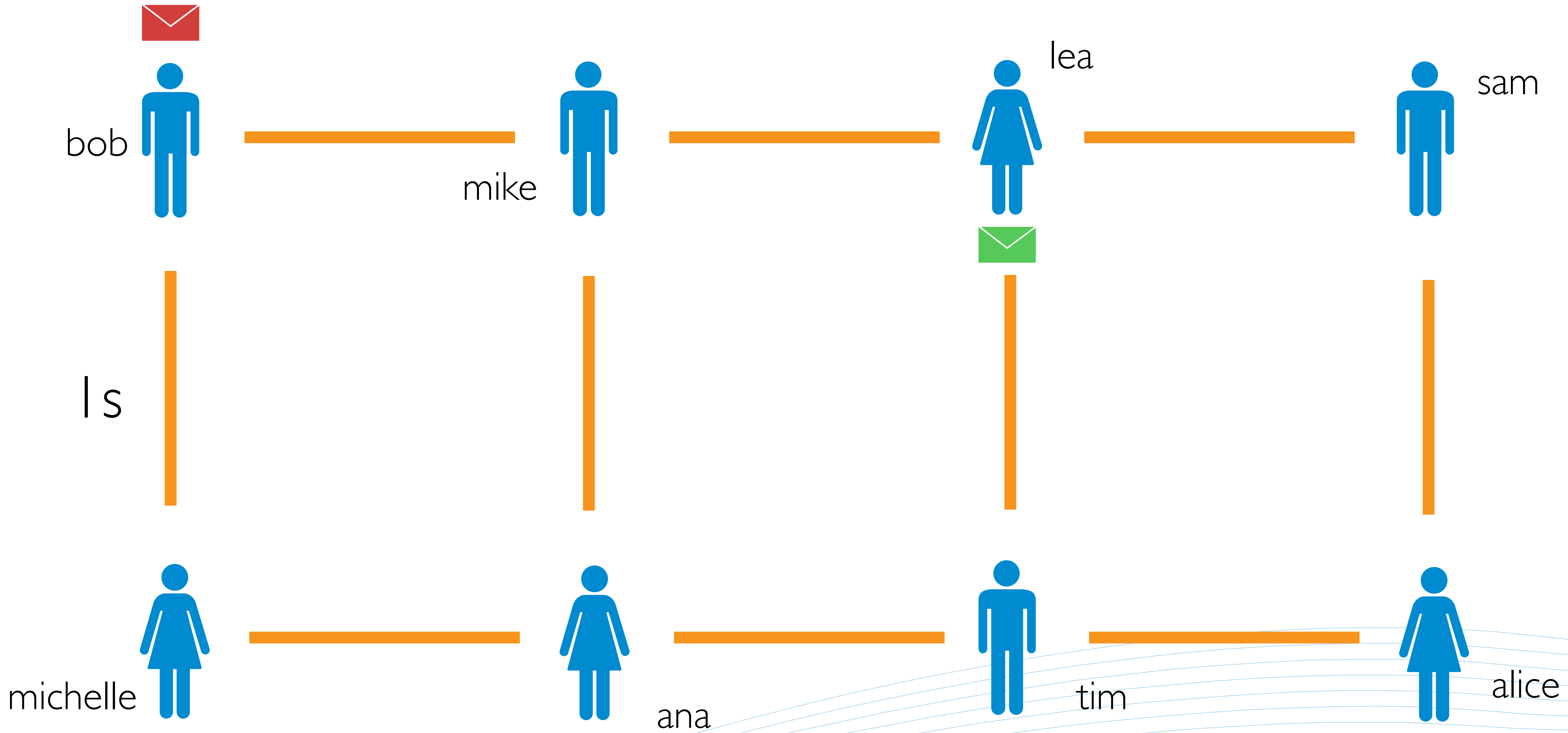
t= 0



maximum latency = 4s

Experiment

t= 0

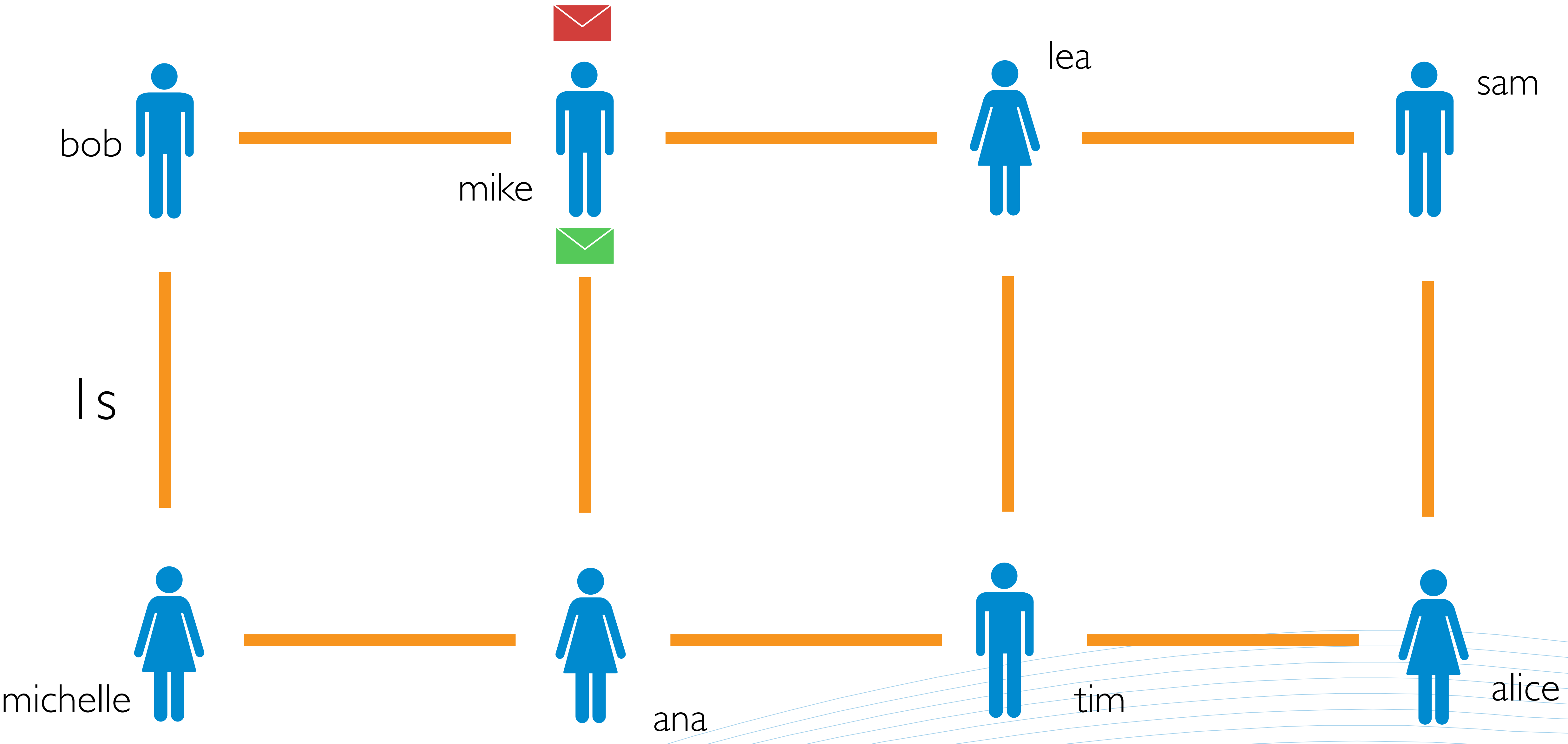


maximum latency = 4s

Experiment

Ensuring Reliable Networks TTTech

t= 1

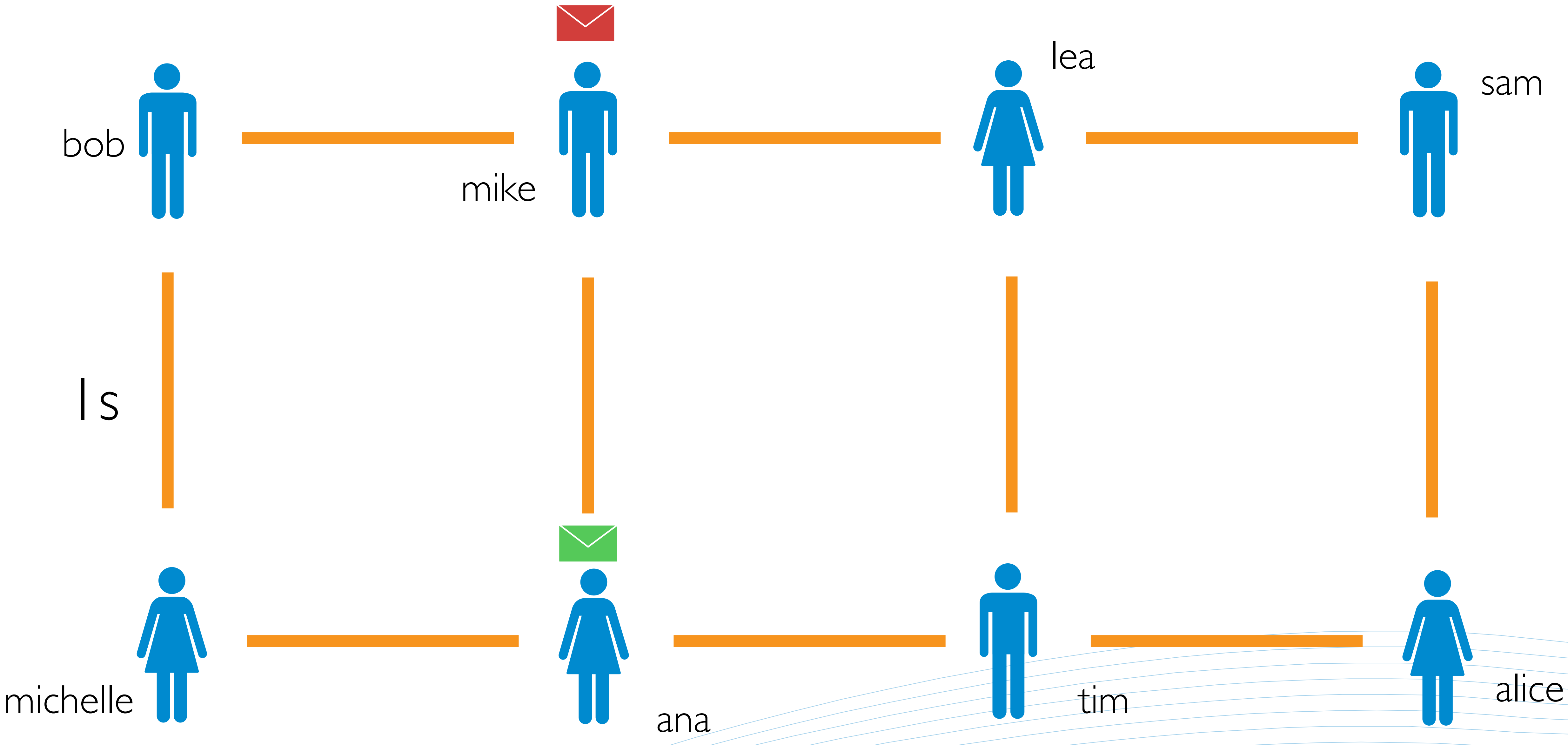


maximum latency = 4s

Experiment

Ensuring Reliable Networks TTTech

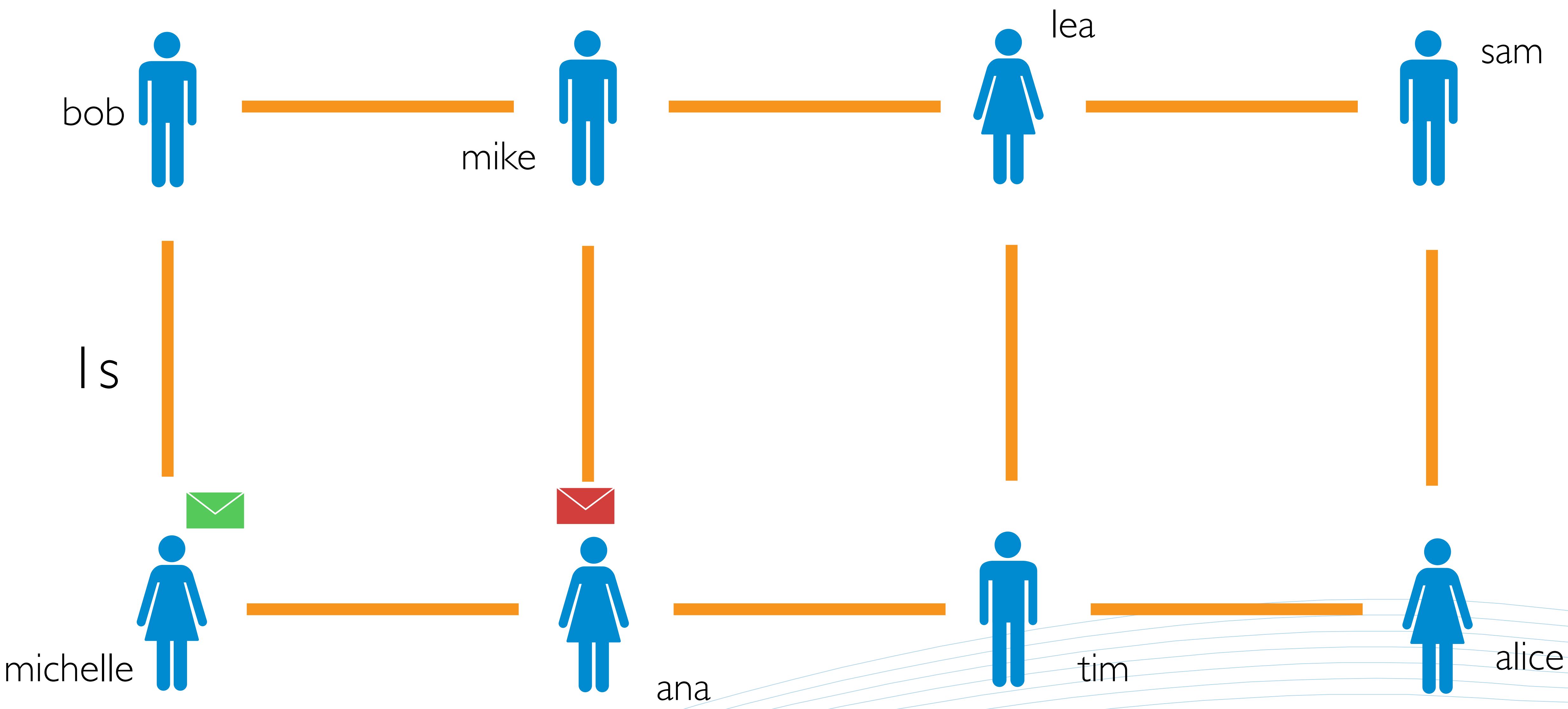
t= 2



maximum latency = 4s

Experiment

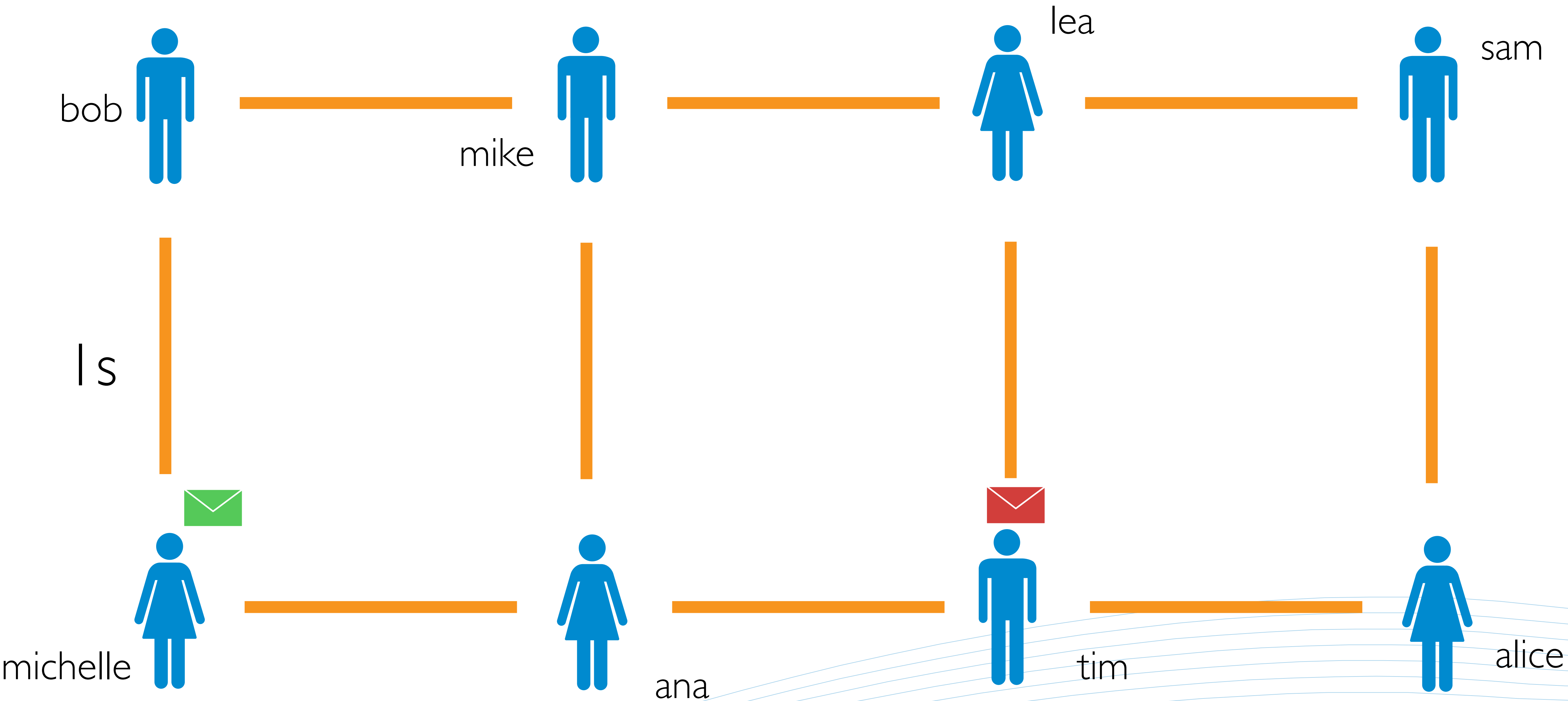
t= 3



maximum latency = 4s

Experiment

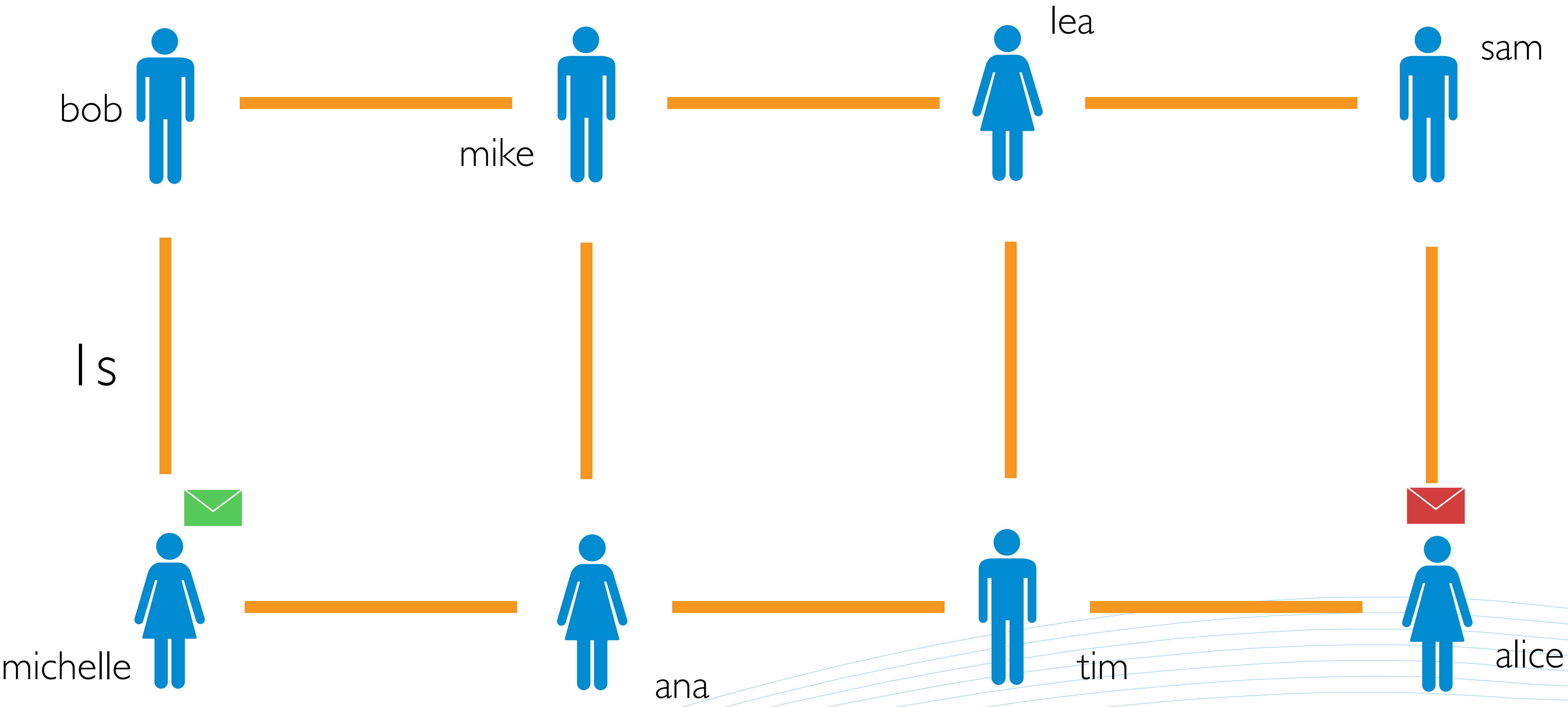
t= 4



maximum latency = 4s

Experiment

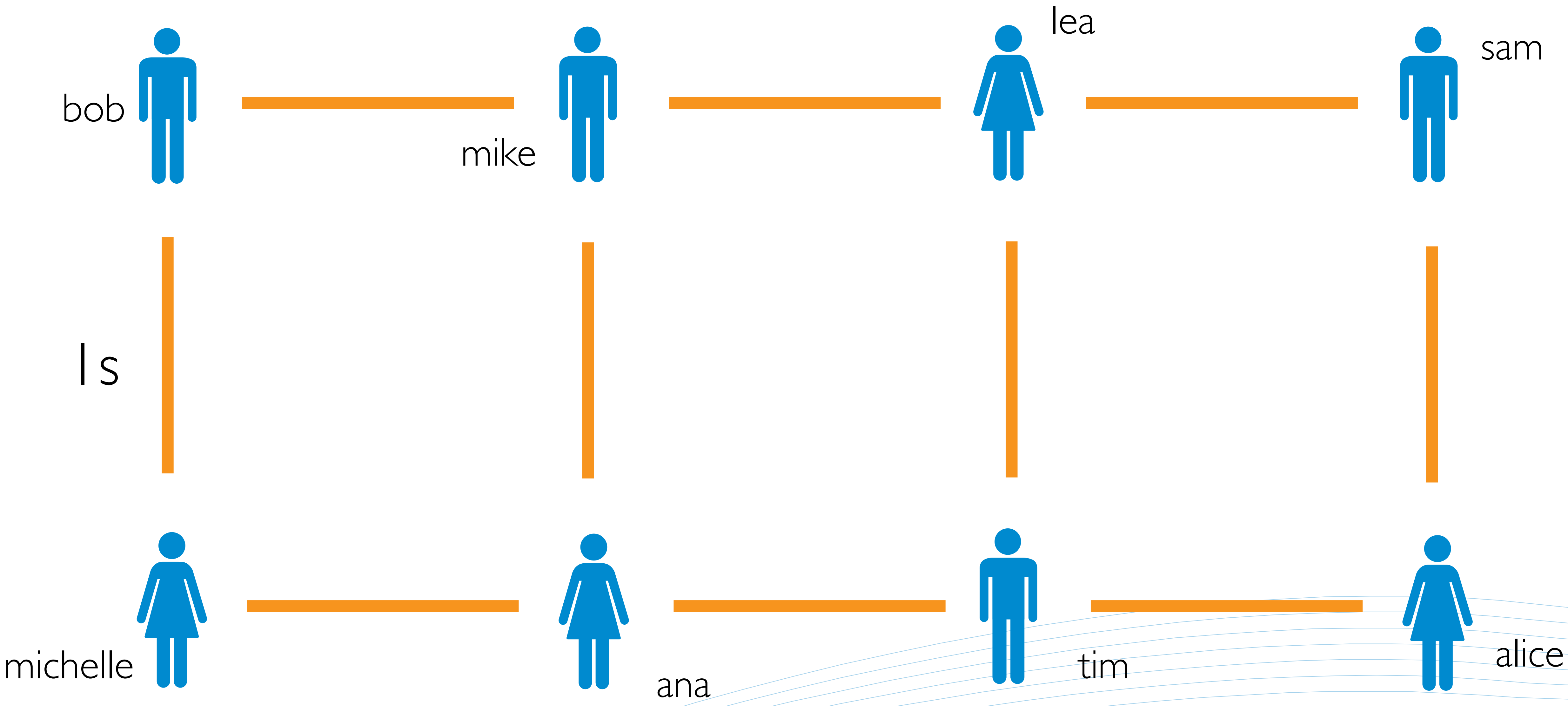
t= 5



maximum latency = 4s

Experiment

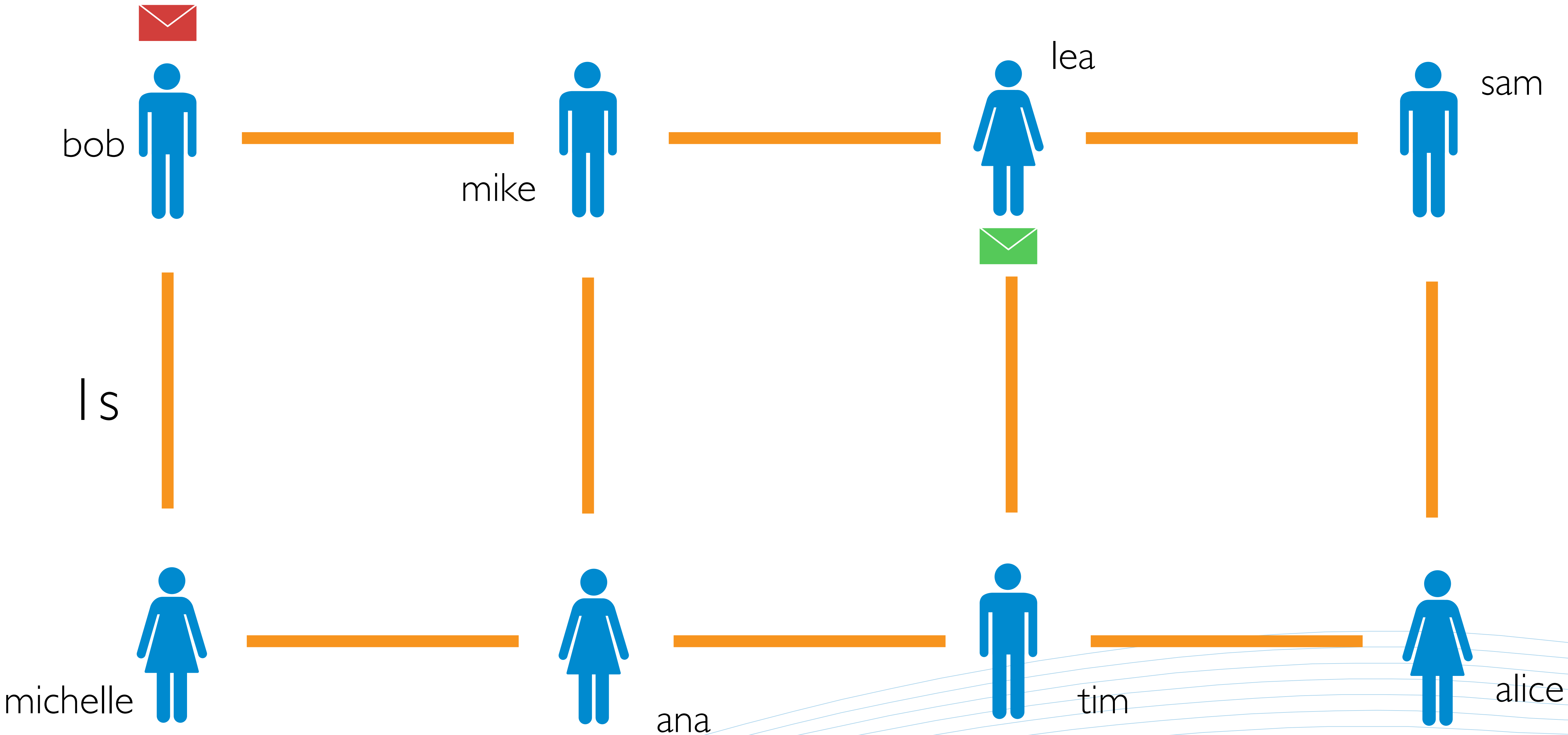
t=



maximum latency = 4s

Experiment

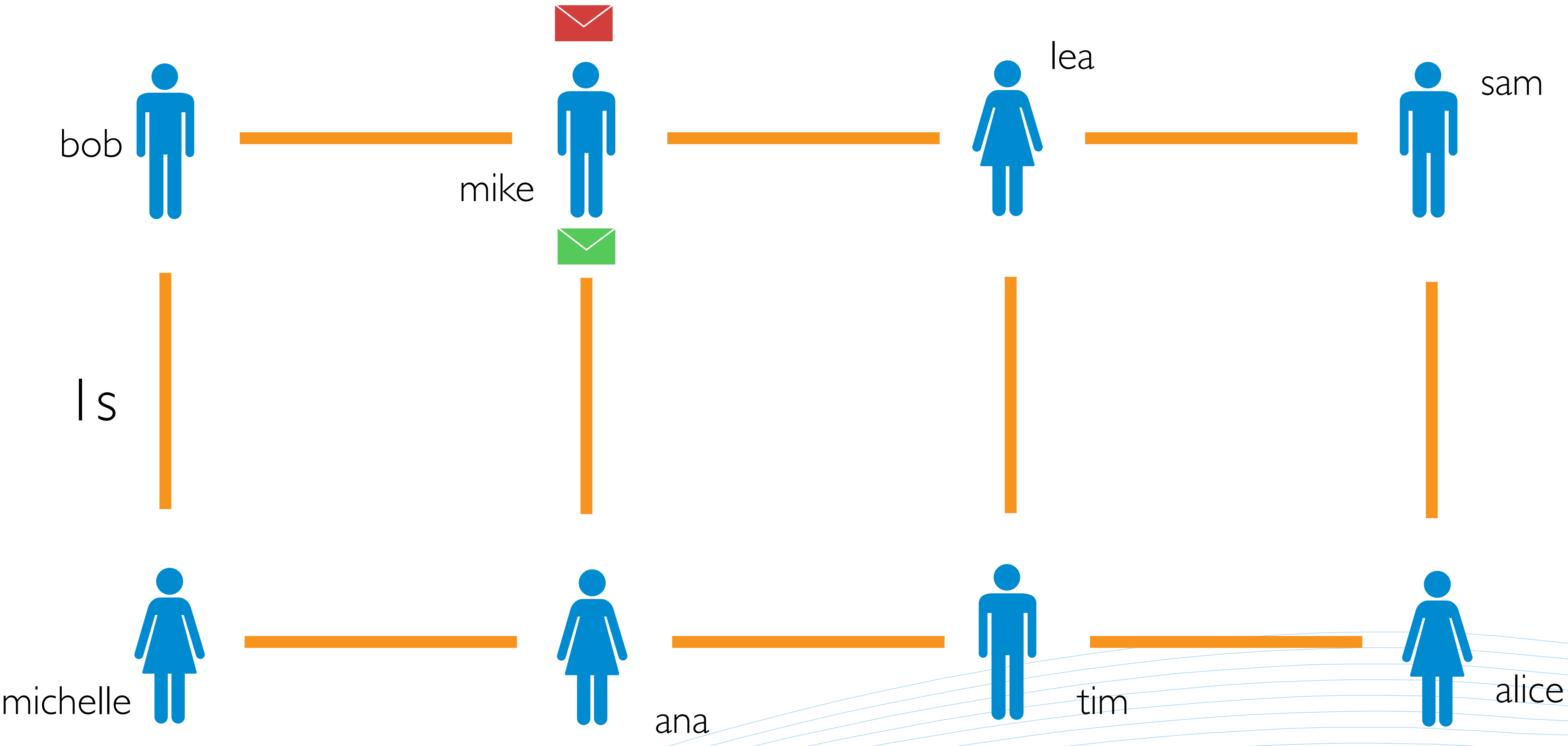
t= 0



maximum latency = 4s

Experiment

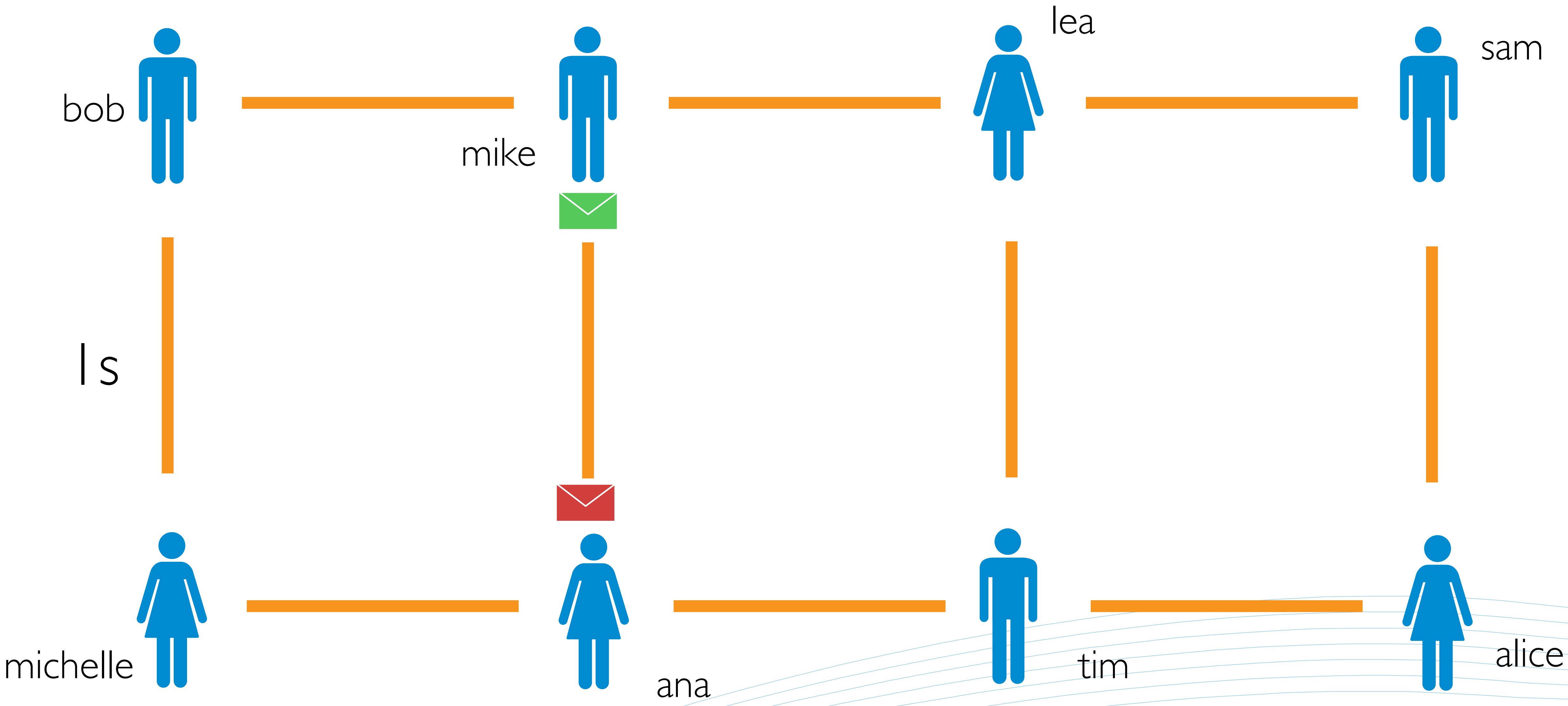
t= 1



maximum latency = 4s

Experiment

t= 2

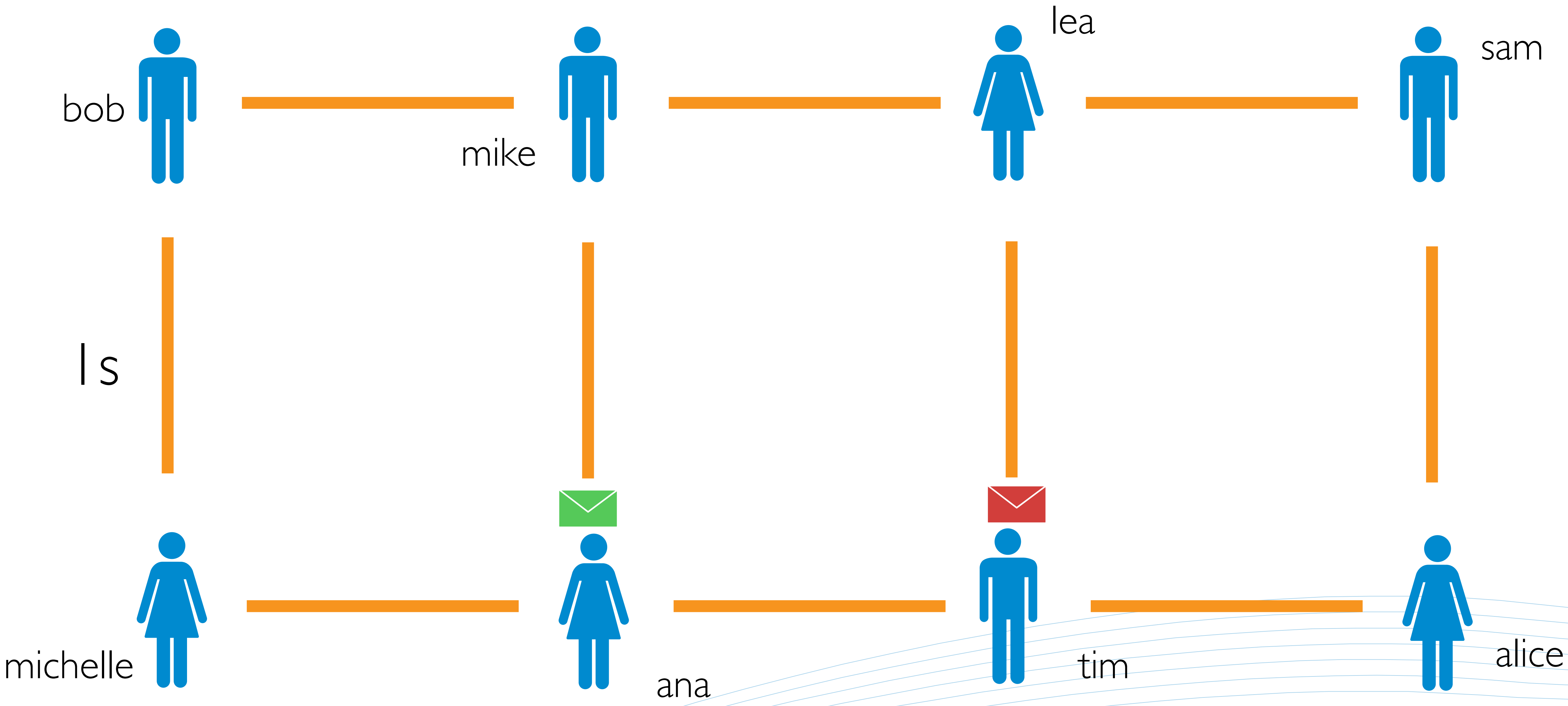


maximum latency = 4s

Experiment

Ensuring Reliable Networks TTTech

t= 3

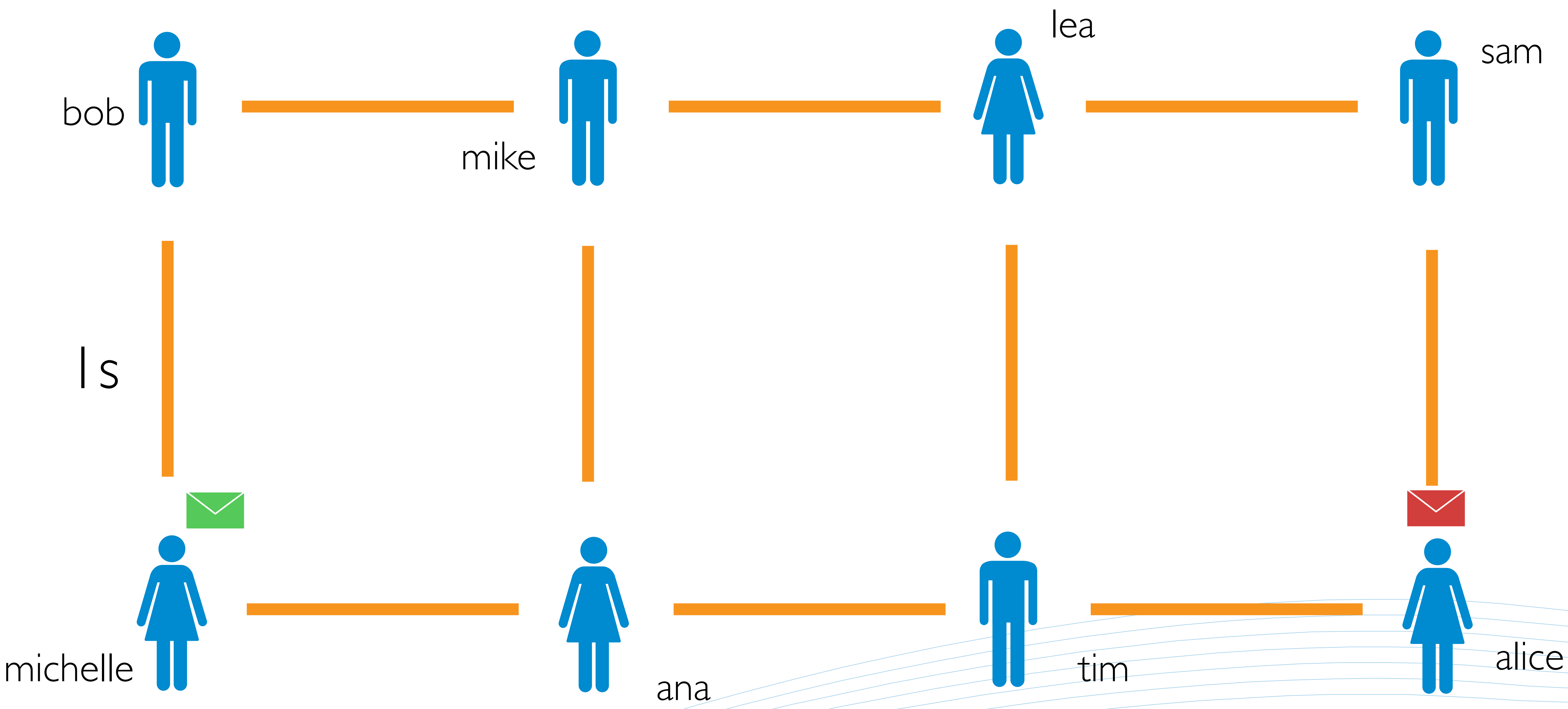


maximum latency = 4s

Experiment

Ensuring Reliable Networks TTTech

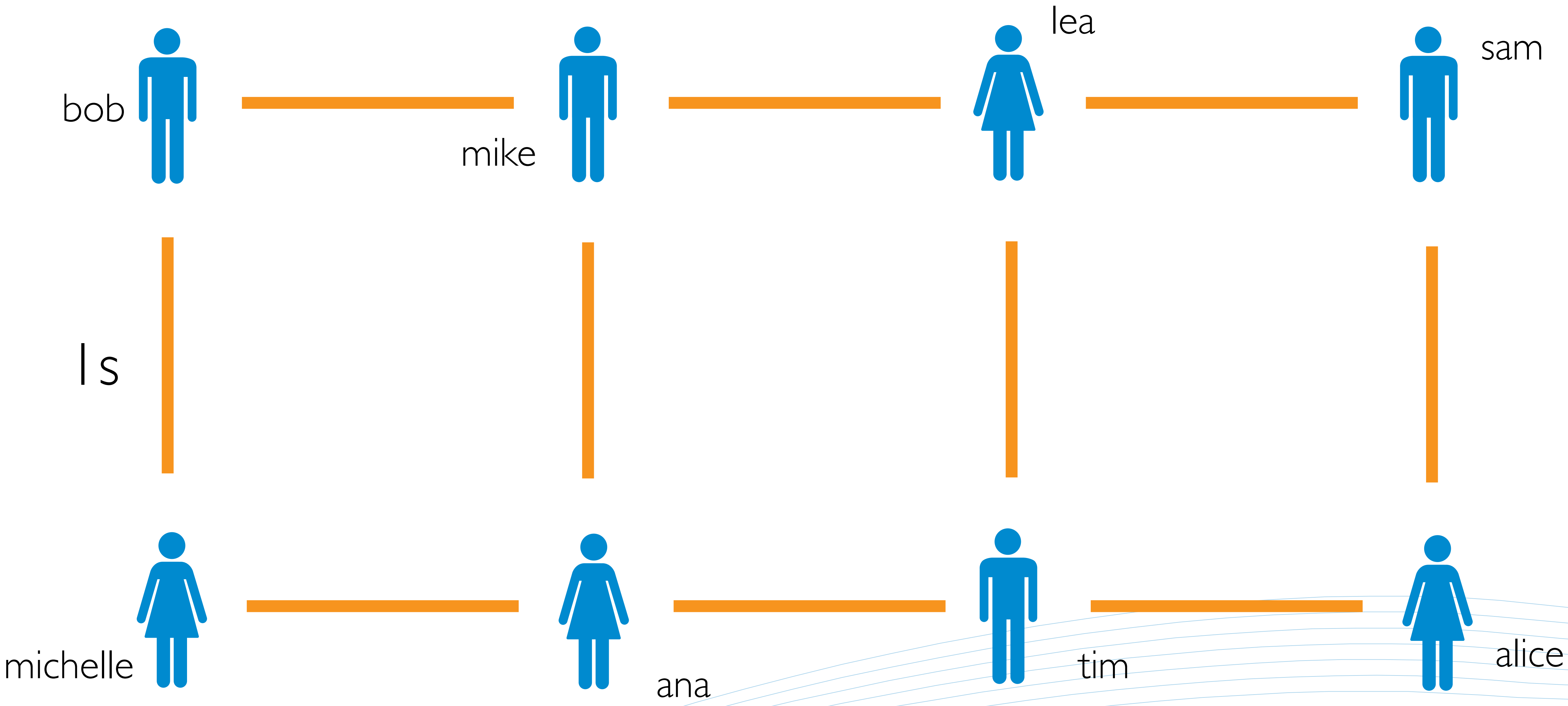
t= 4



maximum latency = 4s

Experiment

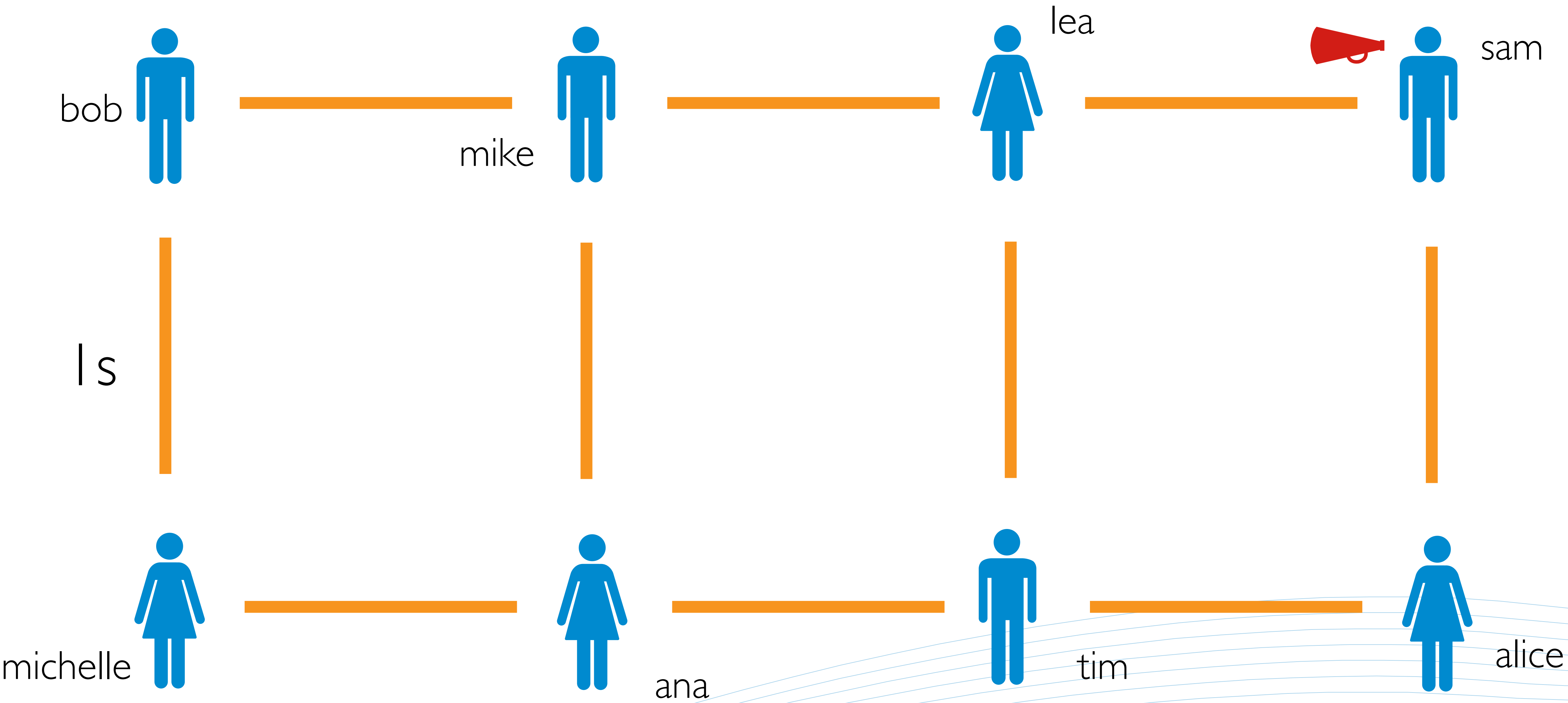
t=



maximum latency = 4s

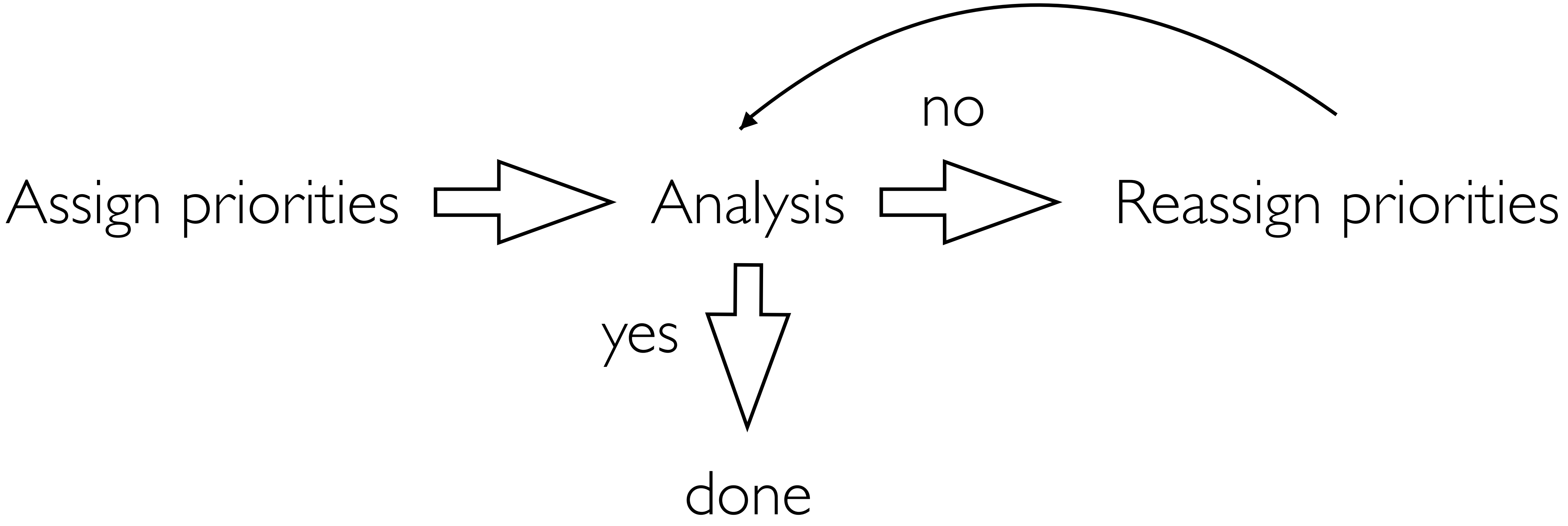
Experiment

t=



maximum latency = 4s

How?



Assign priorities

Analysis

no

Reassign priorities

yes

done

Compositionality?

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

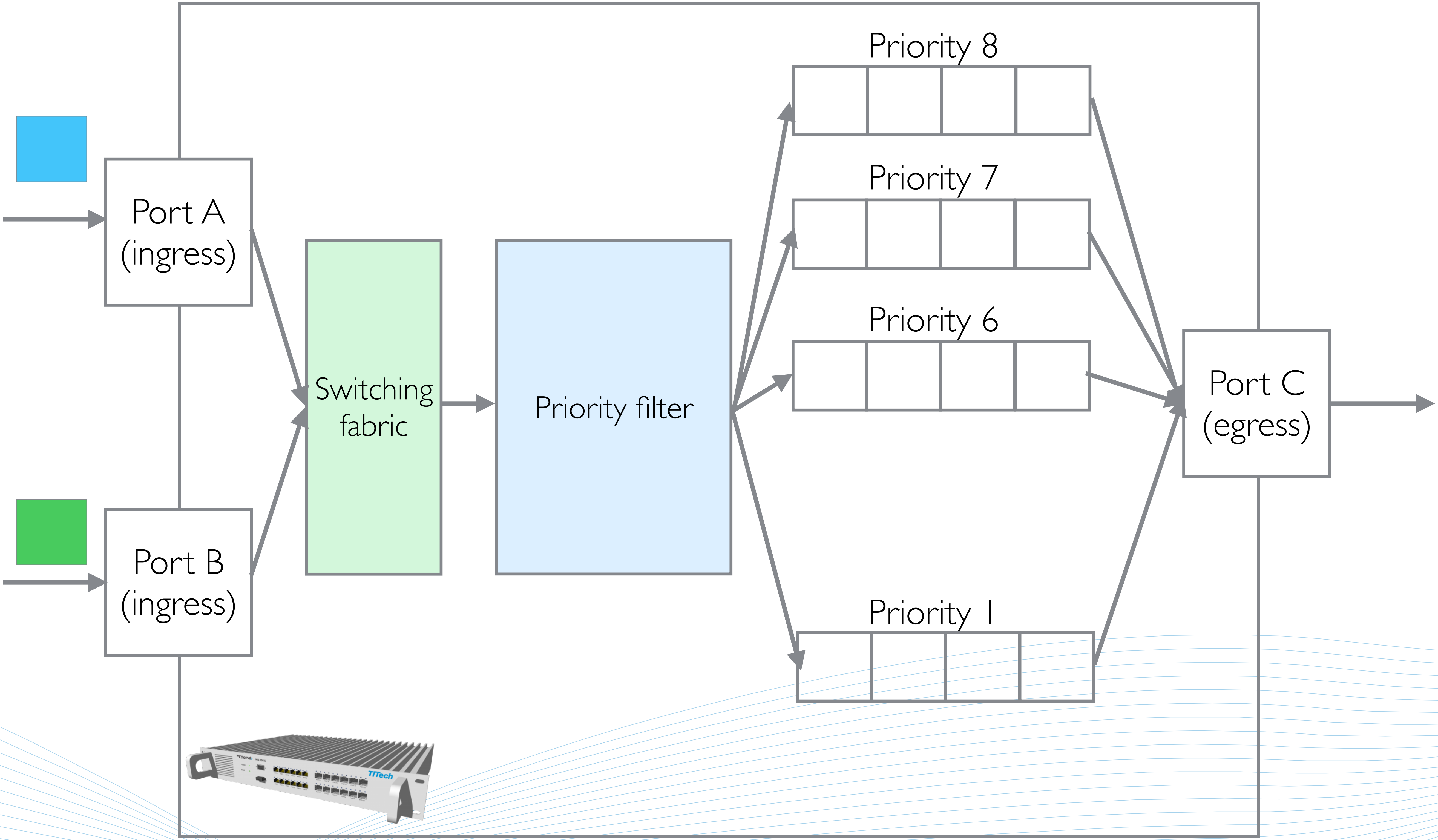
TTP

EtherCAT

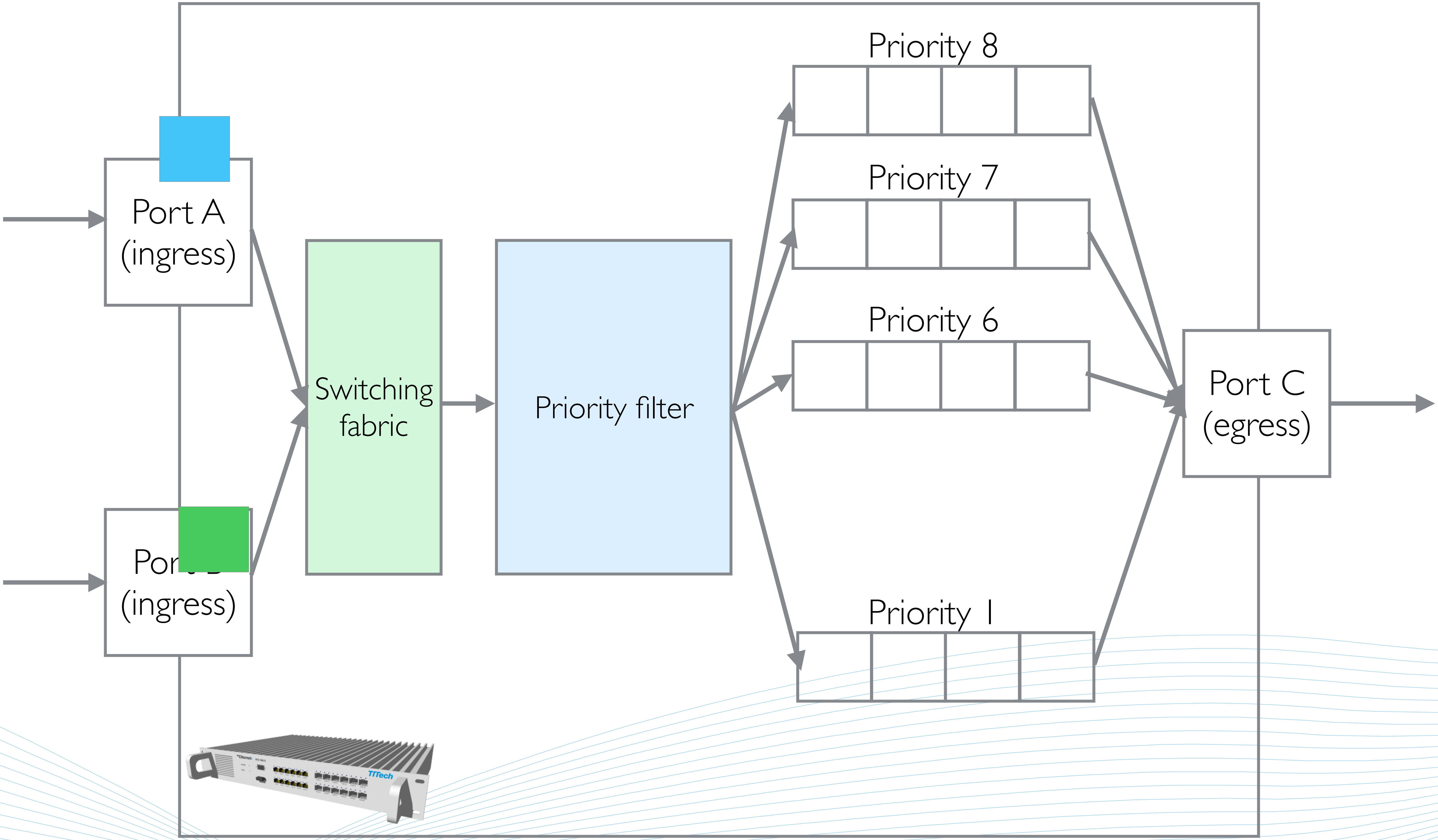
TTEthernet	provides real-time and safety capabilities over Ethernet, in a way that is fully compatible with IEEE 802 Ethernet standards

TSN

Priority switch

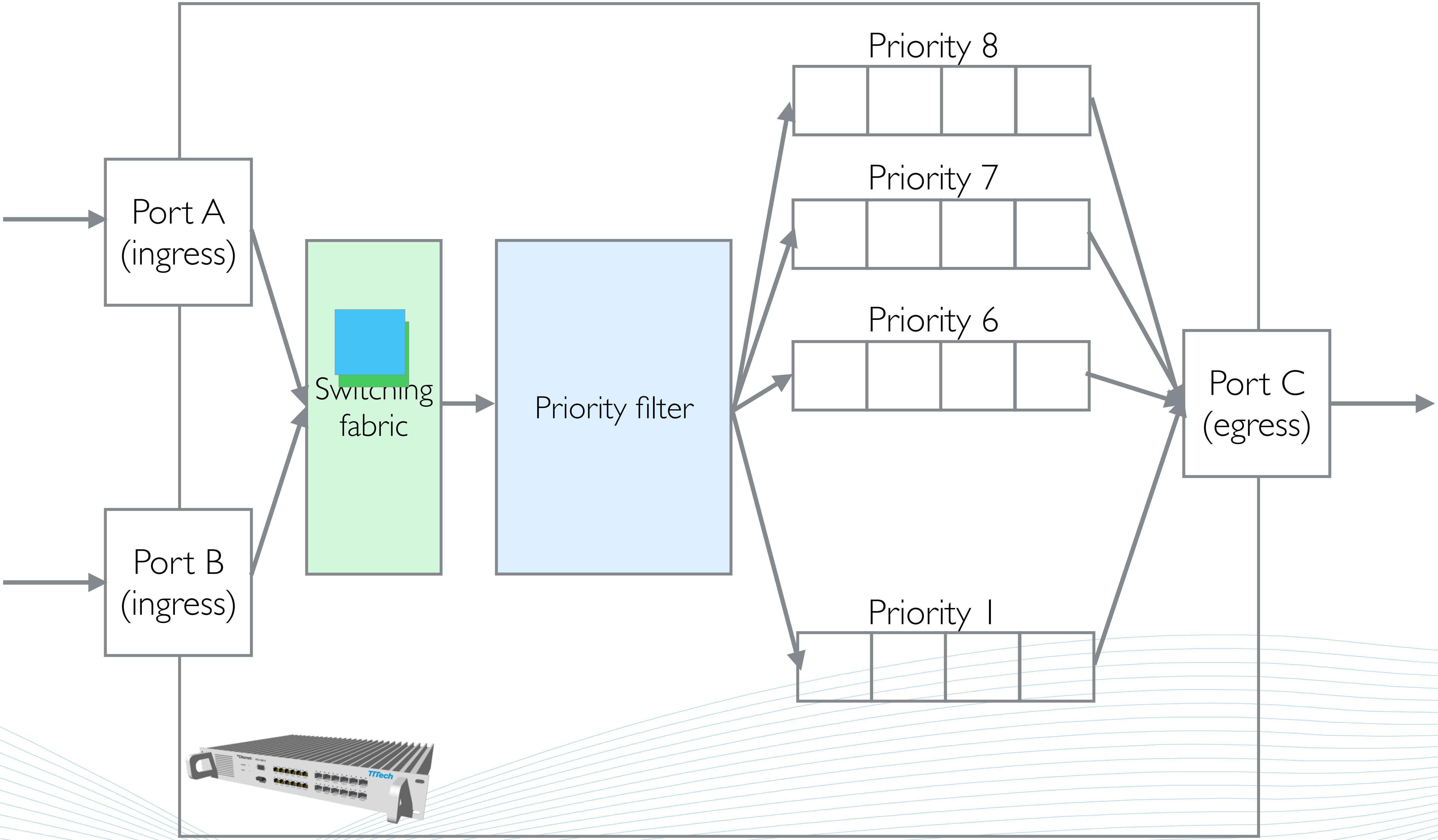


Priority switch

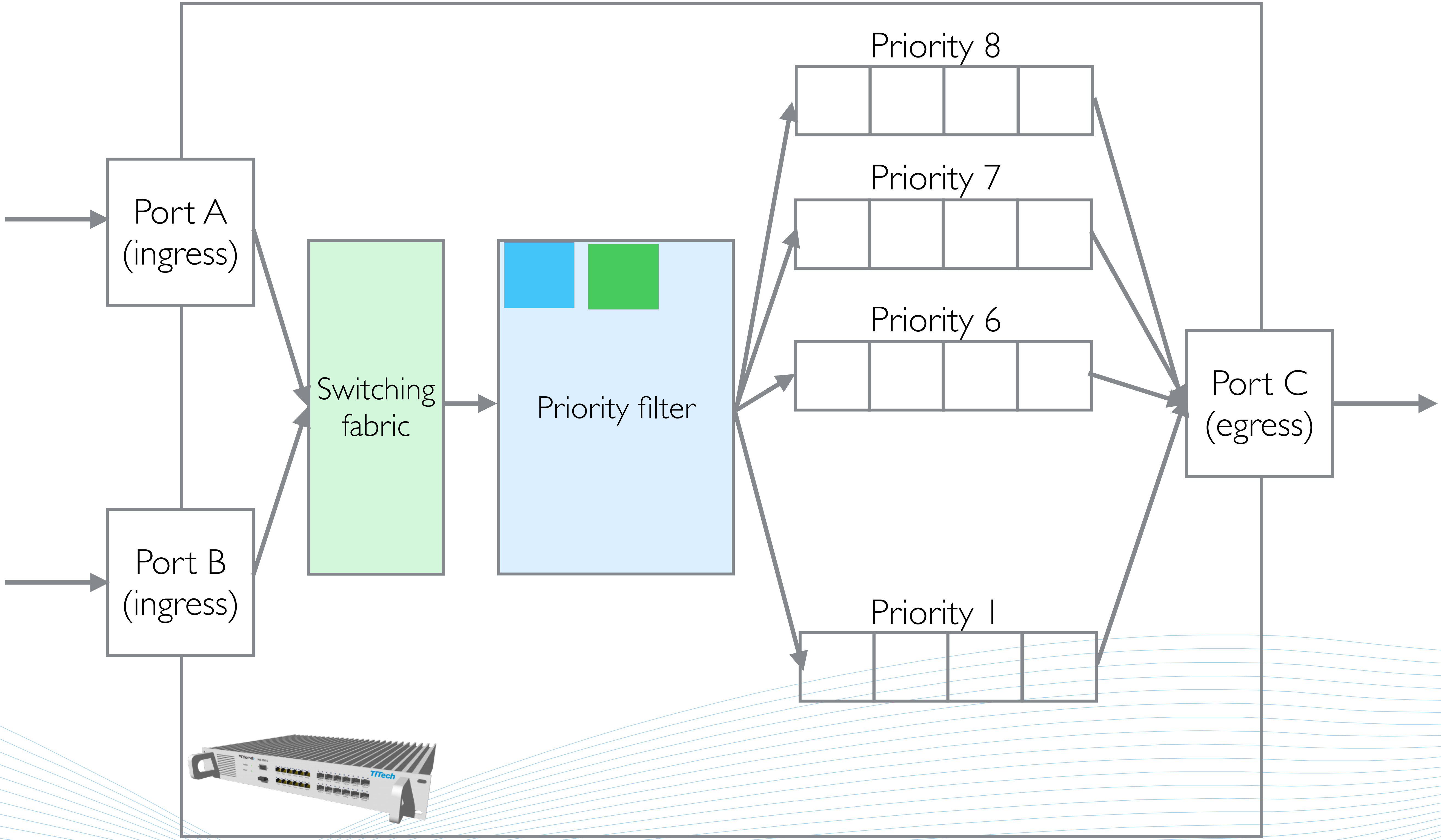


Priority switch

Ensuring Reliable Networks TTTech

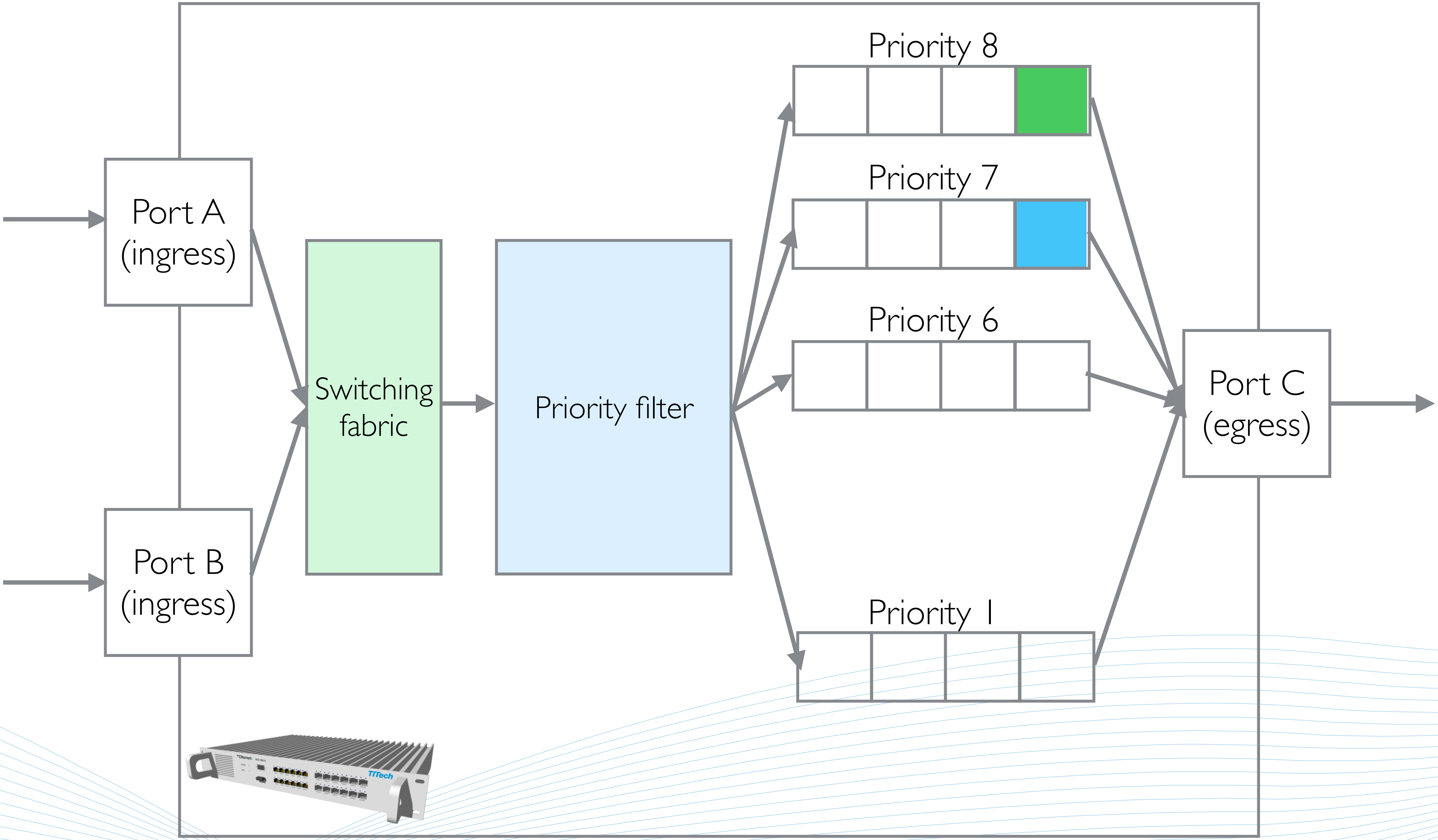


Priority switch

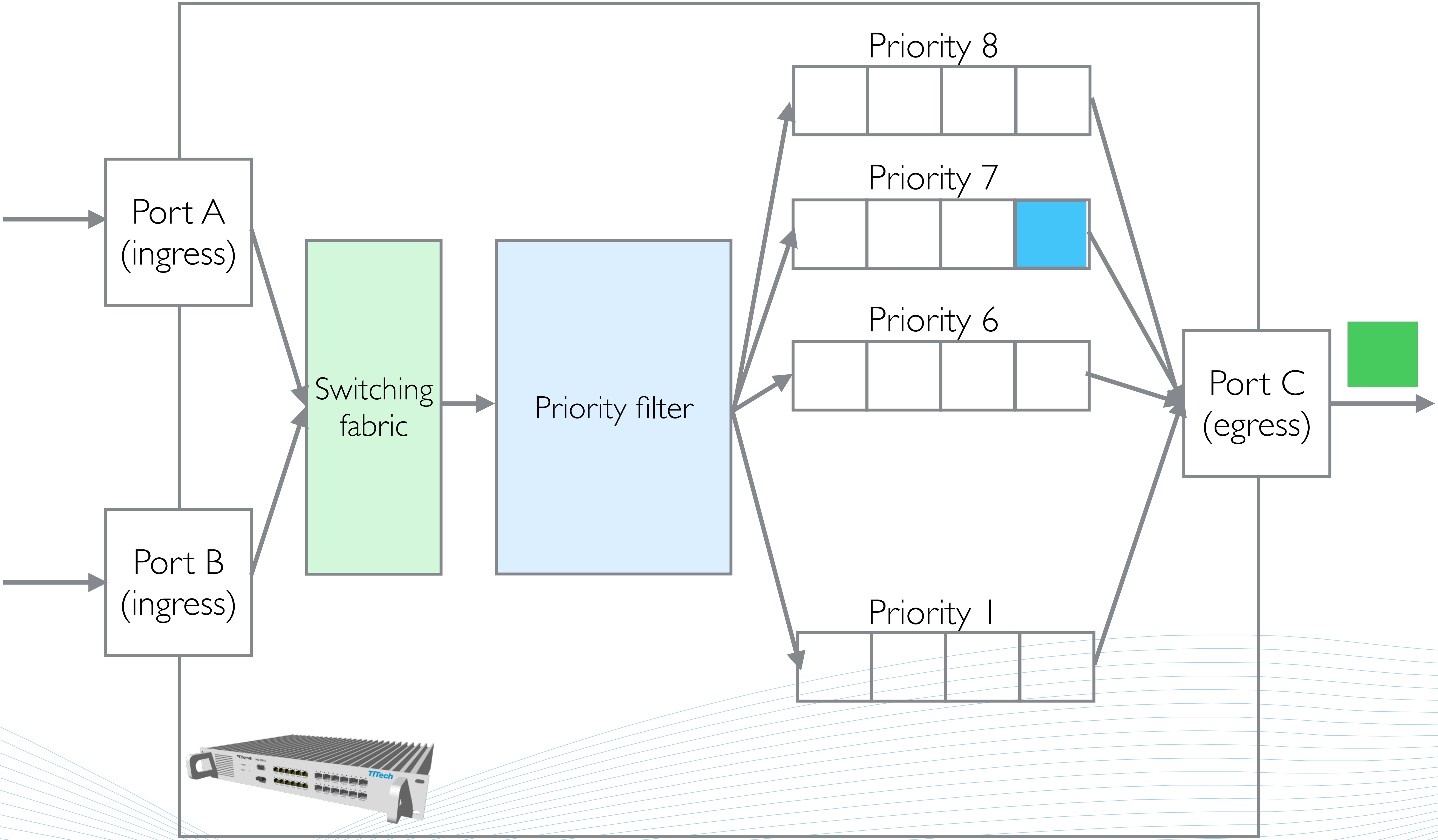


Priority switch

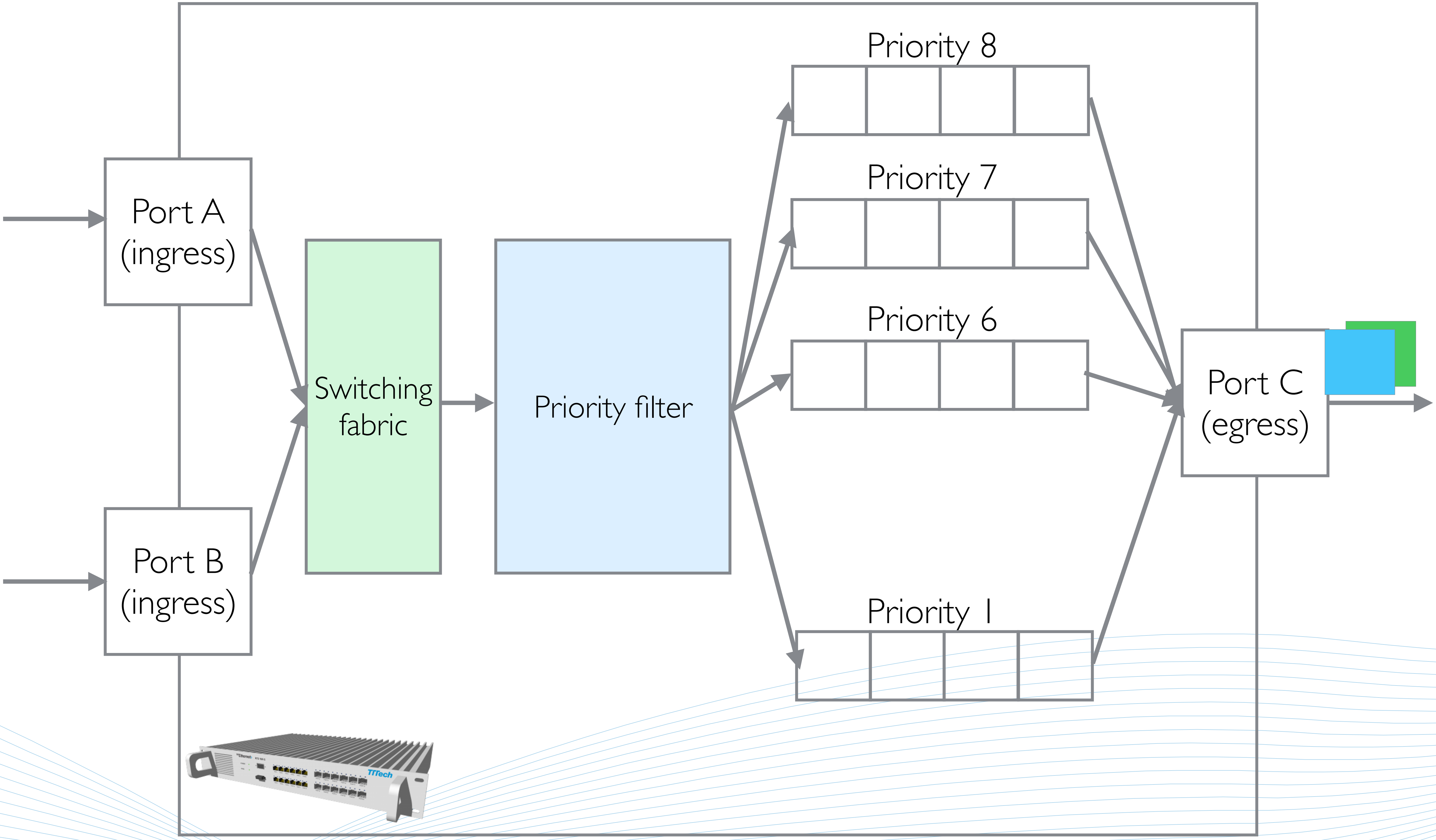
Ensuring Reliable Networks TTTech



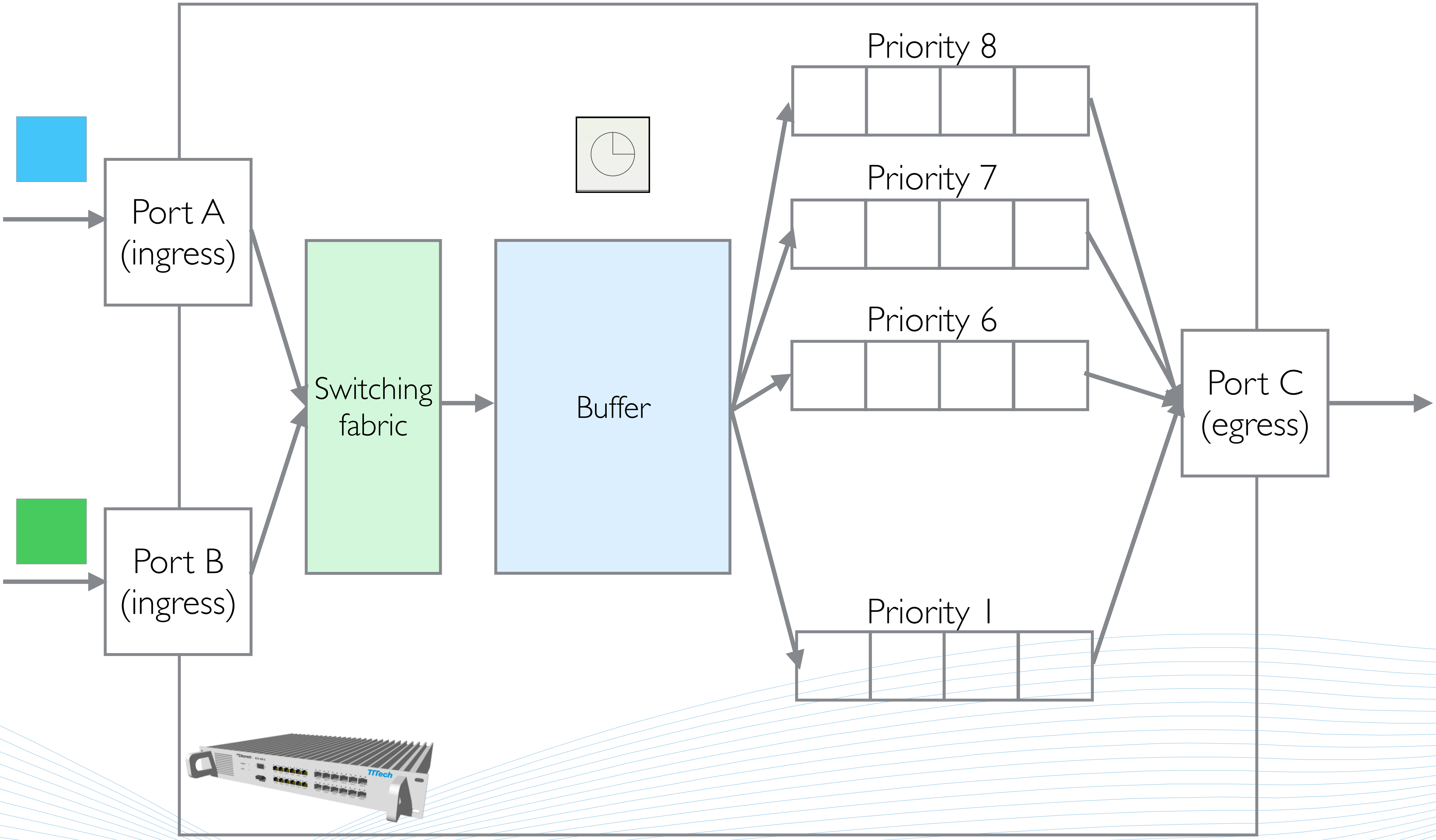
Priority switch



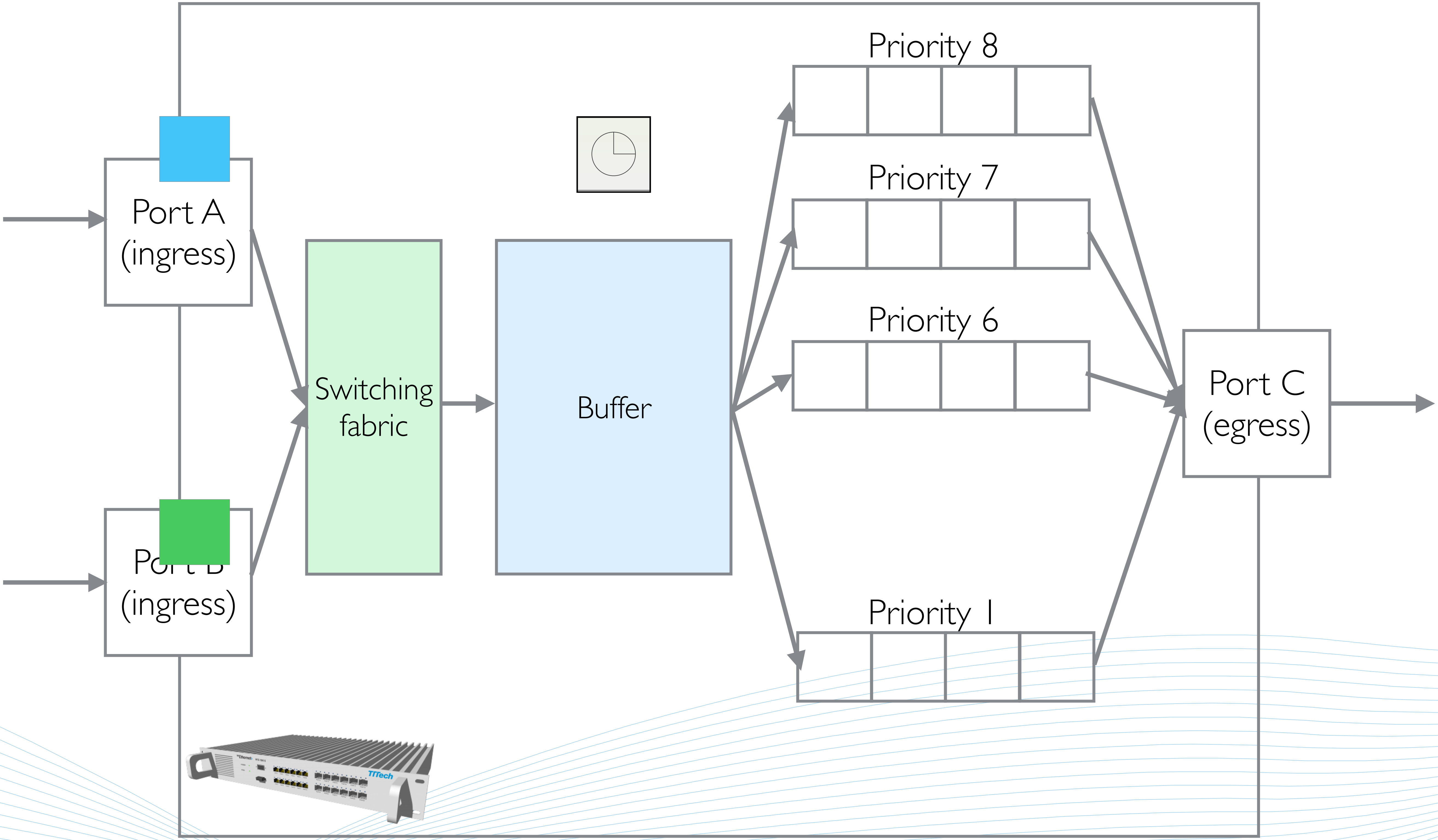
Priority switch



TTEthernet switch

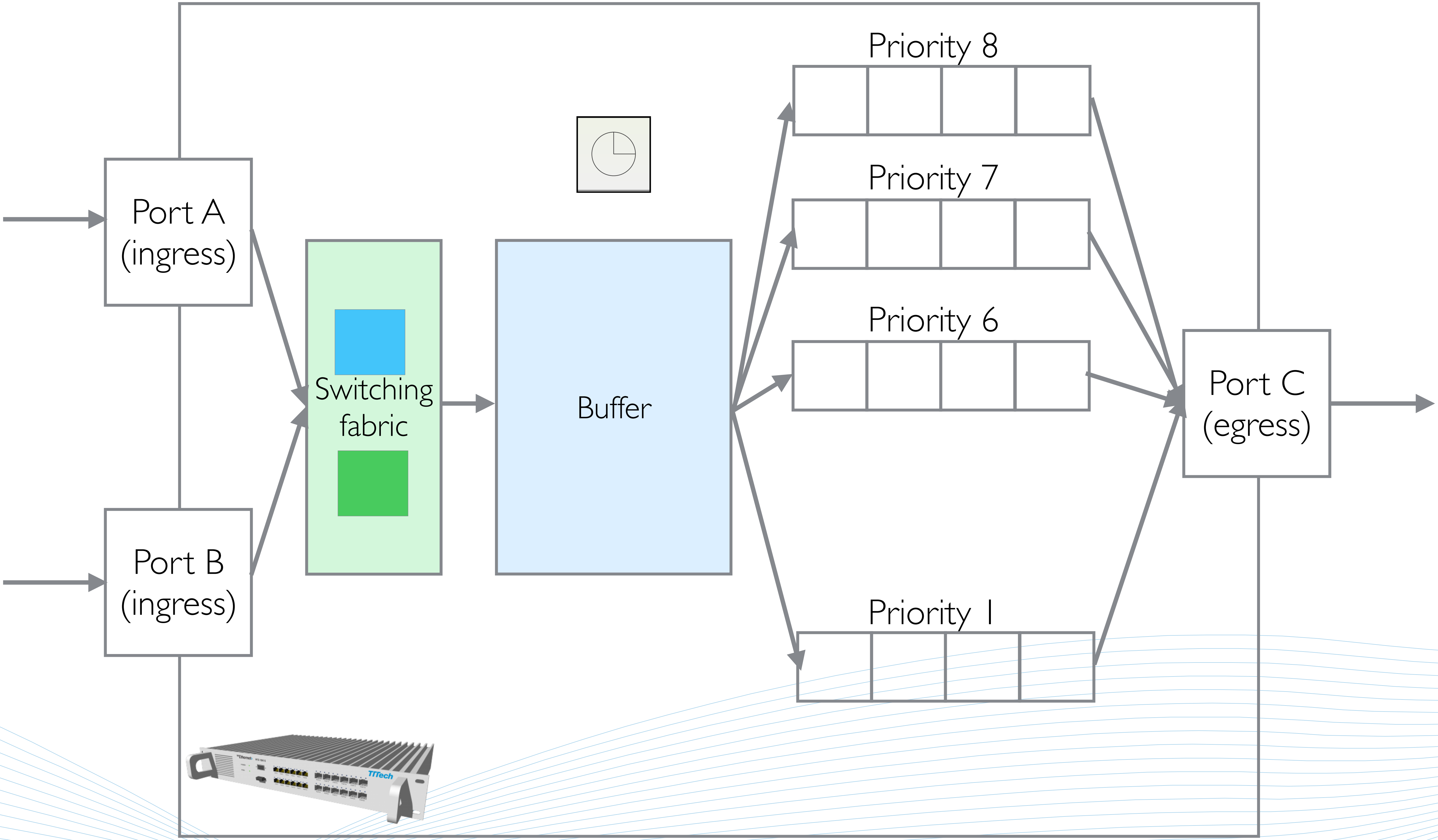


TTEthernet switch

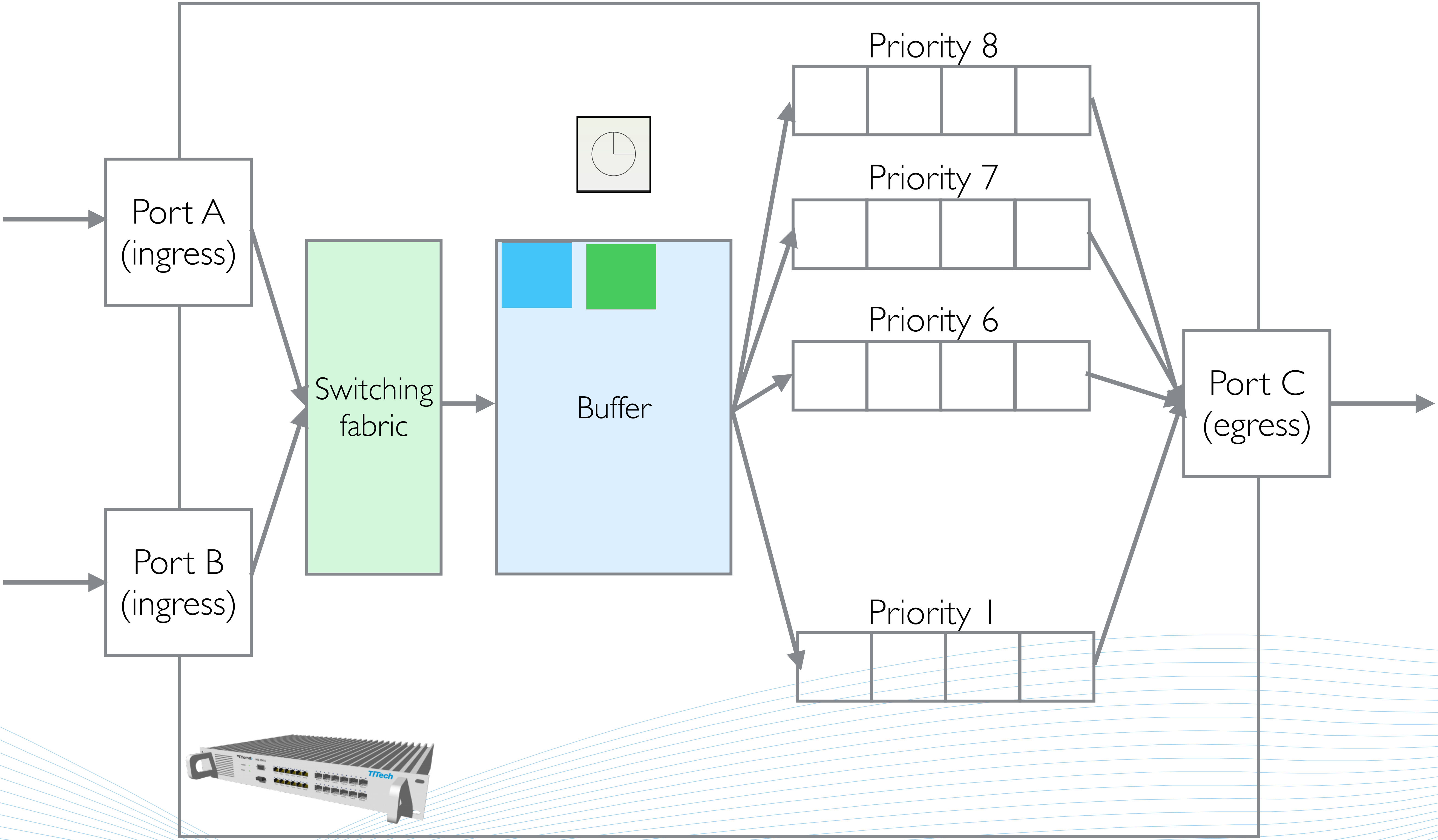


TTEthernet switch

Ensuring Reliable Networks TTTech

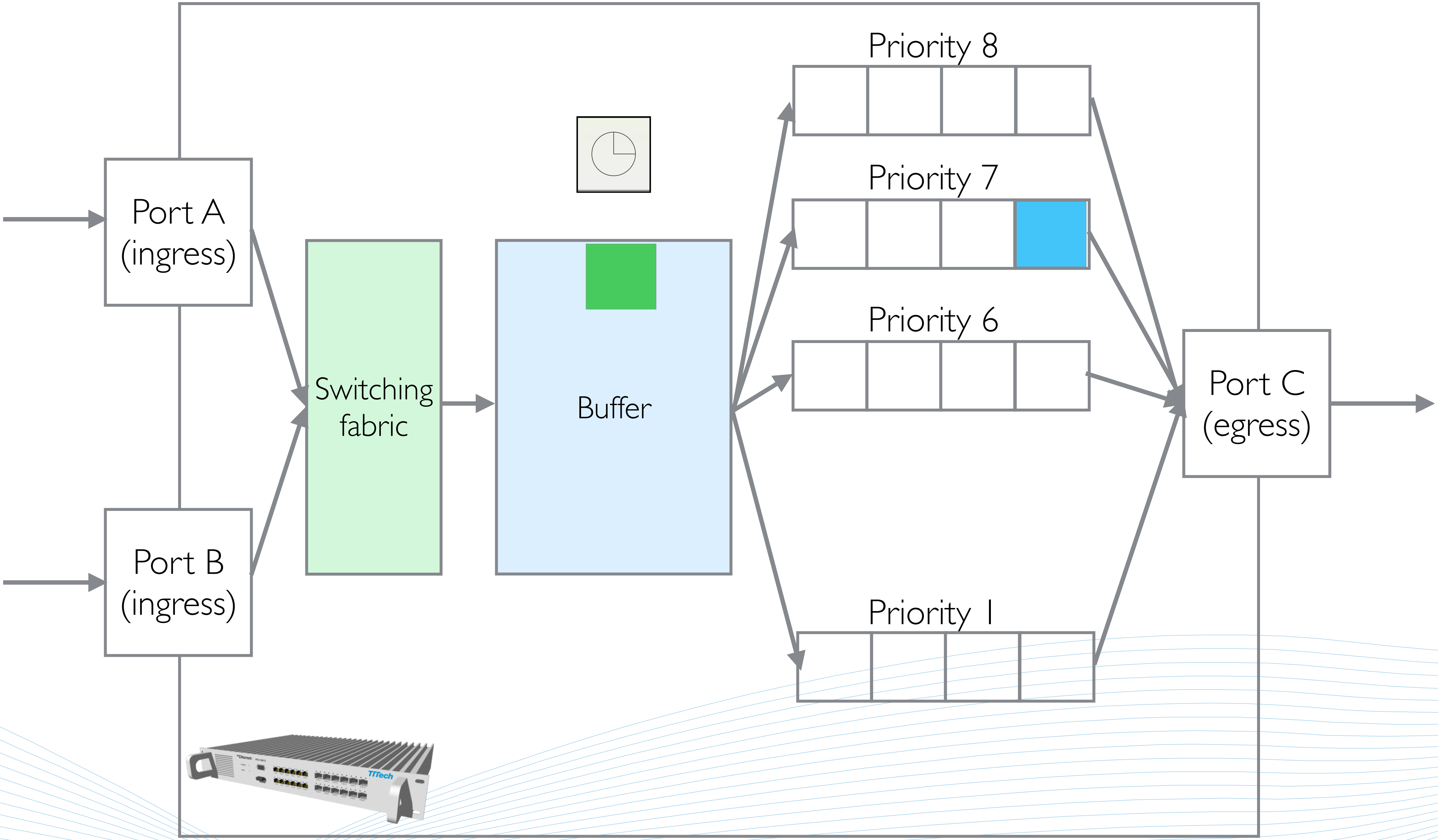


TTEthernet switch

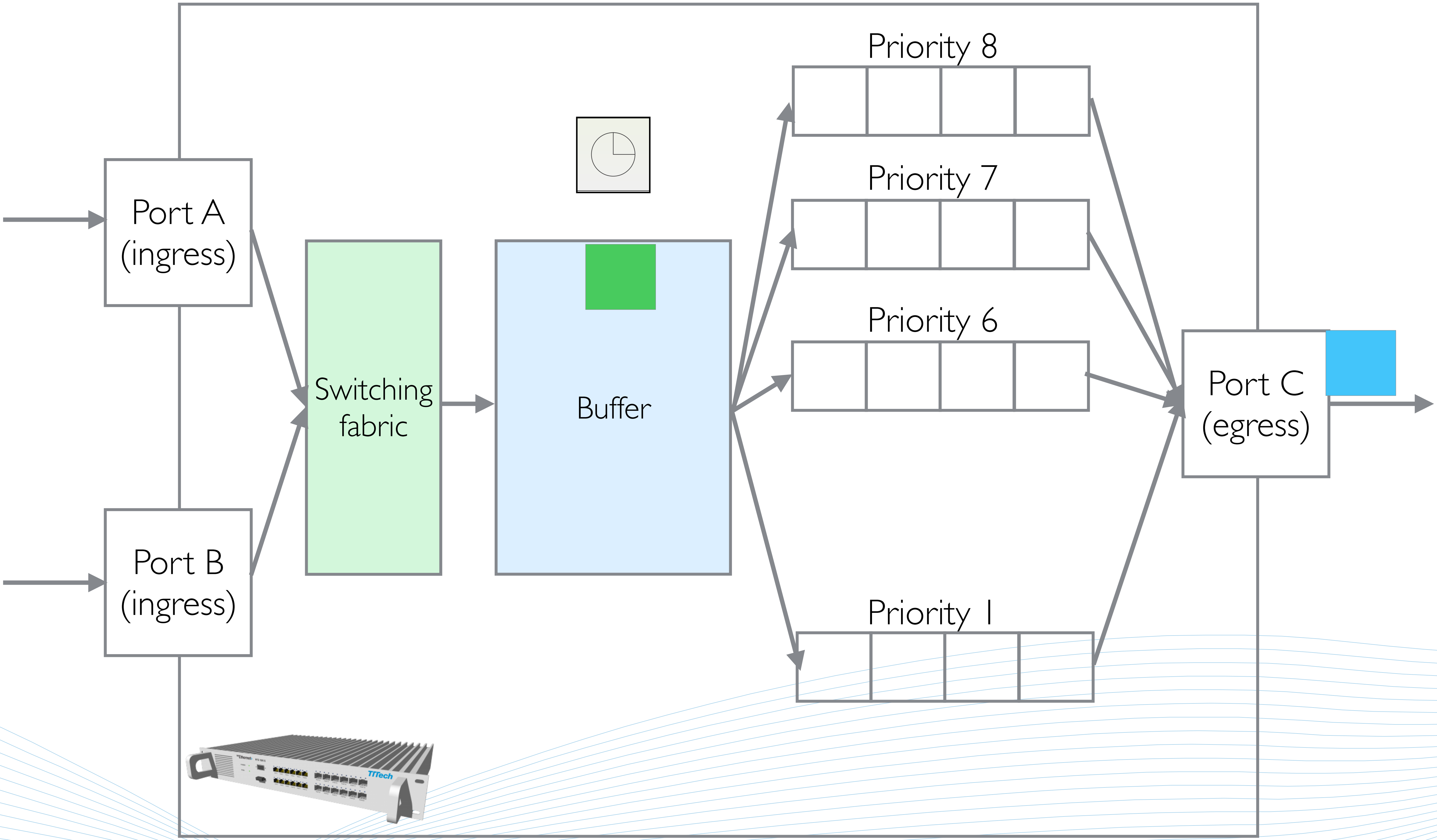


TTEthernet switch

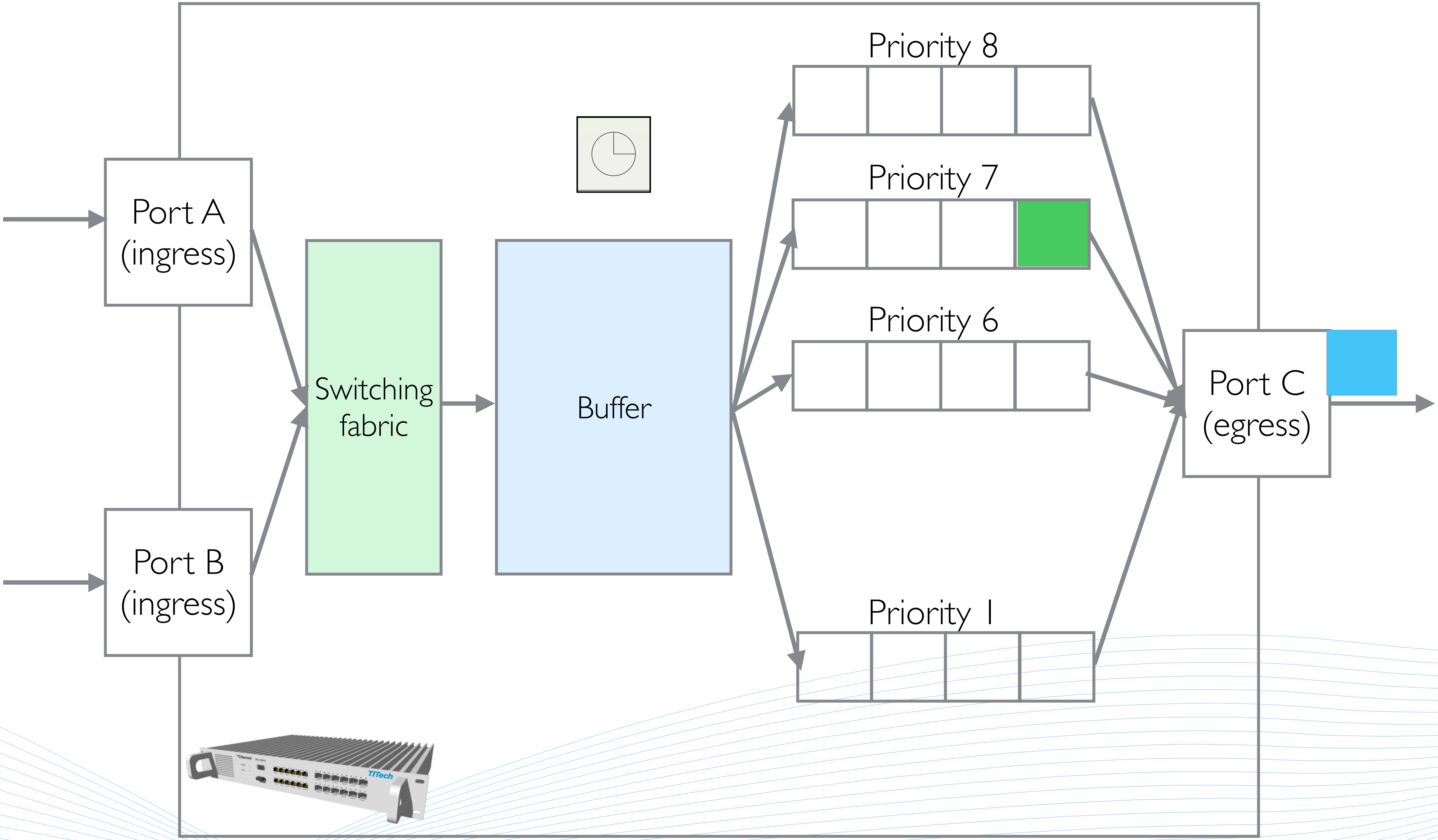
Ensuring Reliable Networks TTTech



TTEthernet switch

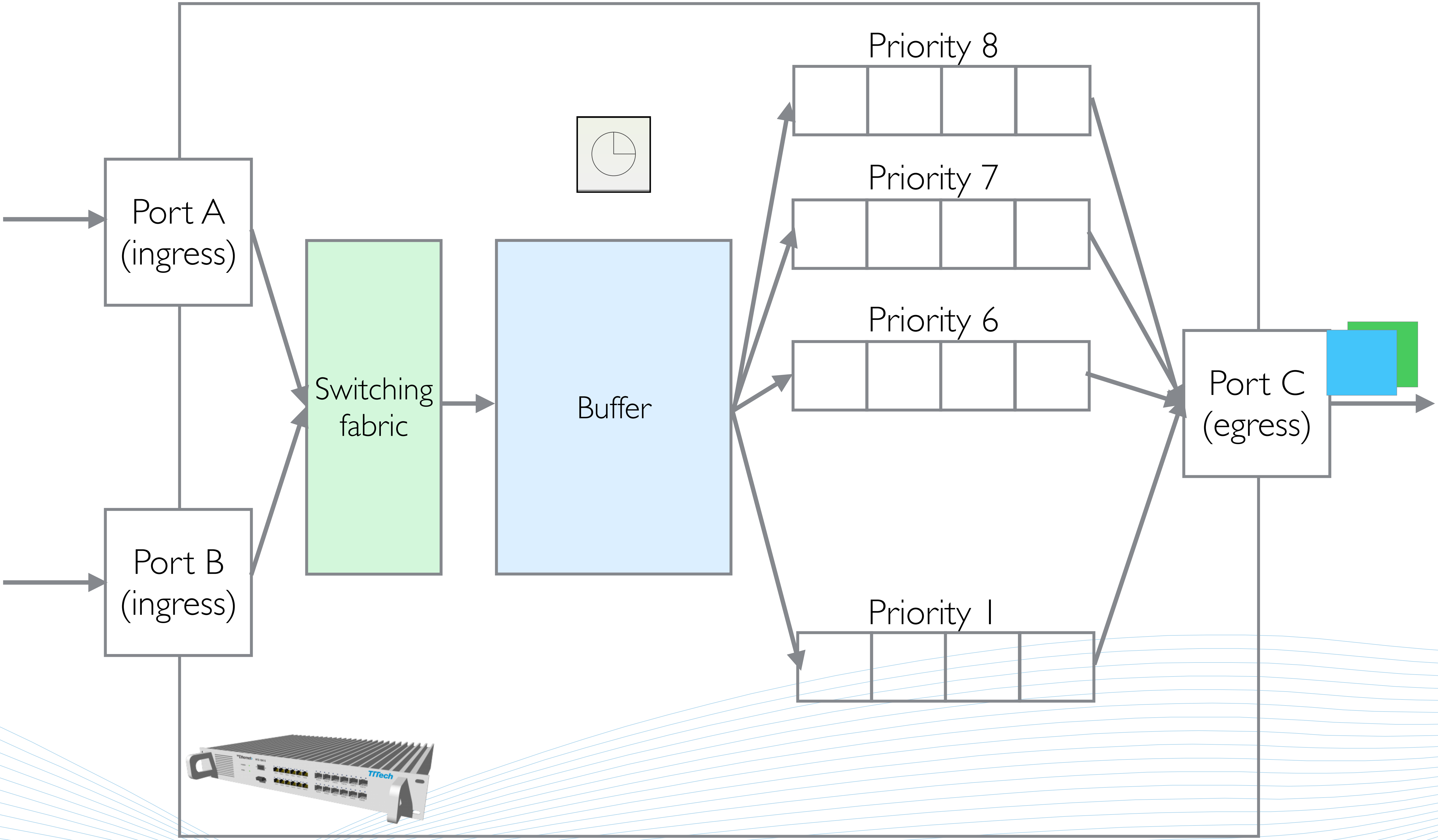


TTEthernet switch

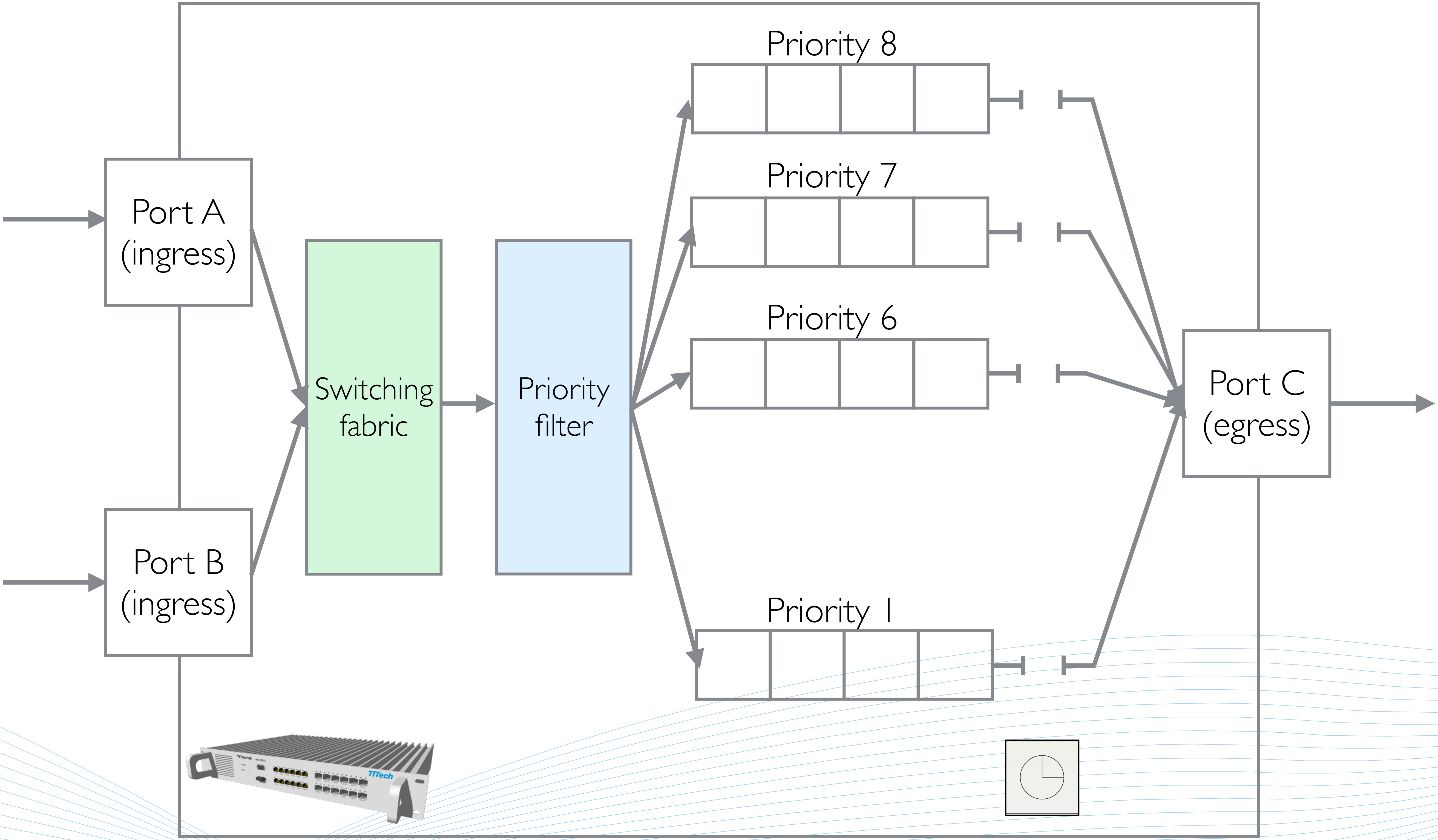


TTEthernet switch

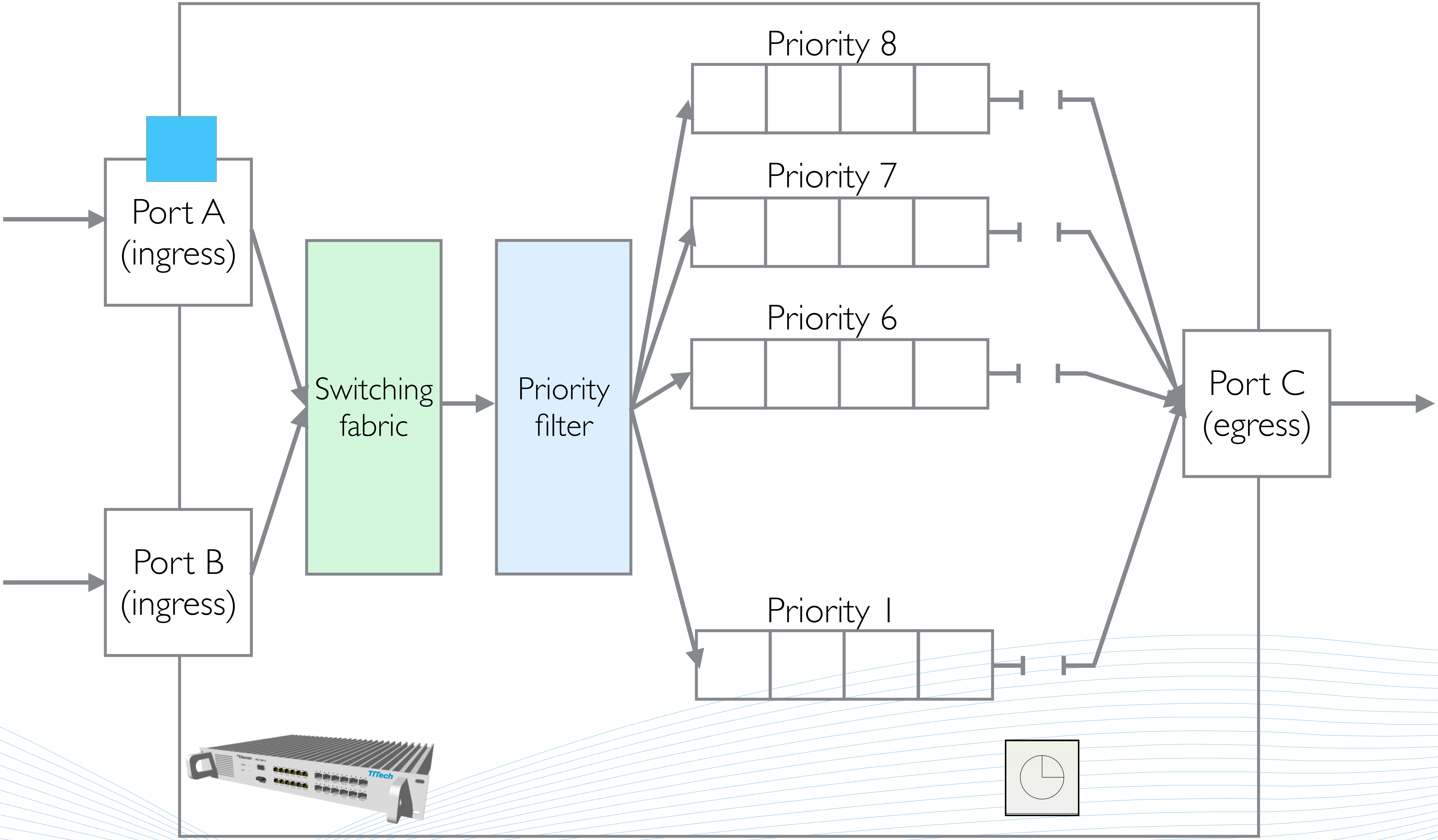
Ensuring Reliable Networks



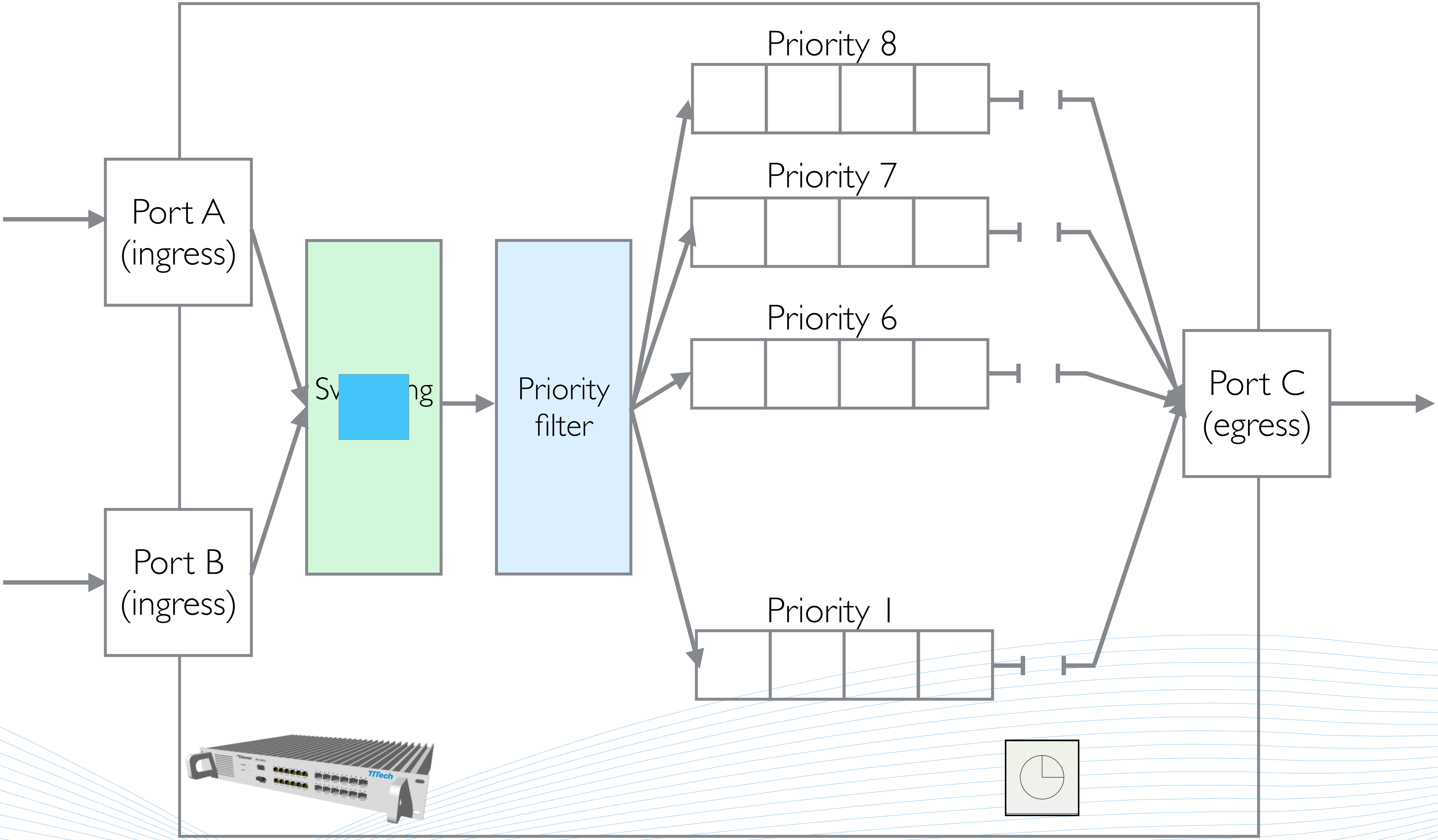
TSN switch


Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Priority 8
Priority 7
Priority 6
Priority 1
Port C
(egress)

TSN switch


Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Priority 8
Priority 7
Priority 6
Priority 1
Port C
(egress)

TSN switch



Port A (ingress)

Port B (ingress)

Sv ng

Priority filter

Priority 8

Priority 7

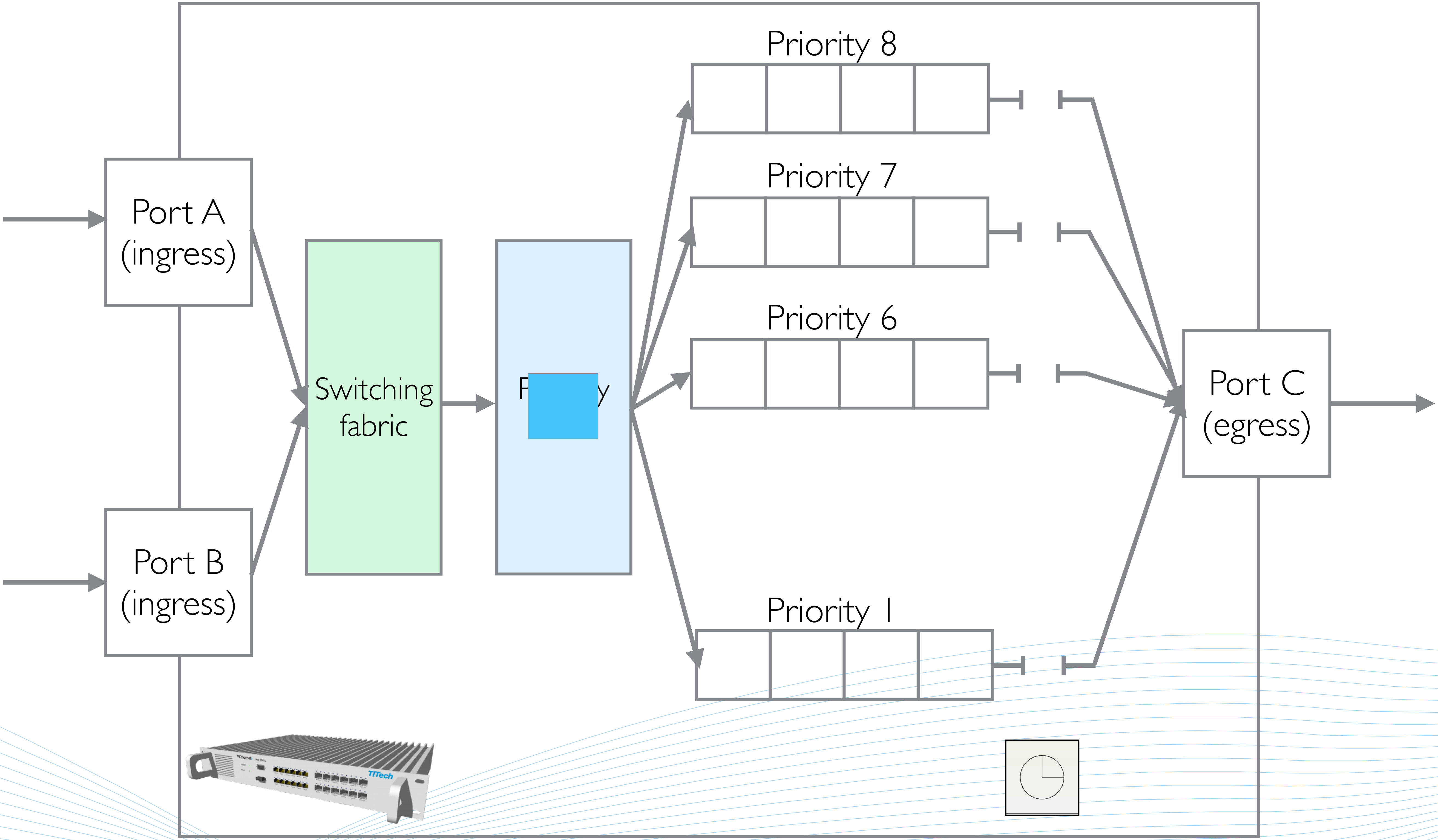
Priority 6

Priority 1

Port C (egress)

TSN switch

Ensuring Reliable Networks TTTech



Port A (ingress)

Port B (ingress)

Switching fabric

F y

Priority 8

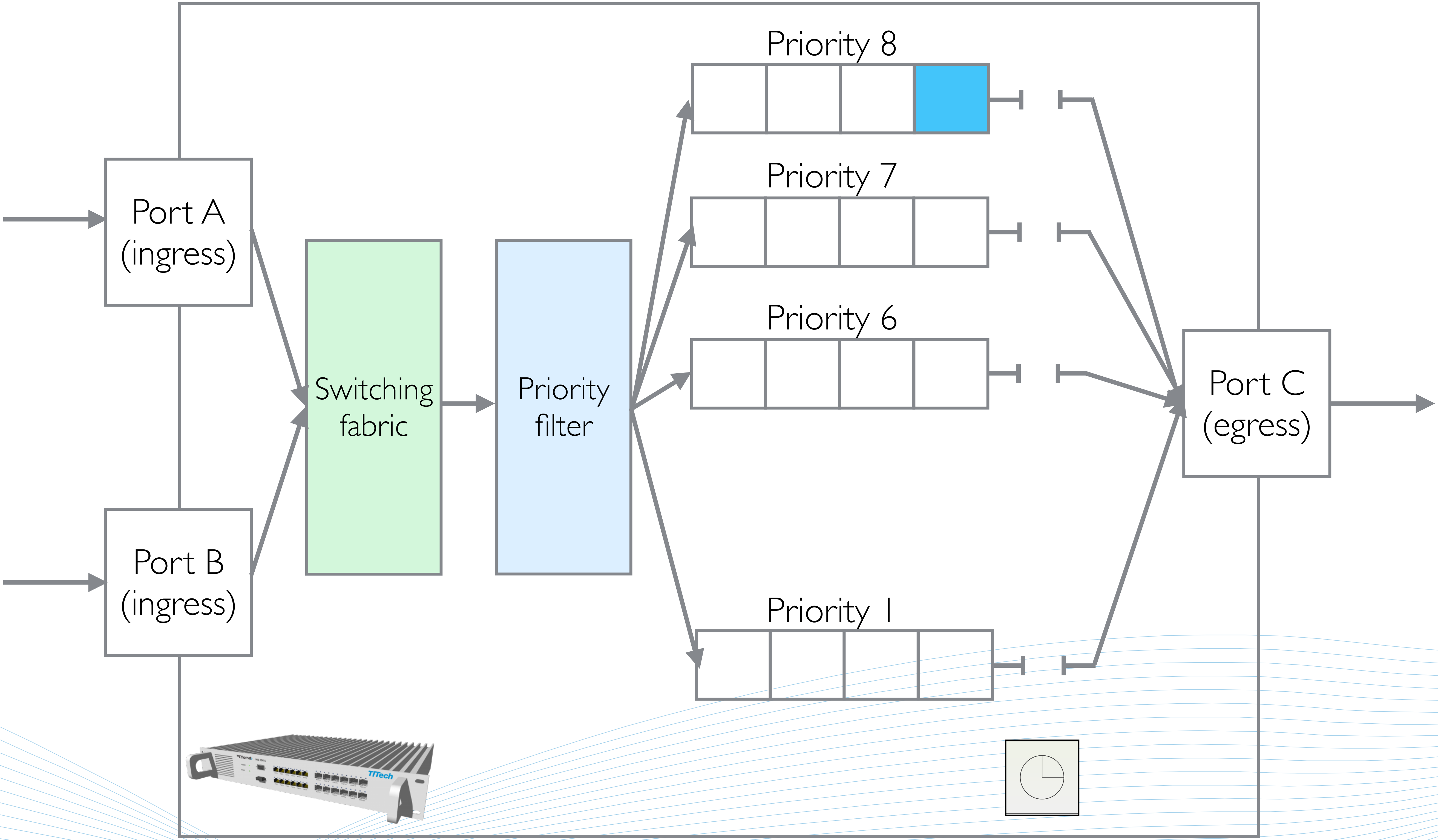
Priority 7

Priority 6

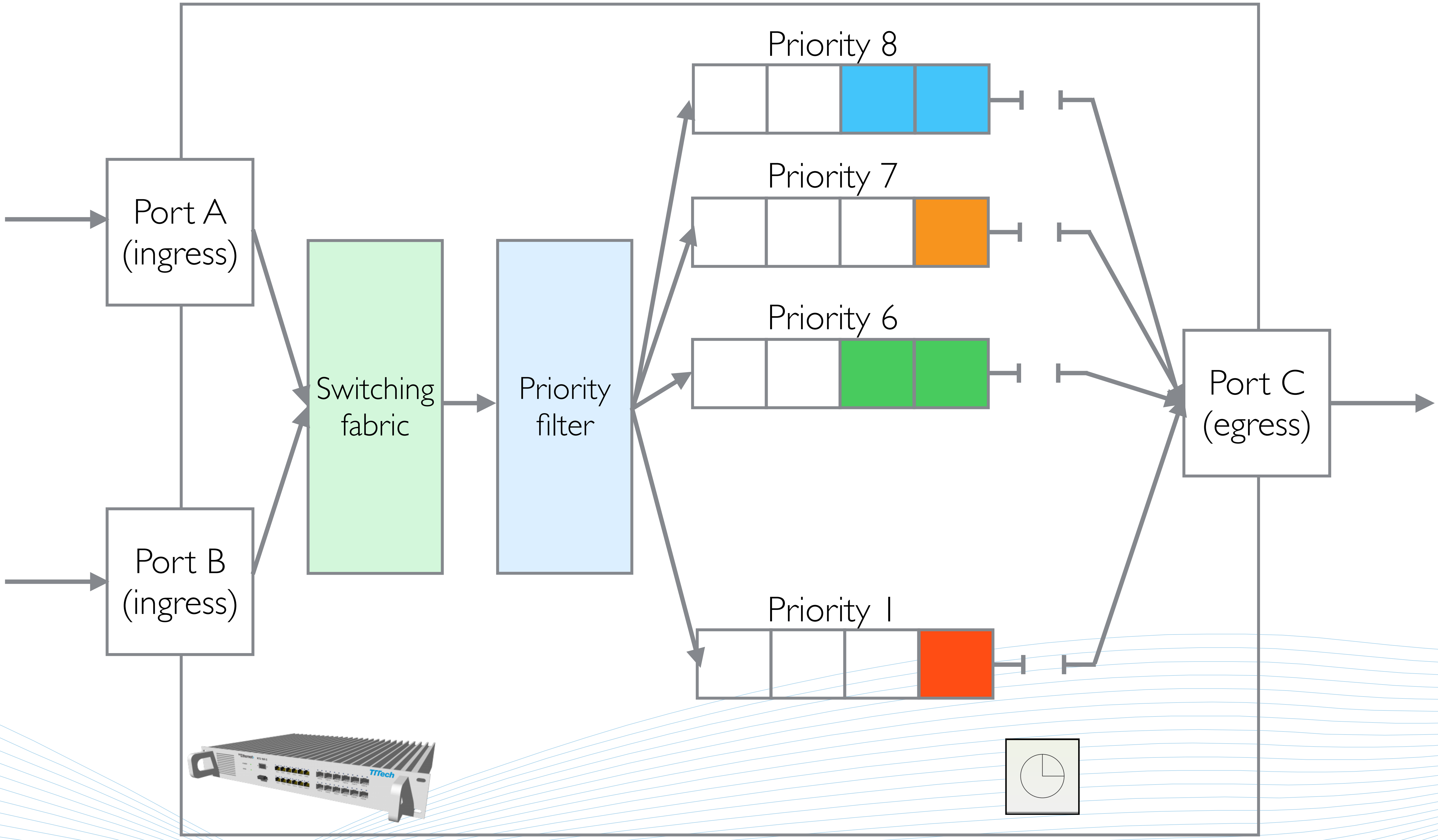
Priority 1

Port C (egress)

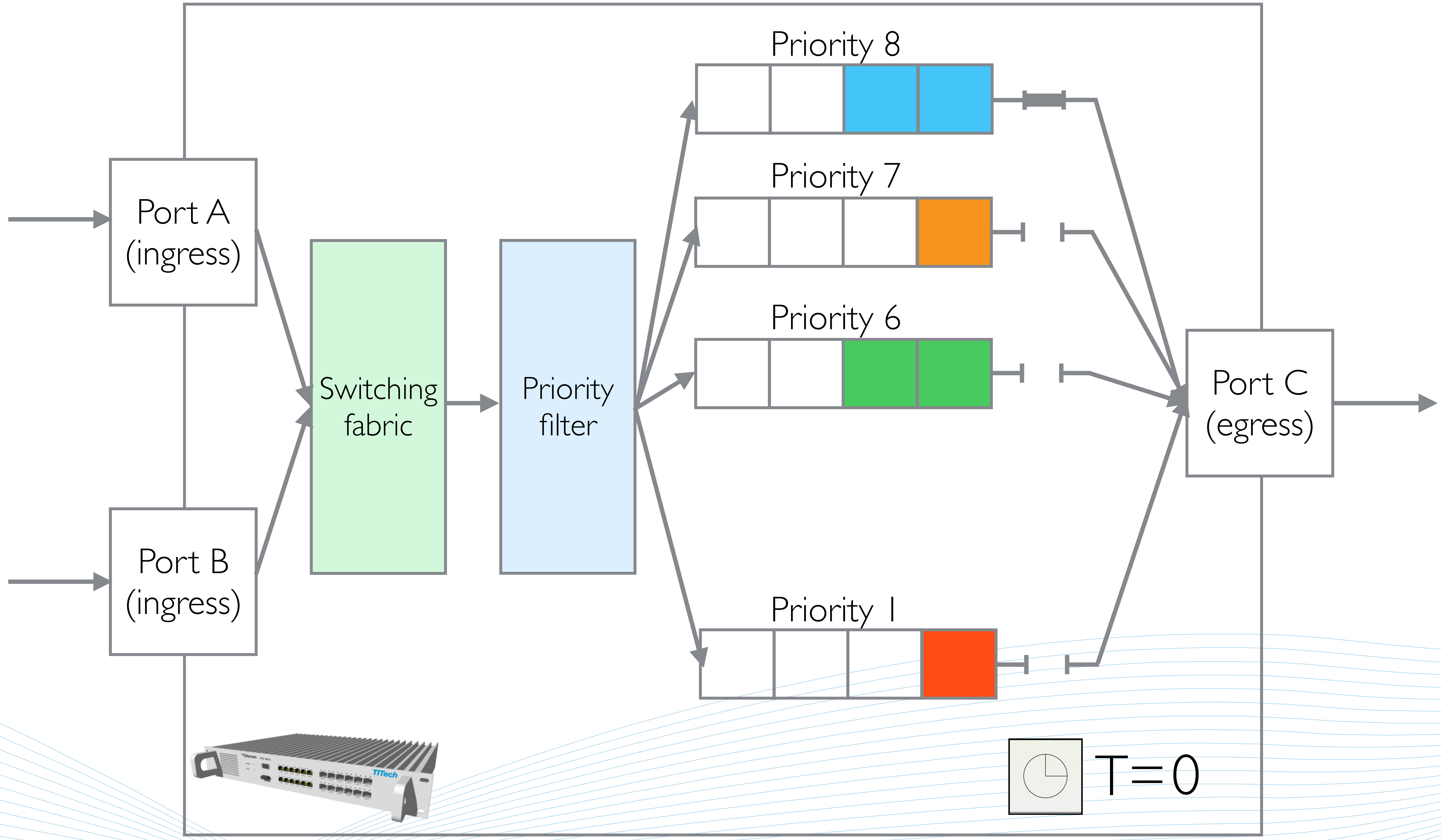
TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Port C
(egress)

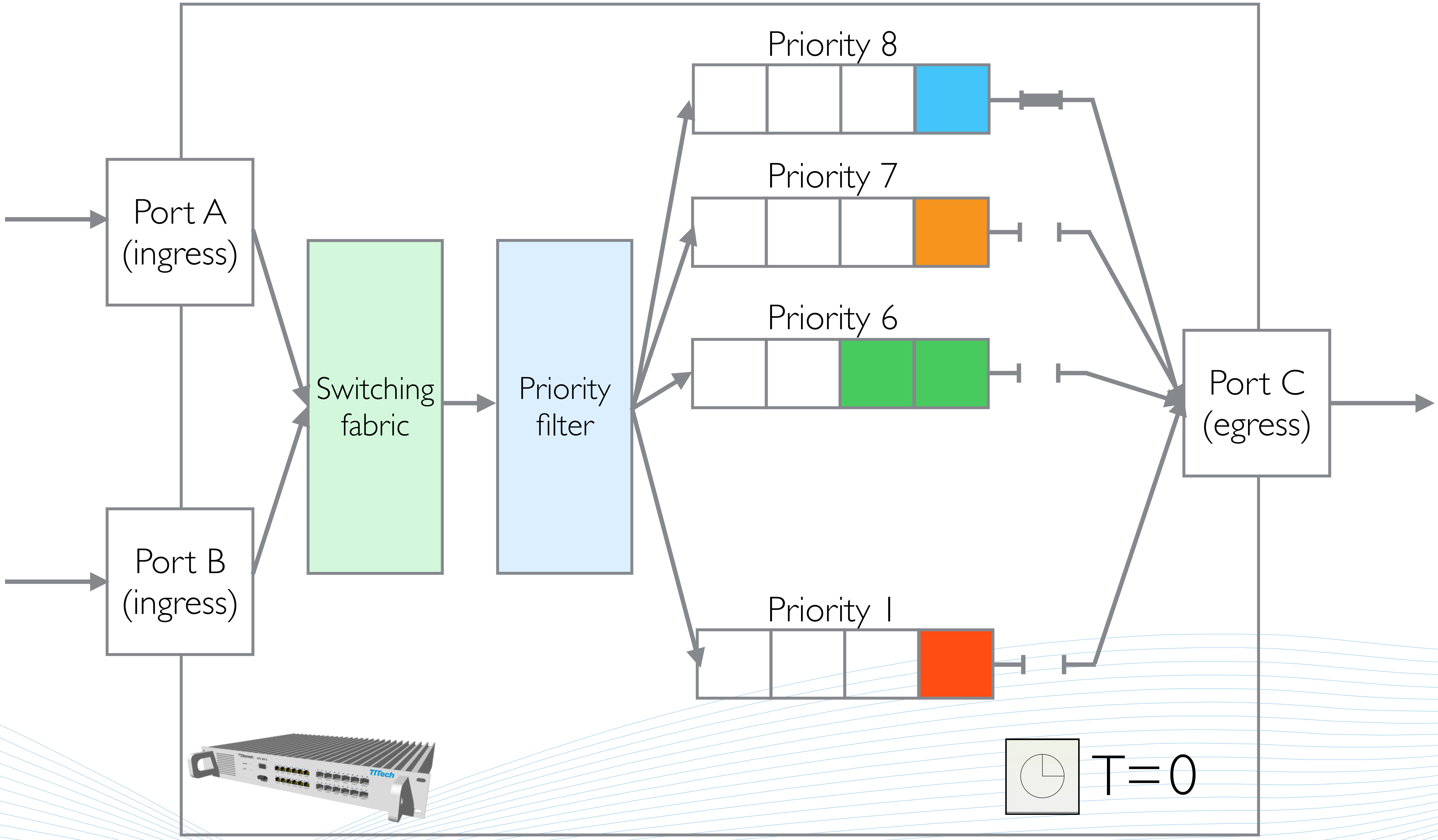
TSN switch


Port A
(ingress)
Port B
(ingress)
Switching fabric
Priority filter
Priority 8
Priority 7
Priority 6
Priority 1
Port C
(egress)

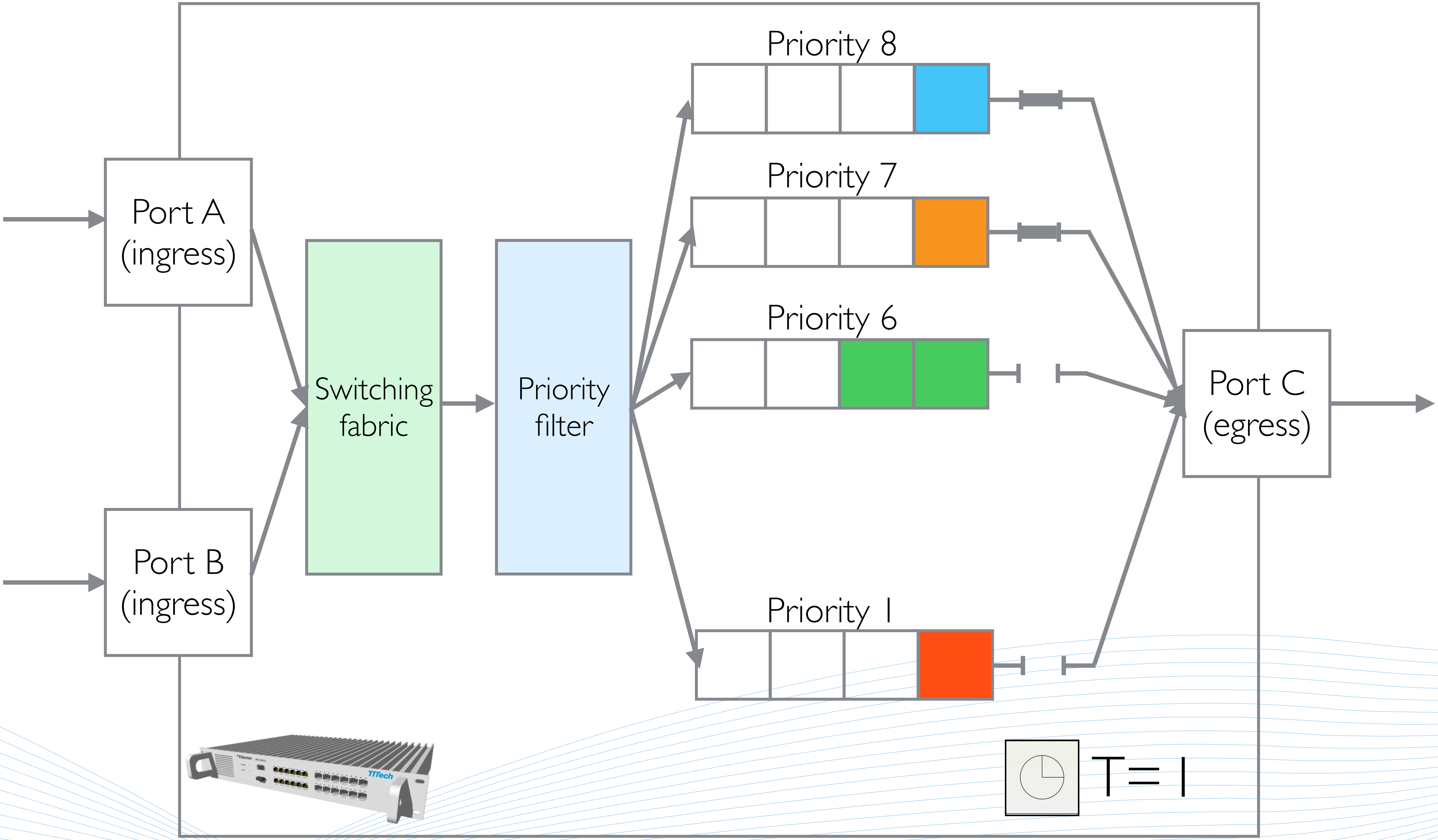
TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Port C
(egress)
T=0

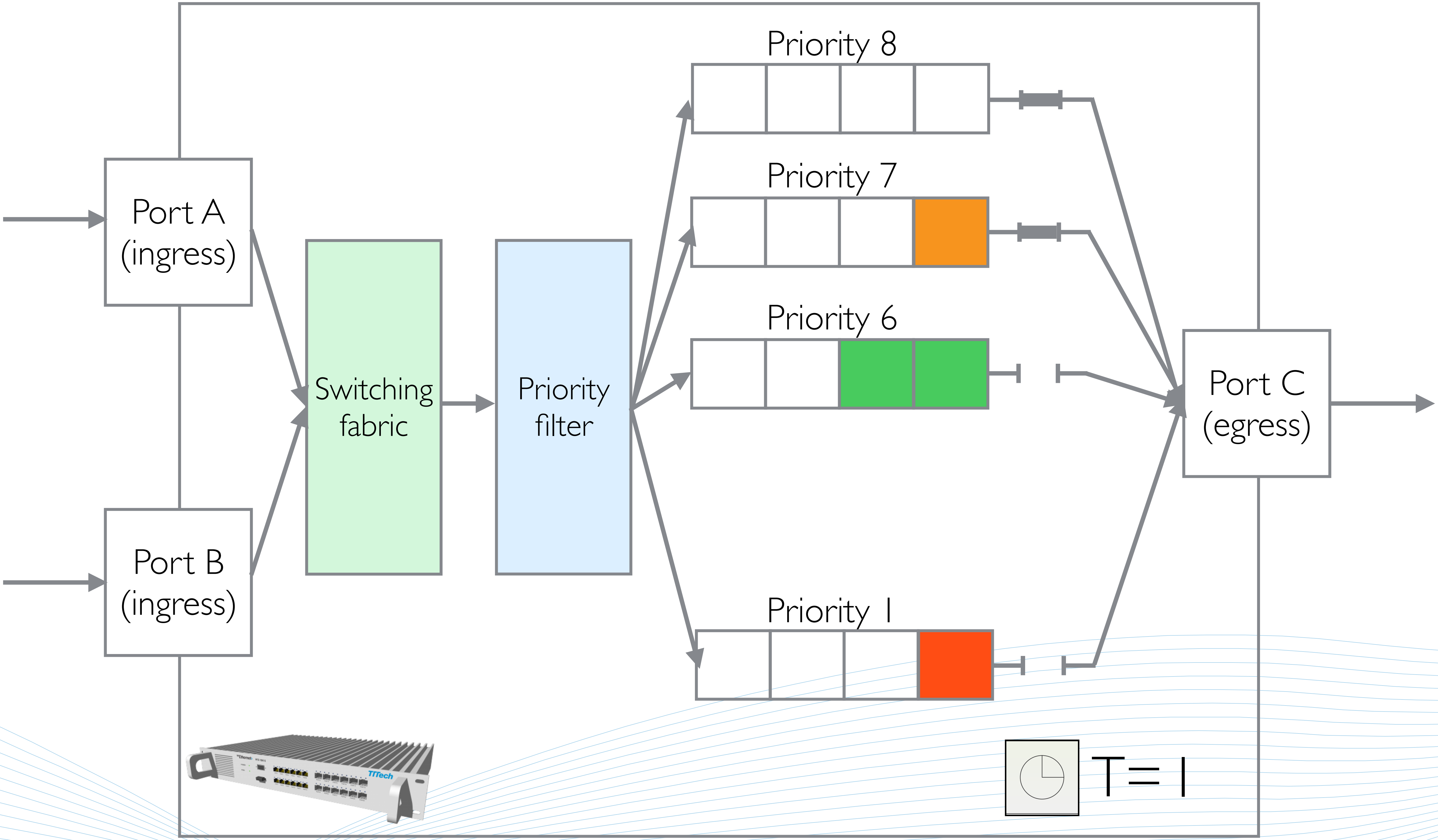
TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching fabric
Priority filter
Port C
(egress)
T=0

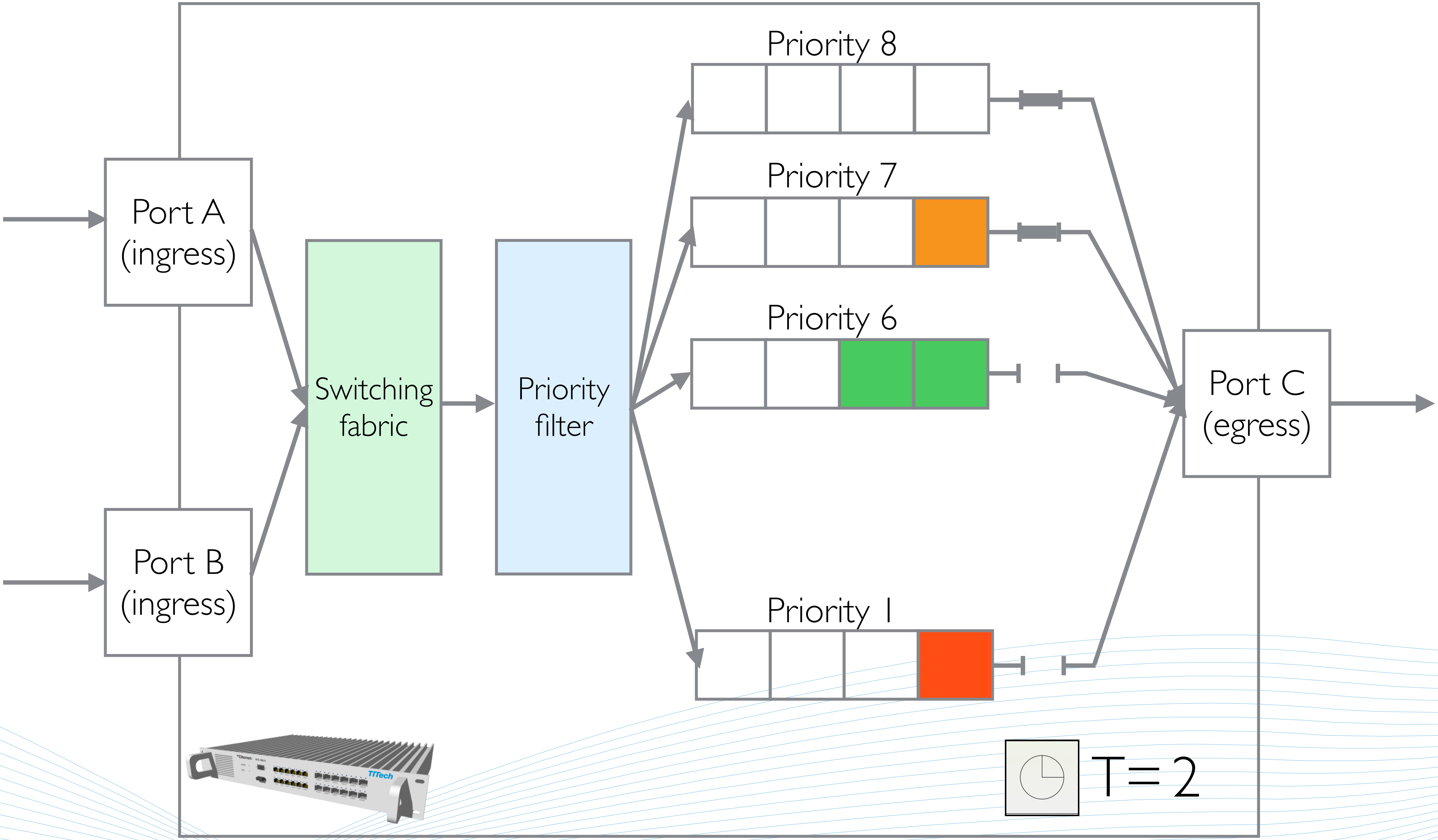
TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Port C
(egress)
T= 1

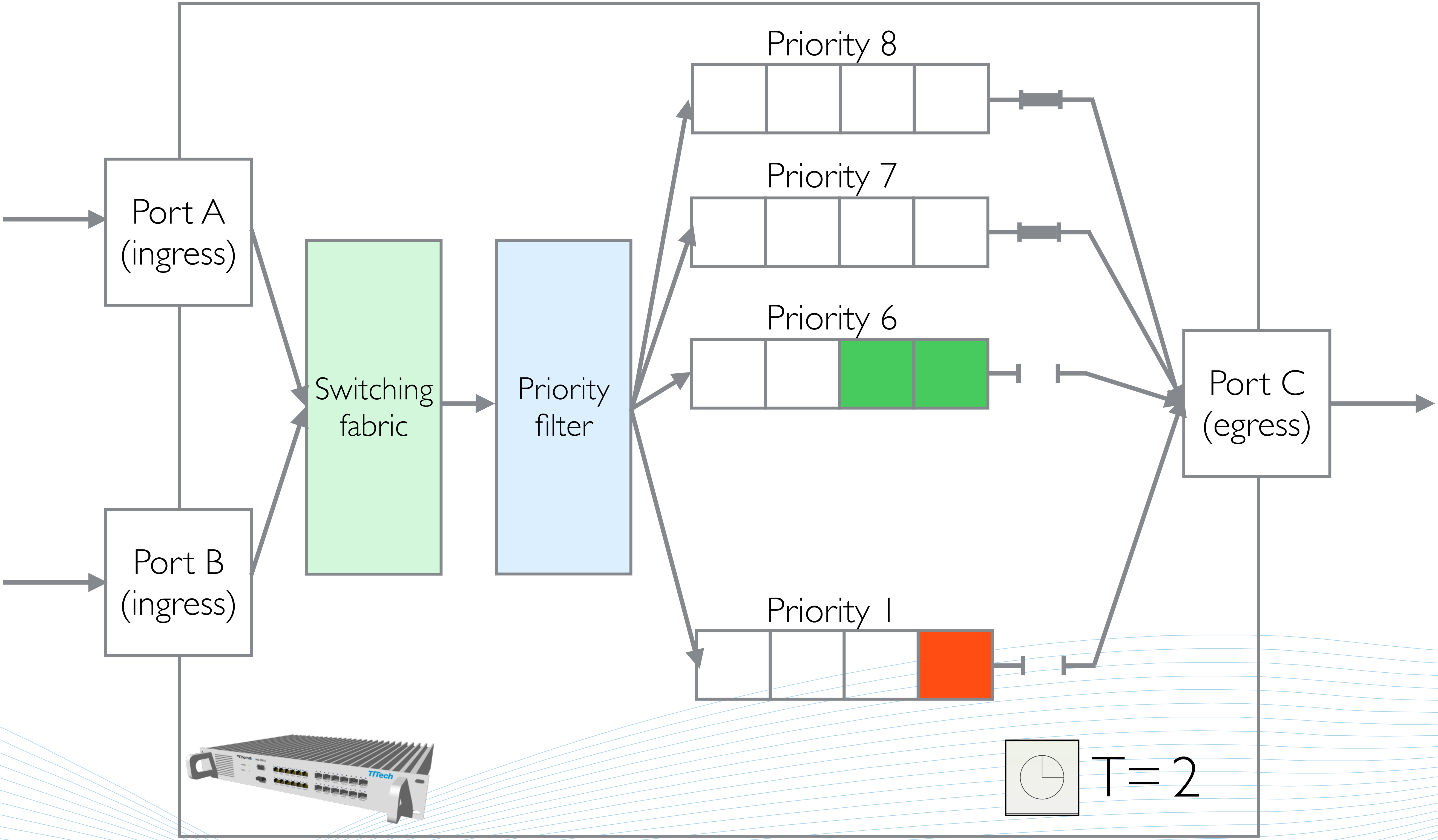
TSN switch


Port A
(ingress)
Port B
(ingress)
Switching fabric
Priority filter
Priority 8
Priority 7
Priority 6
Priority 1
Port C
(egress)
T=1

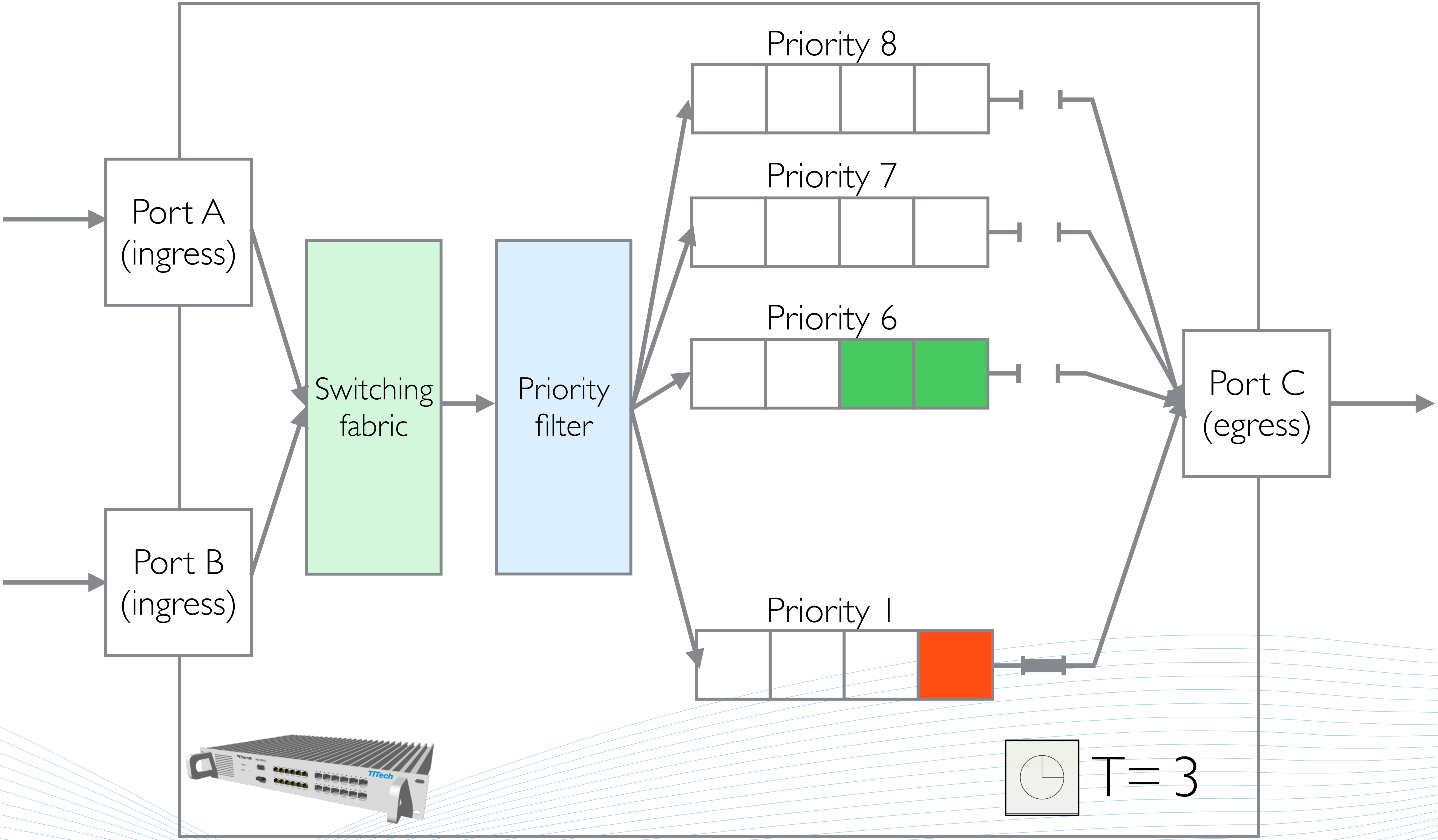
TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching fabric
Priority filter
Port C
(egress)
T=2

TSN switch

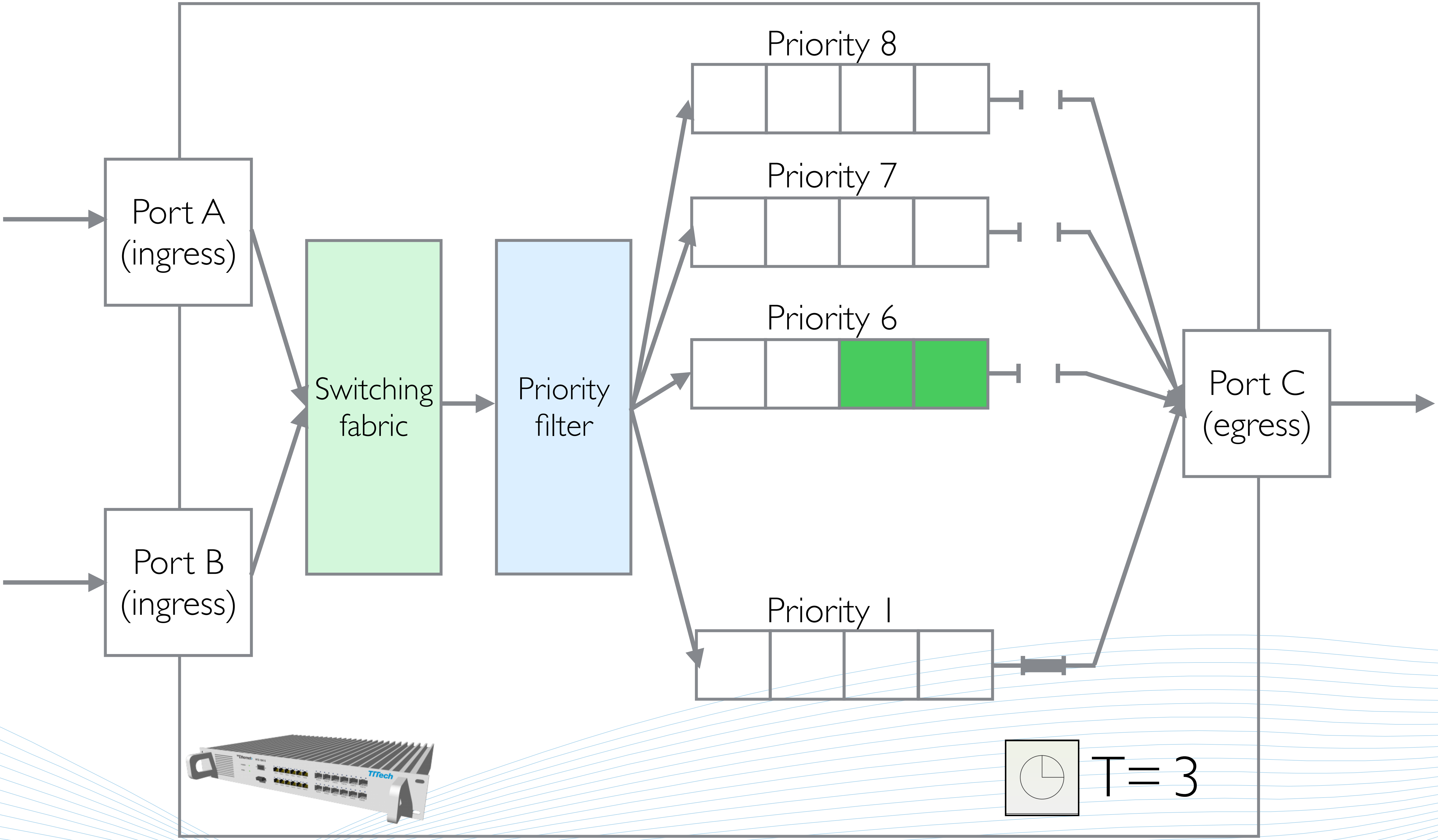

Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching fabric
Priority filter
Port C
(egress)
T=2

TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Port C
(egress)
T= 3
TTTech

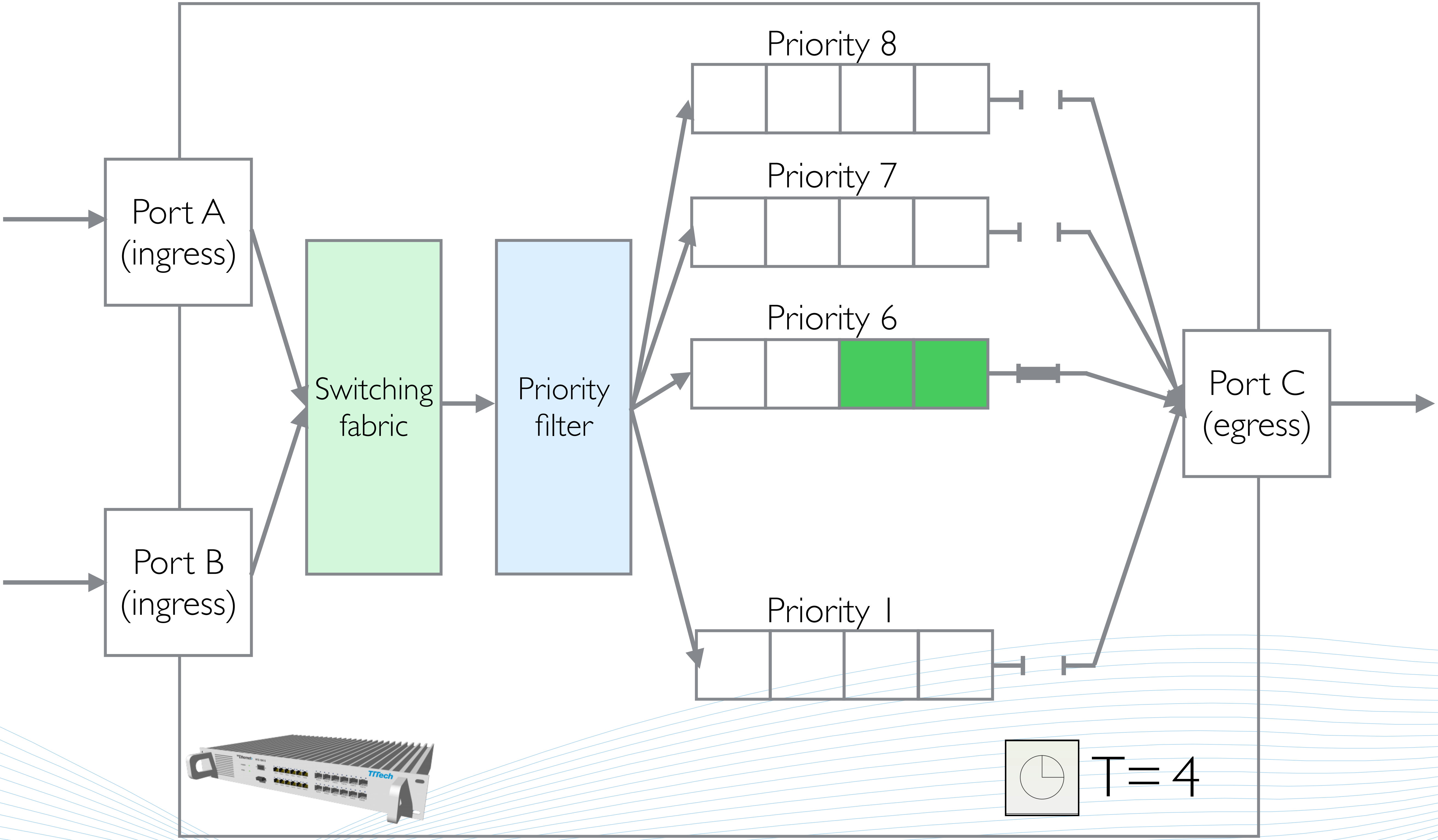
TSN switch

Ensuring Reliable Networks TTTech

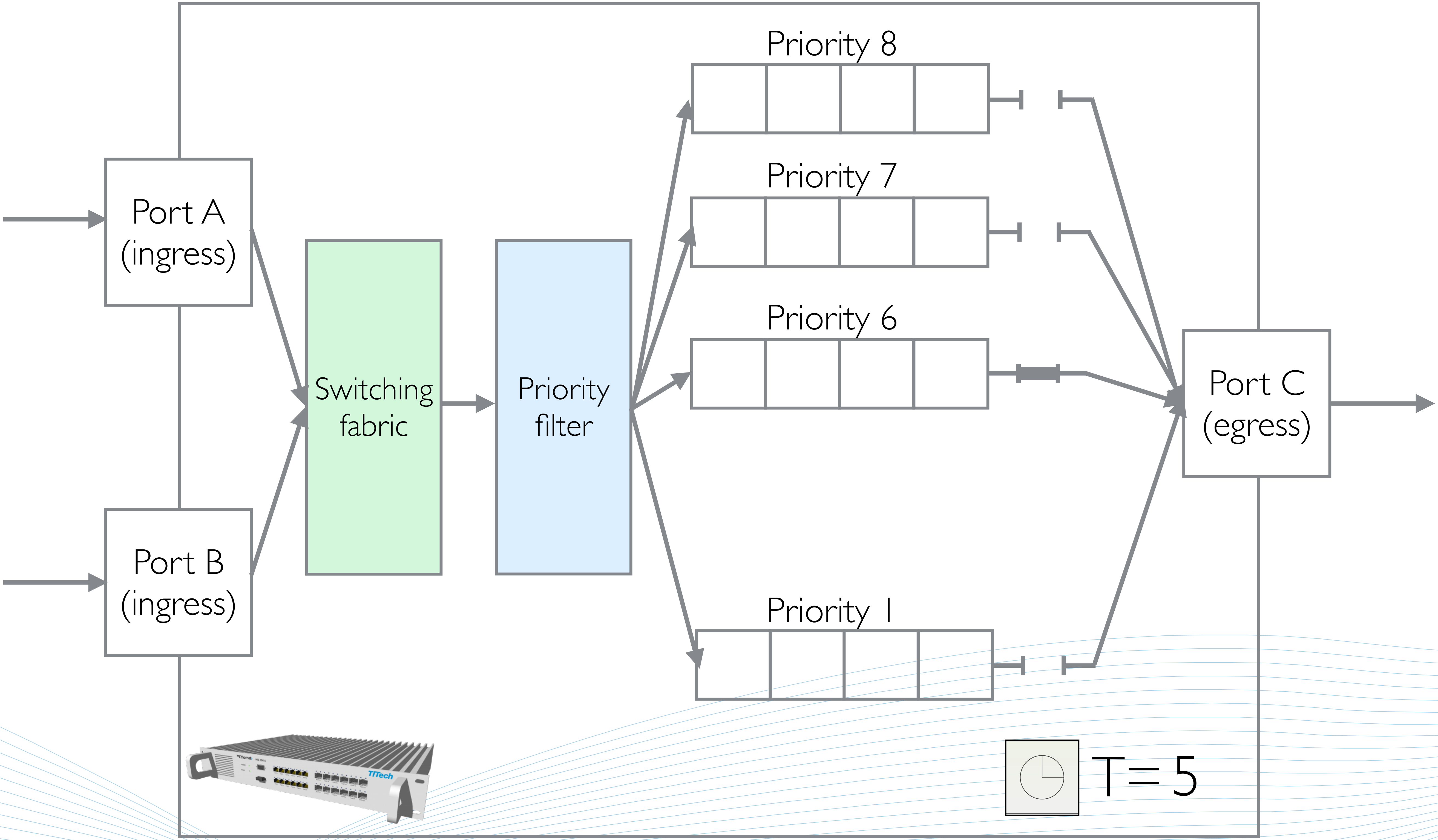


TSN switch

Ensuring Reliable Networks TTTech



TSN switch


Priority 8
Priority 7
Priority 6
Priority 1
Port A
(ingress)
Port B
(ingress)
Switching
fabric
Priority
filter
Port C
(egress)
T=5

Time-Sensitive 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

Time-Sensitive Networks

Ensuring Reliable Networks TTTech

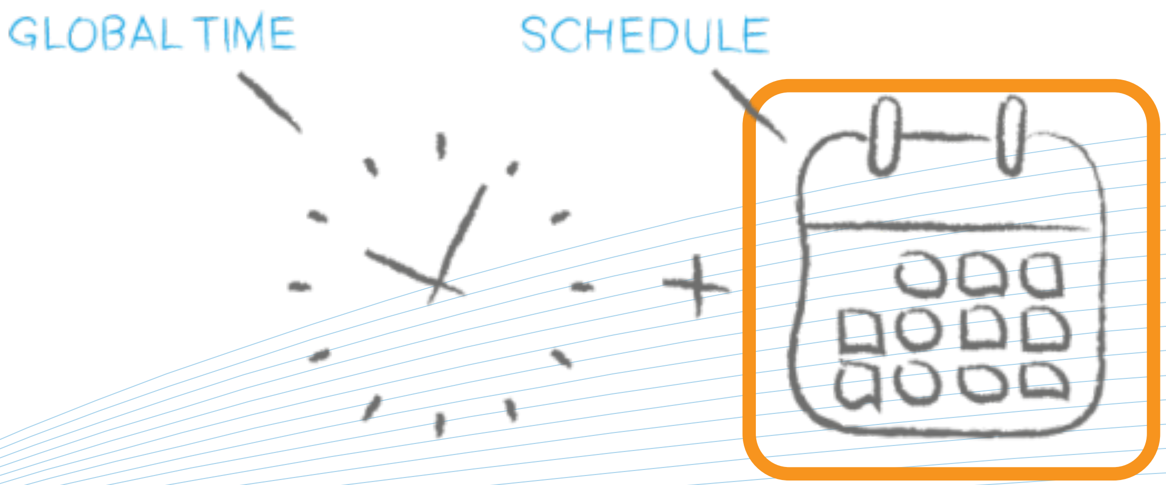
IEEE TSN task group - collection of sub-standards that enhance 802 Ethernet with real-time capabilities

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

Time-Sensitive Networks

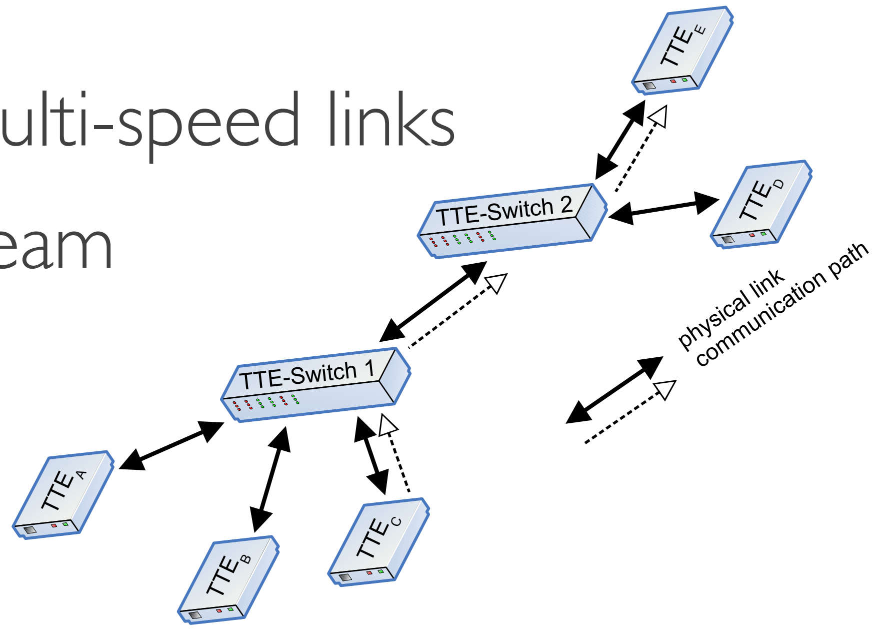
IEEE TSN task group - collection of sub-standards that enhance 802 Ethernet with real-time capabilities

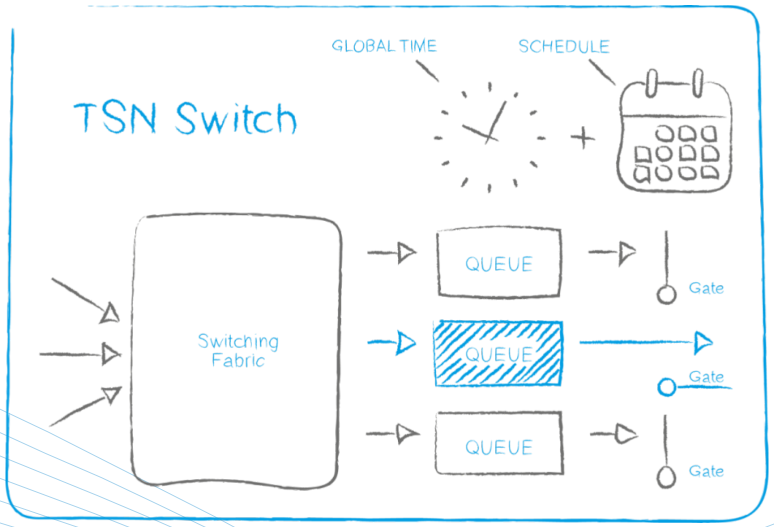
Standard	Description
802.1ASrev	Timing & Synchronization
802.1Qbv	Enhancements for Scheduled Traffic (Timed Gates for Egress Queues)
802.1Qbu	Frame Preemption
802.1Qca	Path Control and Reservation
802.1Qcc	Central Configuration Management
802.1Qci	Per-Stream Time-based Ingress Filtering and Policing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



Network & traffic model

- 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 Scheduled Es

V_s Scheduled Sw

V_{e+s} Scheduled Es+Sw

Queue configuration

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

Functional parameters

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

Device capabilities

$$G(E)$$

V_e

Scheduled Es

V_s

Scheduled Sw

V_{e+s}

Scheduled Es+Sw

Queue configuration

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

Functional parameters

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

Device capabilities

$$G(E)$$

V_e

Scheduled Es

V_s

Scheduled Sw

V_{e+s}

Scheduled Es+Sw

Queue configuration

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

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

Functional parameters

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

Device capabilities

$$G(E)$$

V_e Scheduled Es

V_s Scheduled Sw

$\boxed{V_{e+s}}$ Scheduled Es+Sw

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

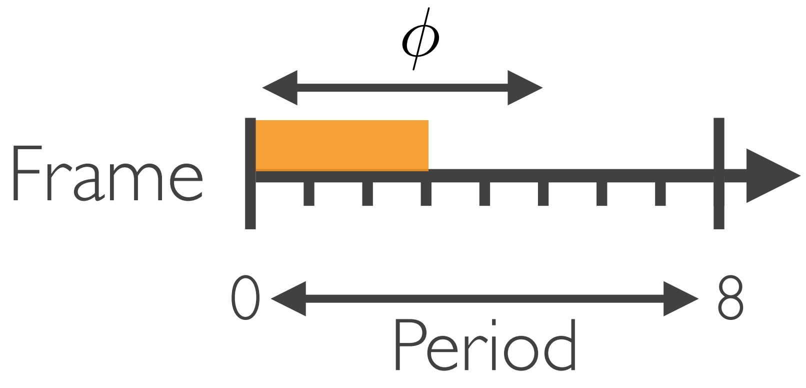
$\{V_{e+s}, \langle n|m|n-m\rangle\}$

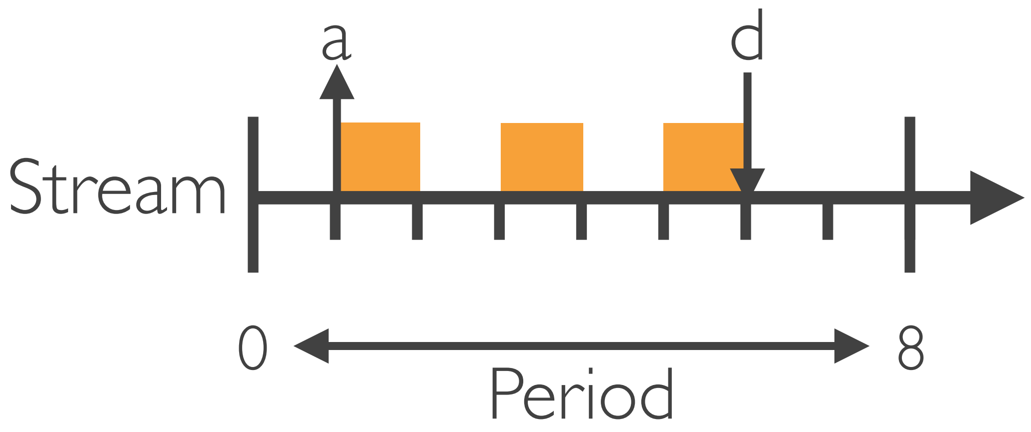
High-criticality applications that feature both scheduled and non-scheduled traffic, trade-off between schedulability of critical traffic and timeliness properties and flexibility for non-scheduled traffic

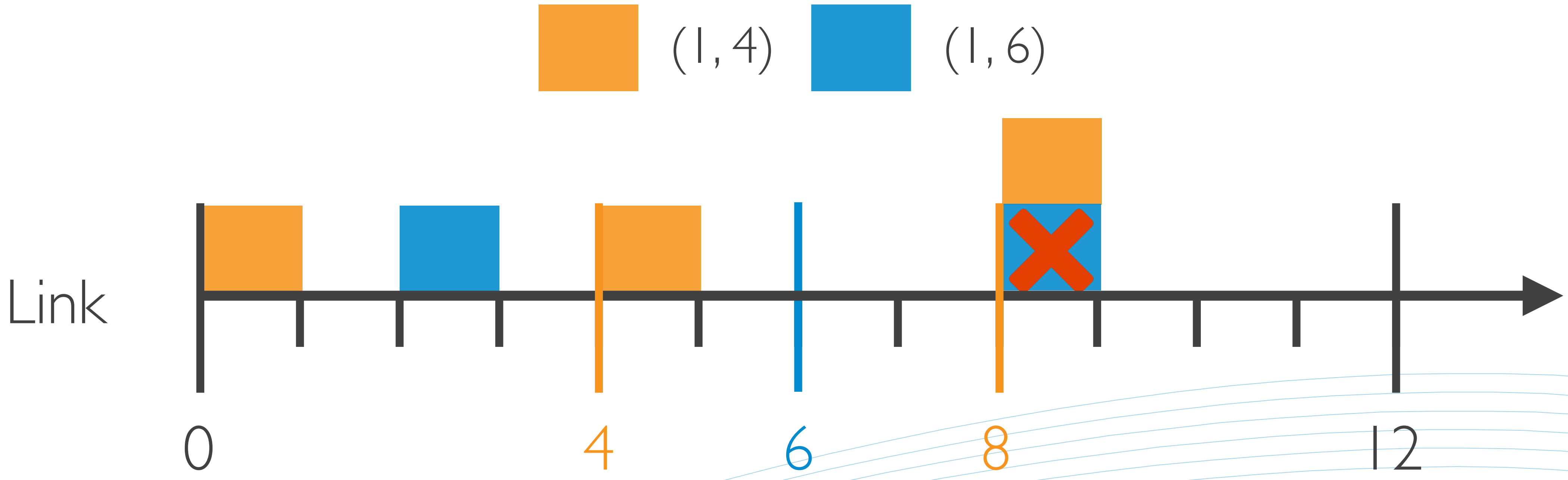
$\{V_{e+s}, \langle n|0|n\rangle\}$

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

Deterministic Ethernet Constraints



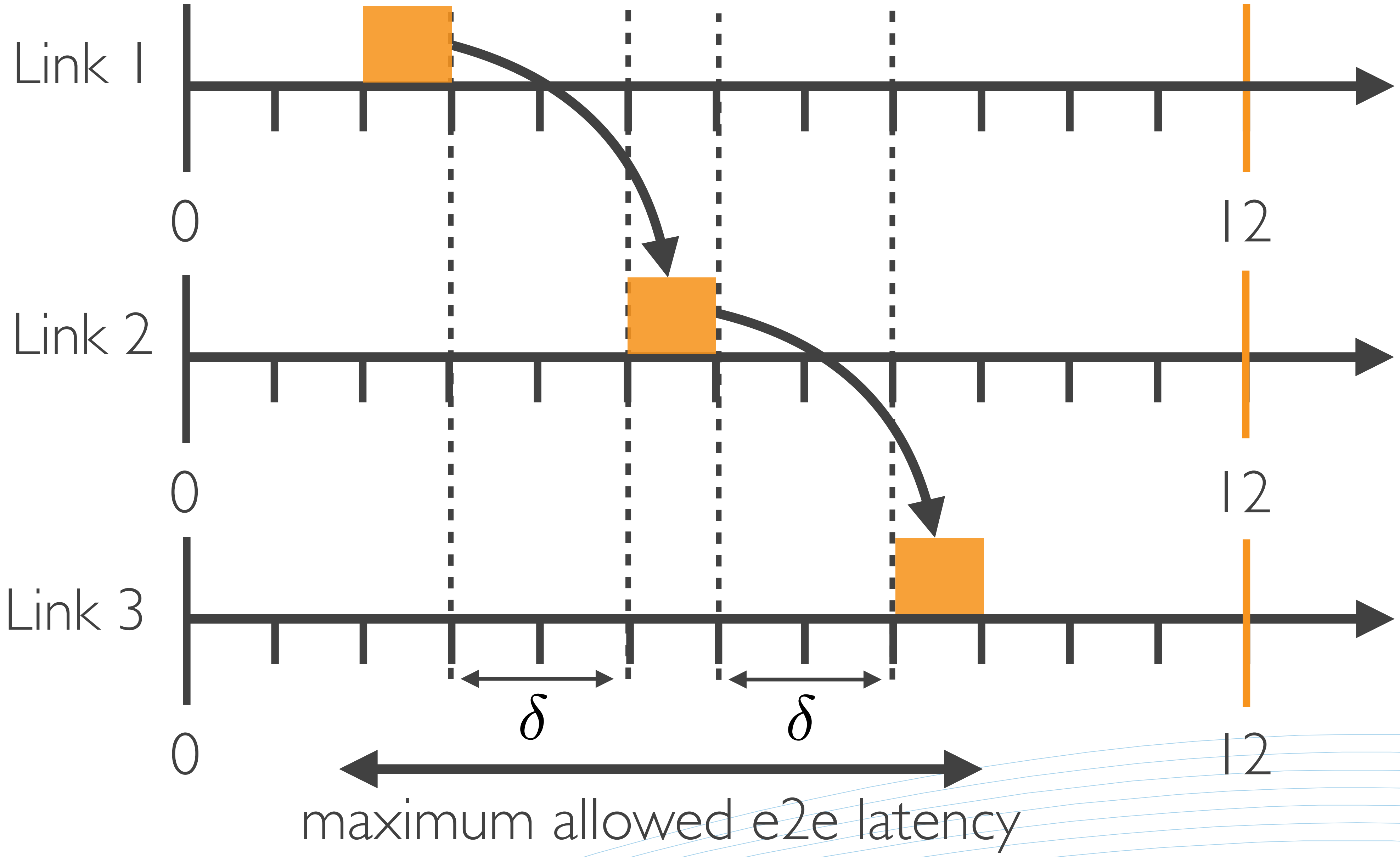




see also [Steiner@RTSS10] or [Craciunas@RTNS14]

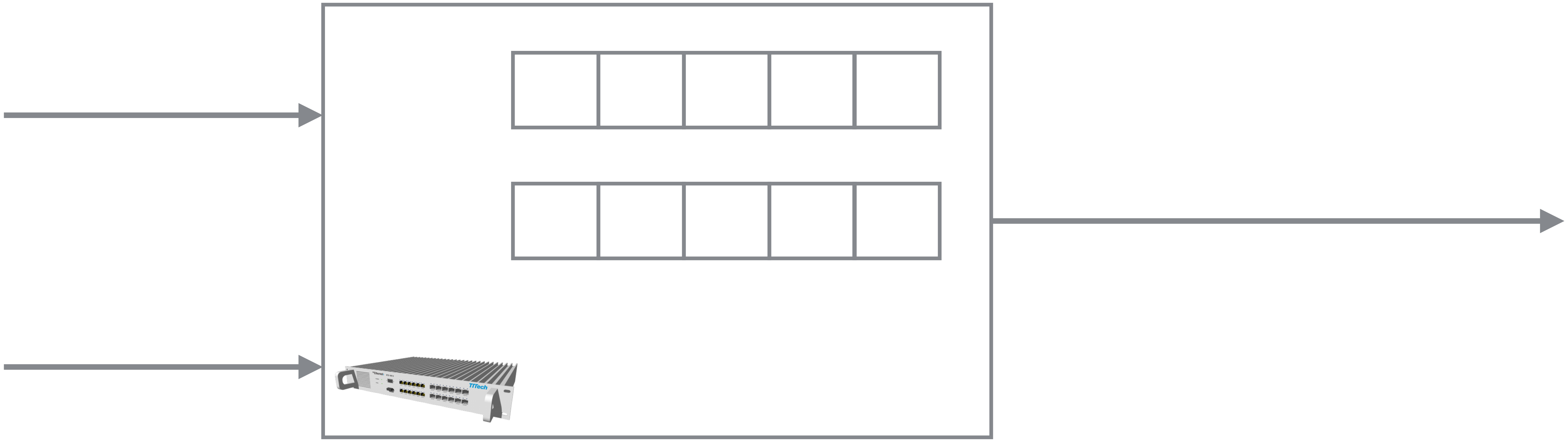
Stream and e2e latency constraints

Ensuring Reliable Networks TTTech



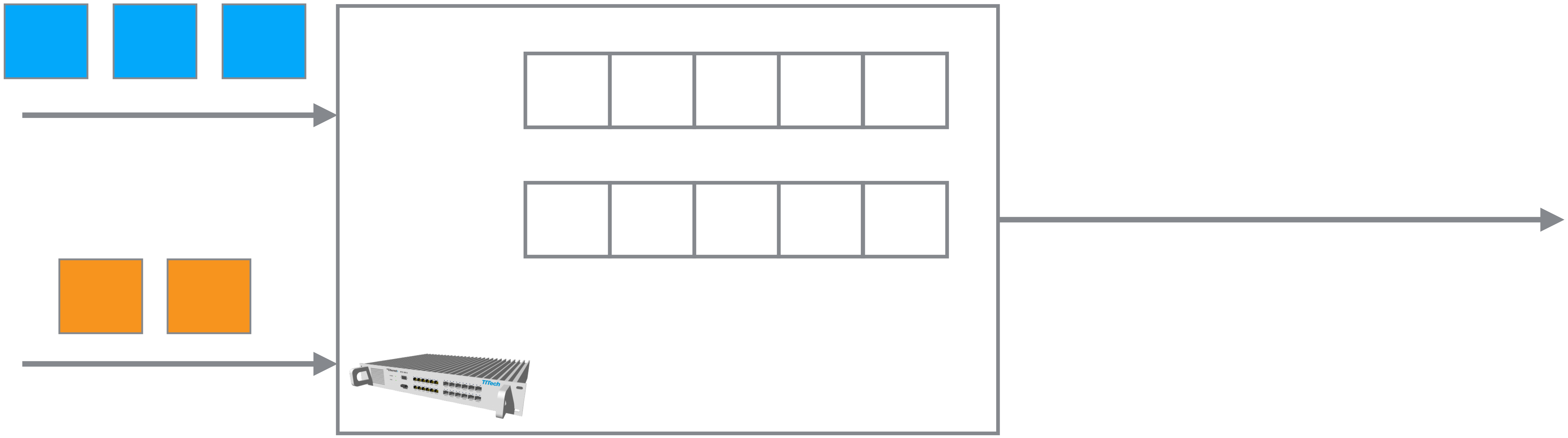
see also [Steiner@RTSS10] or [Craciunas@RTNS14]

Queue Interleaving

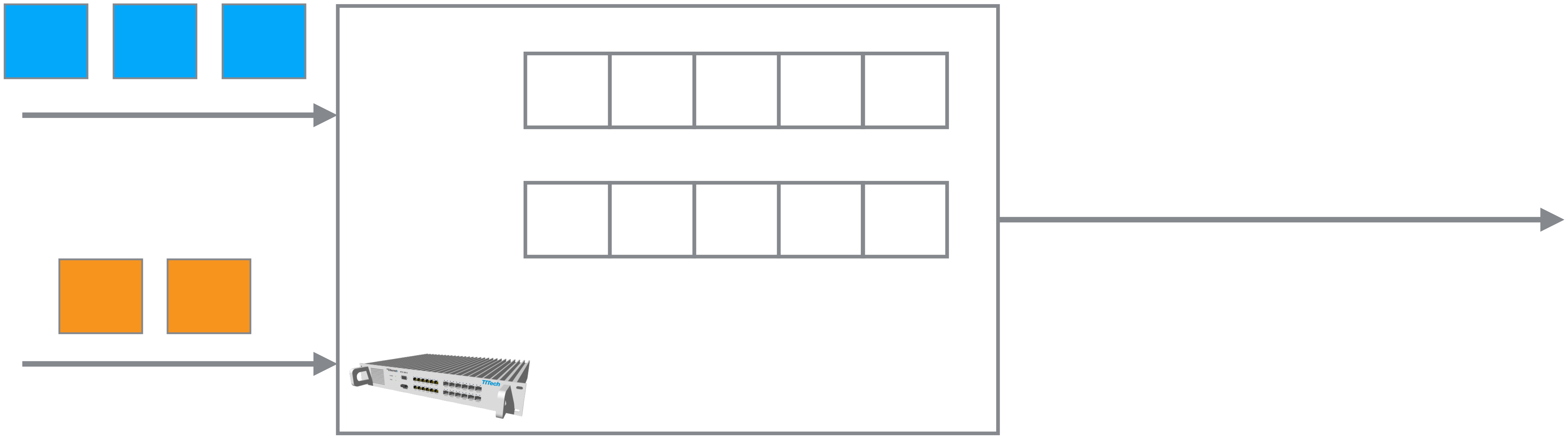


Queue Interleaving

Ensuring Reliable Networks TTTech

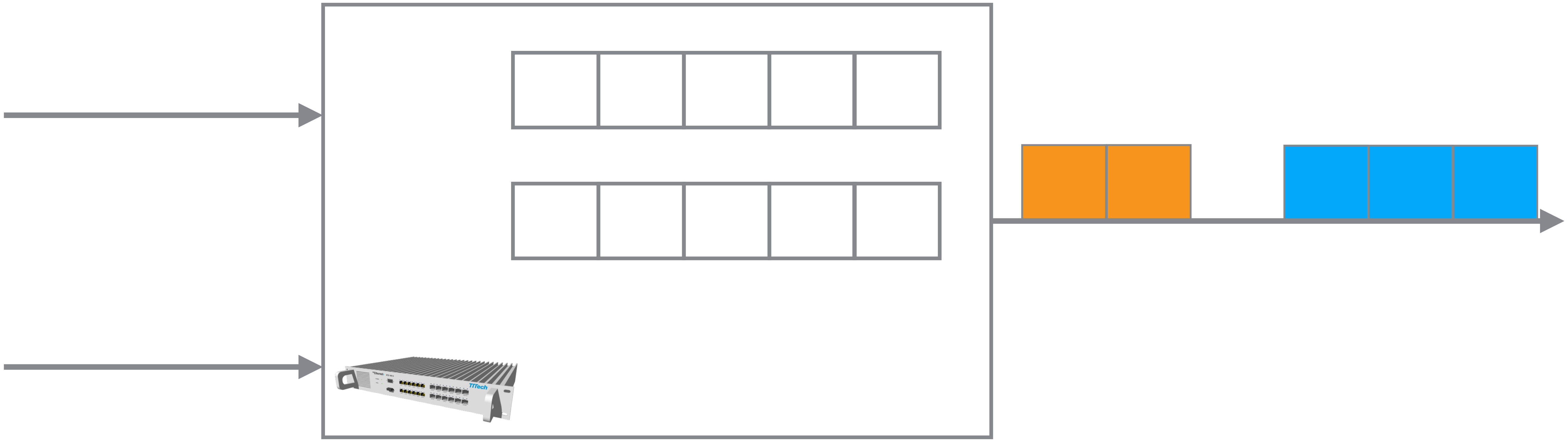


Queue Interleaving



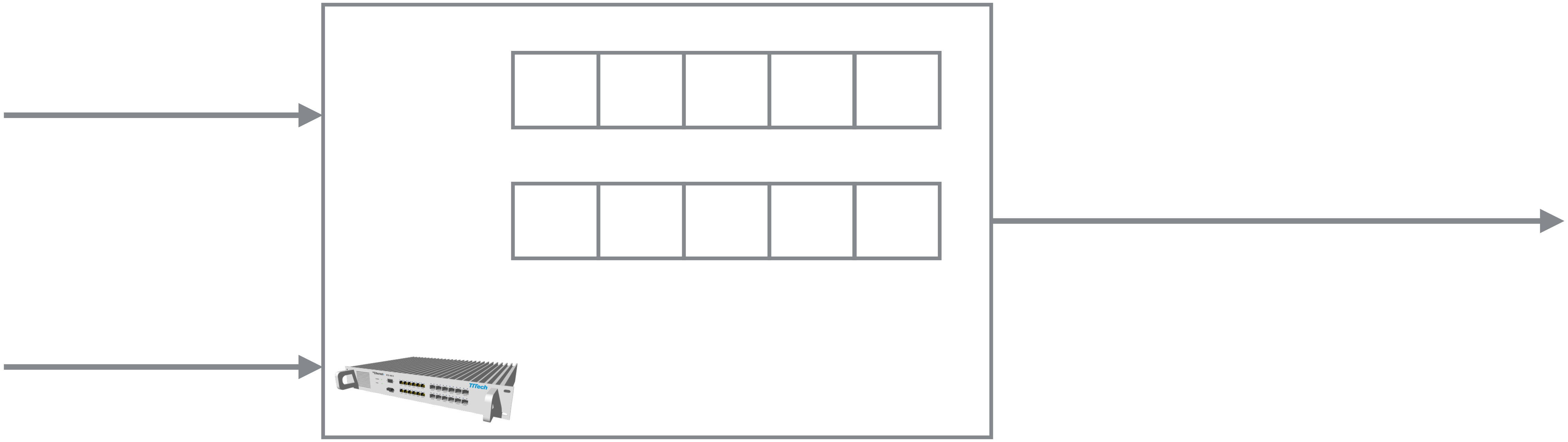
In order to maintain jitter and latency requirements we expect at each device a certain timely order of frames

Queue Interleaving

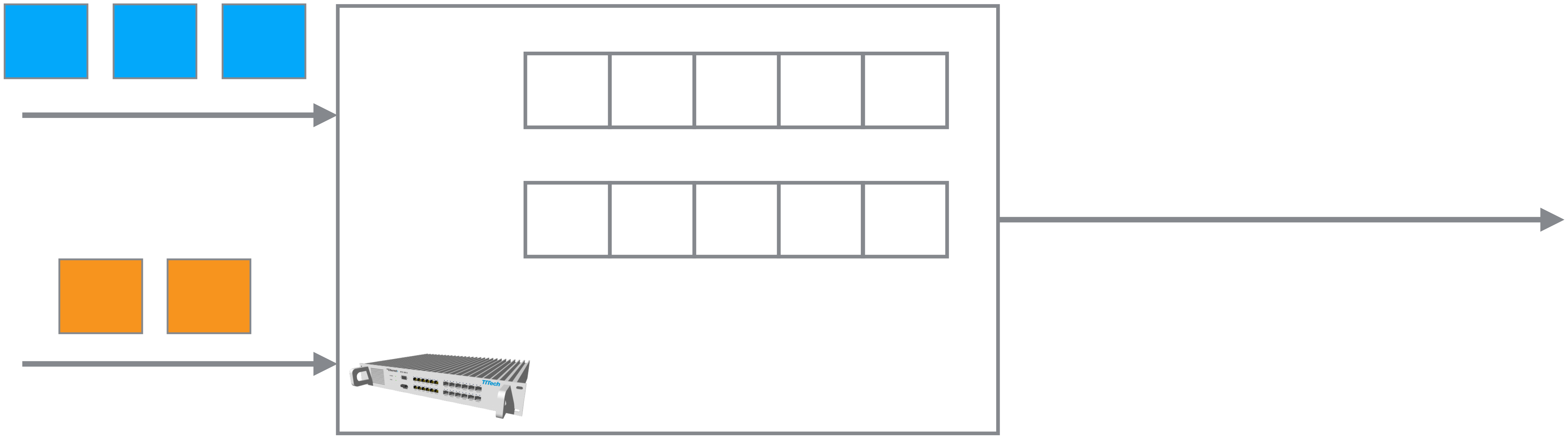


In order to maintain jitter and latency requirements we expect at each device a certain timely order of frames

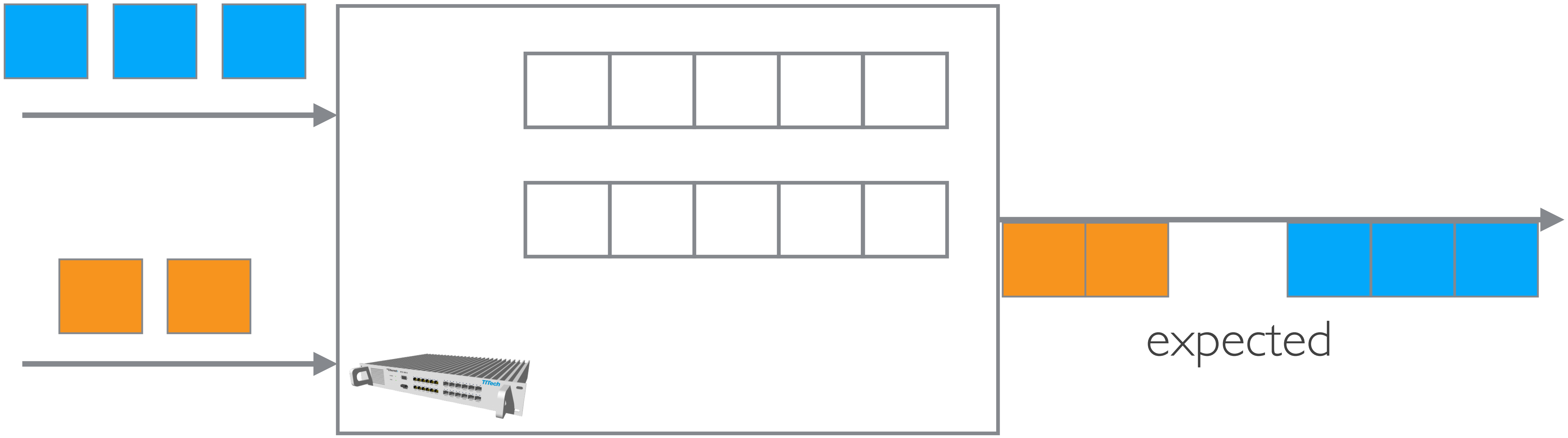
Queue Interleaving



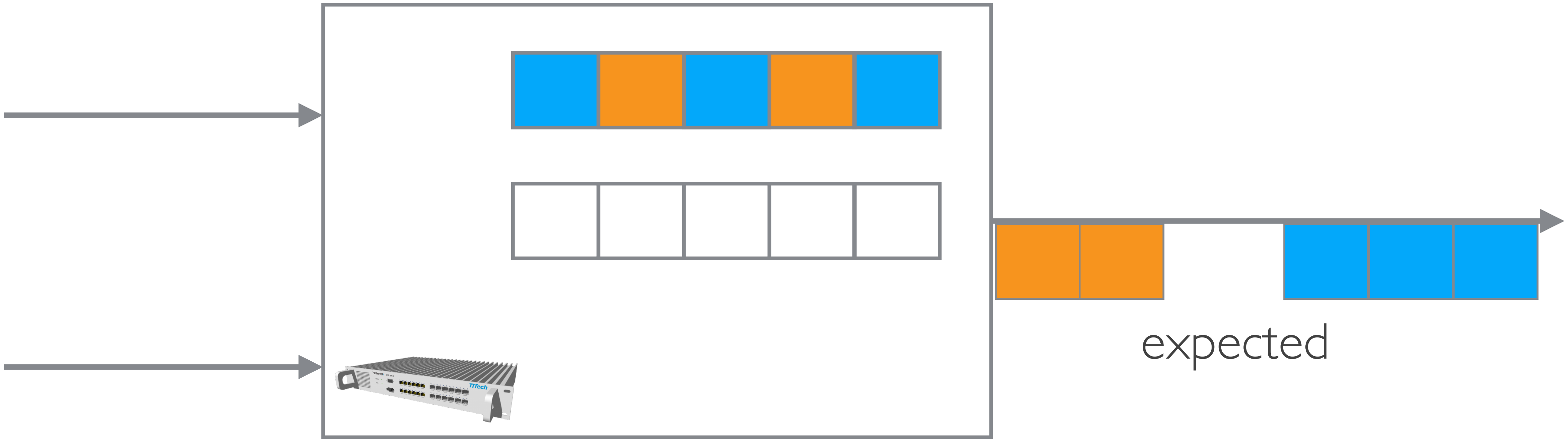
Queue Interleaving



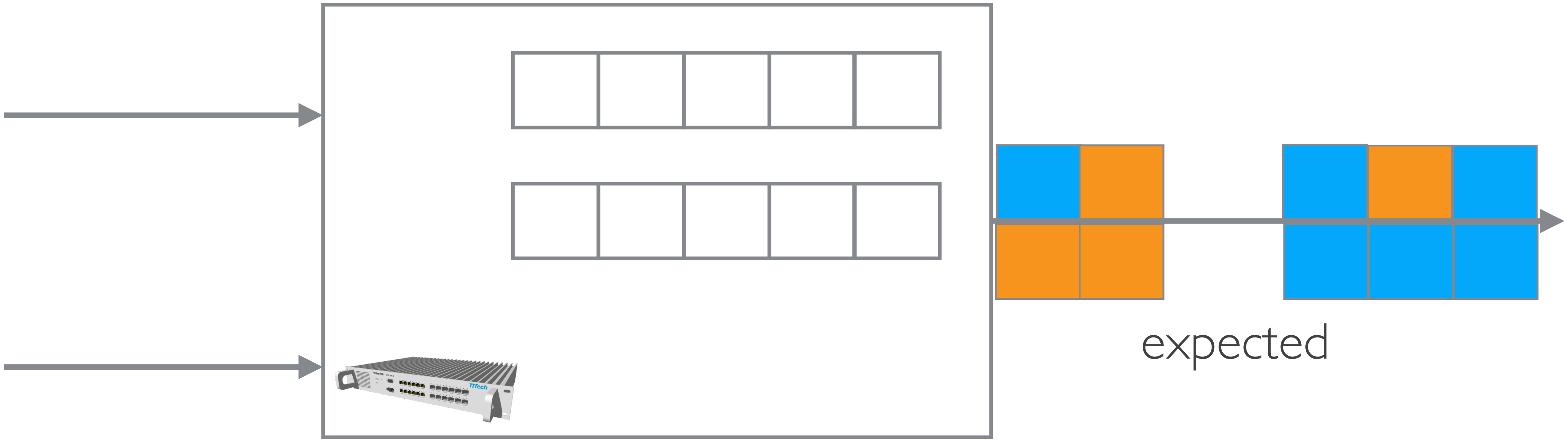
Queue Interleaving



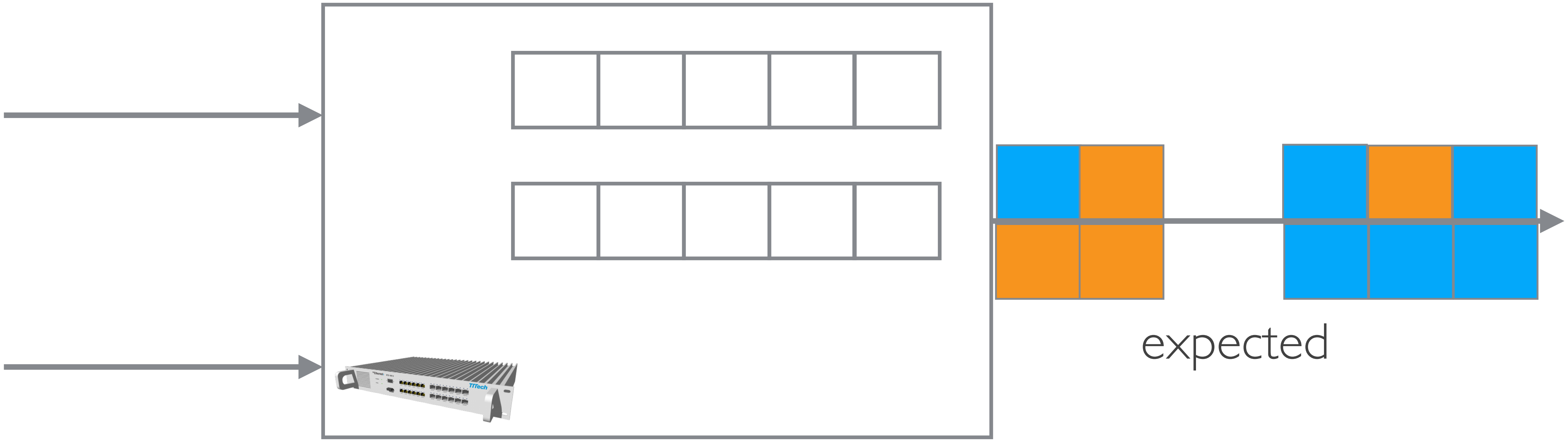
Queue Interleaving



Queue Interleaving



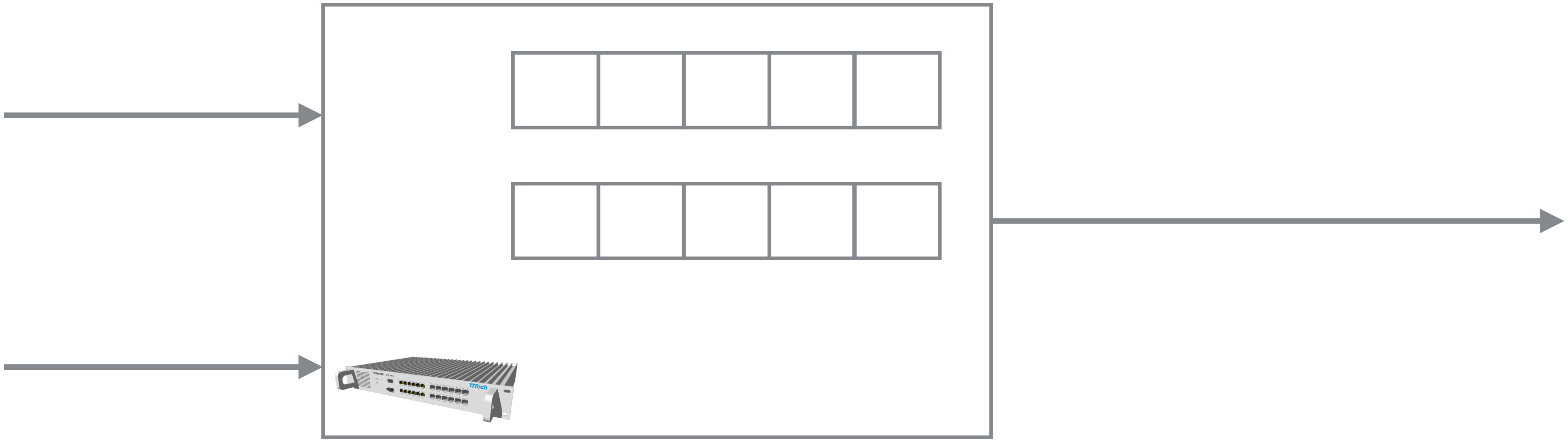
Queue Interleaving



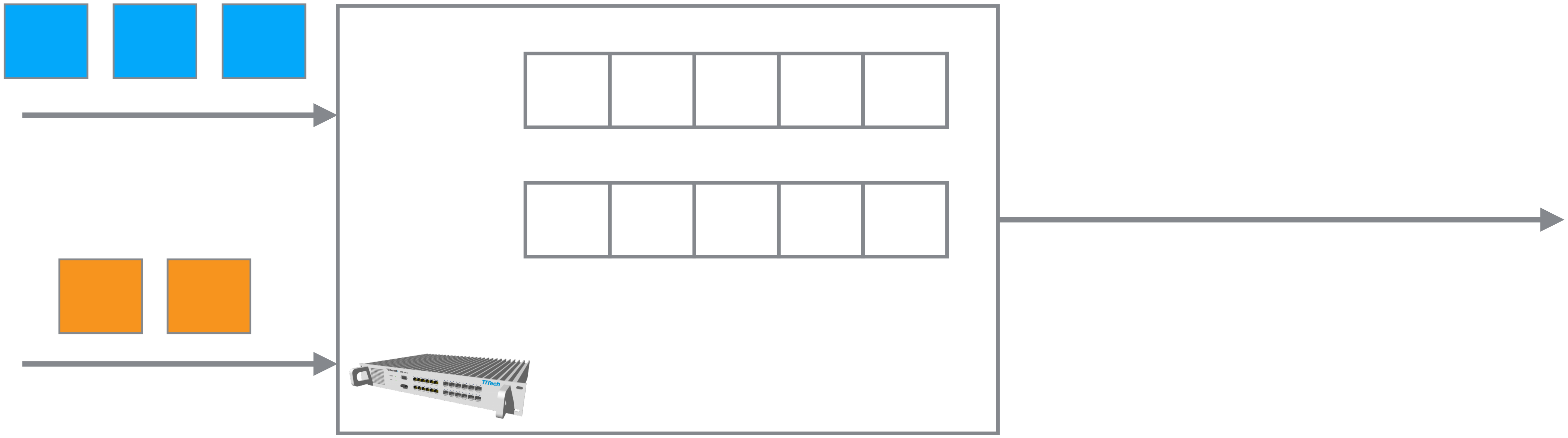
- synchronization errors, frame loss, time-based ingress policing (e.g. IEEE 802.1Qci) may lead to non-deterministic placement in queues during runtime
- timed gates control events on the egress port, not the order of frames in the queue
- placing of frames in the scheduled queues at runtime may be non-deterministic

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

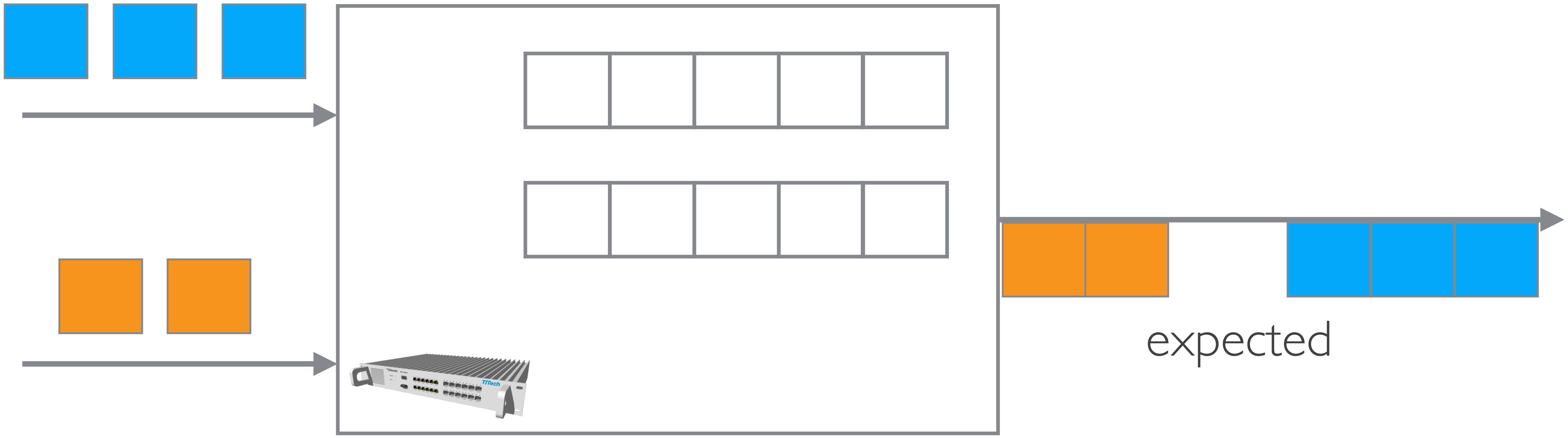
Queue Isolation



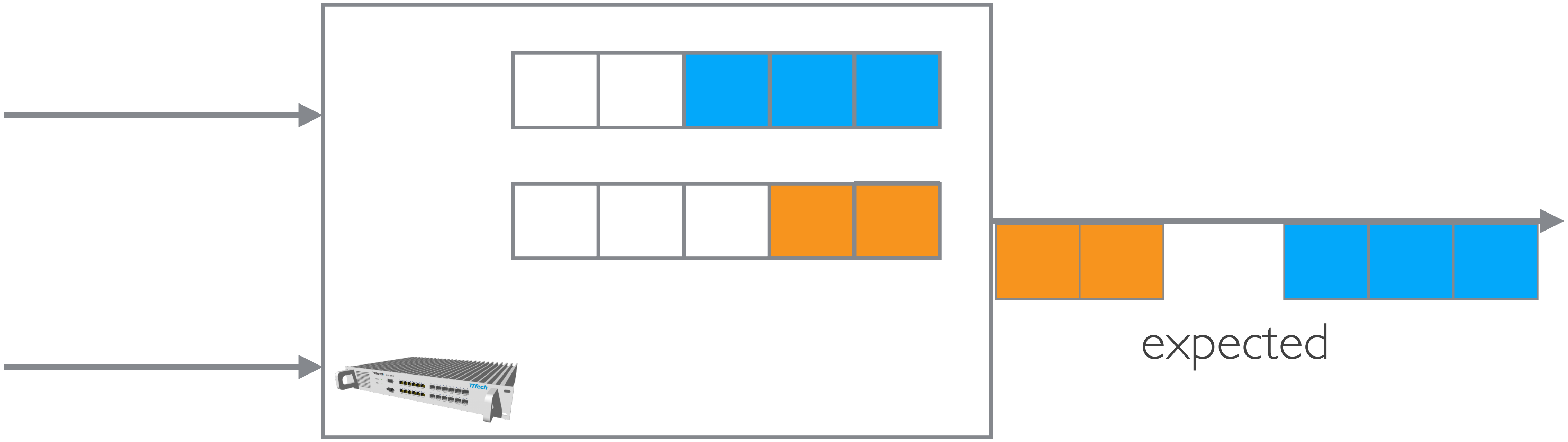
Queue Isolation



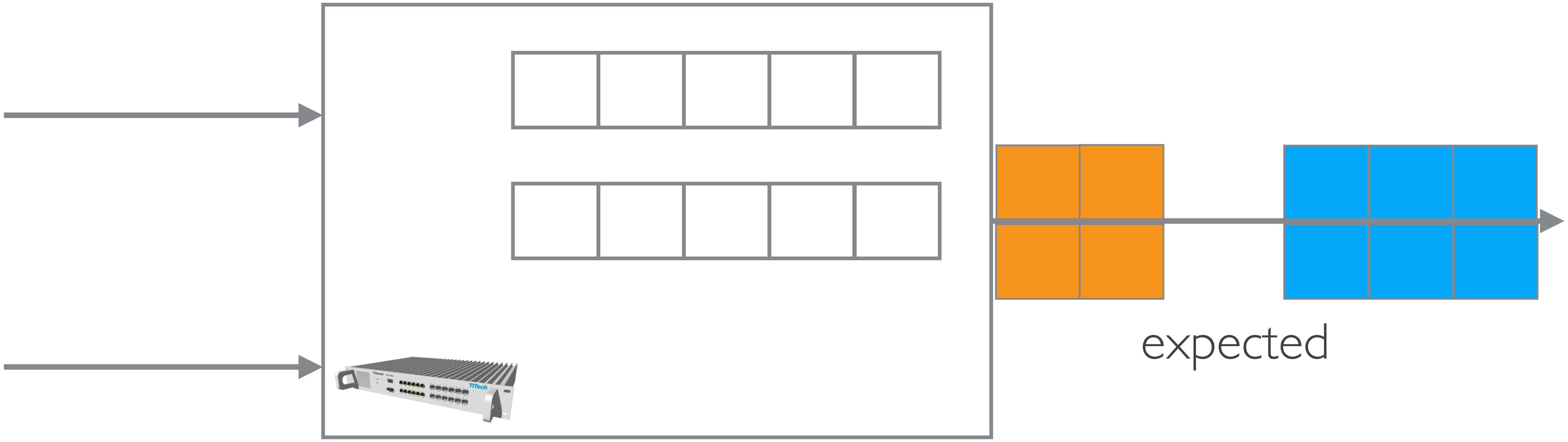
Queue Isolation



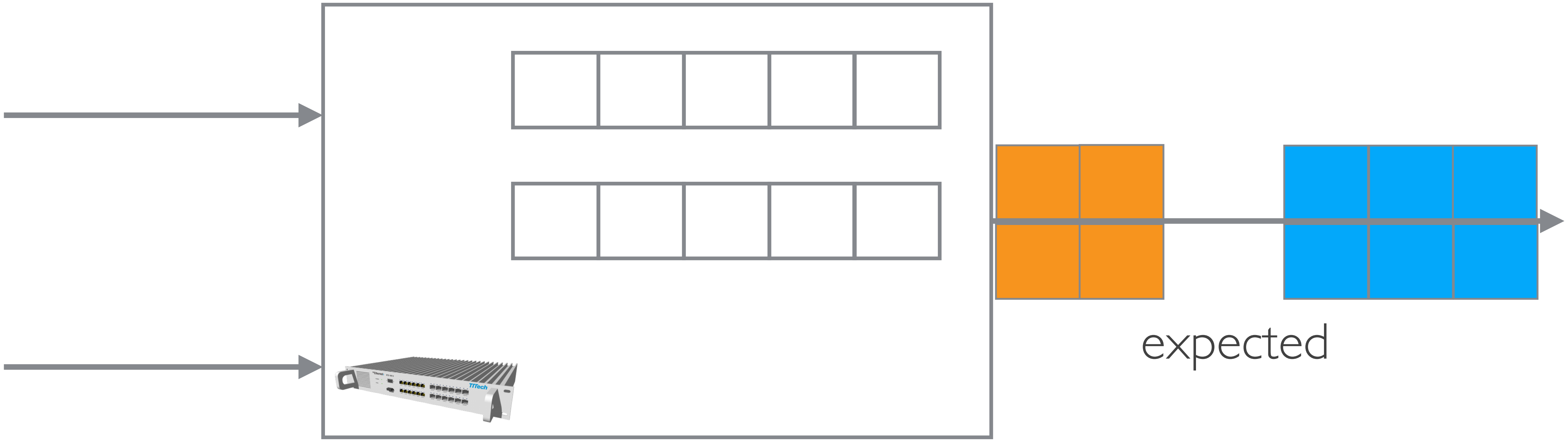
Queue Isolation



Queue Isolation

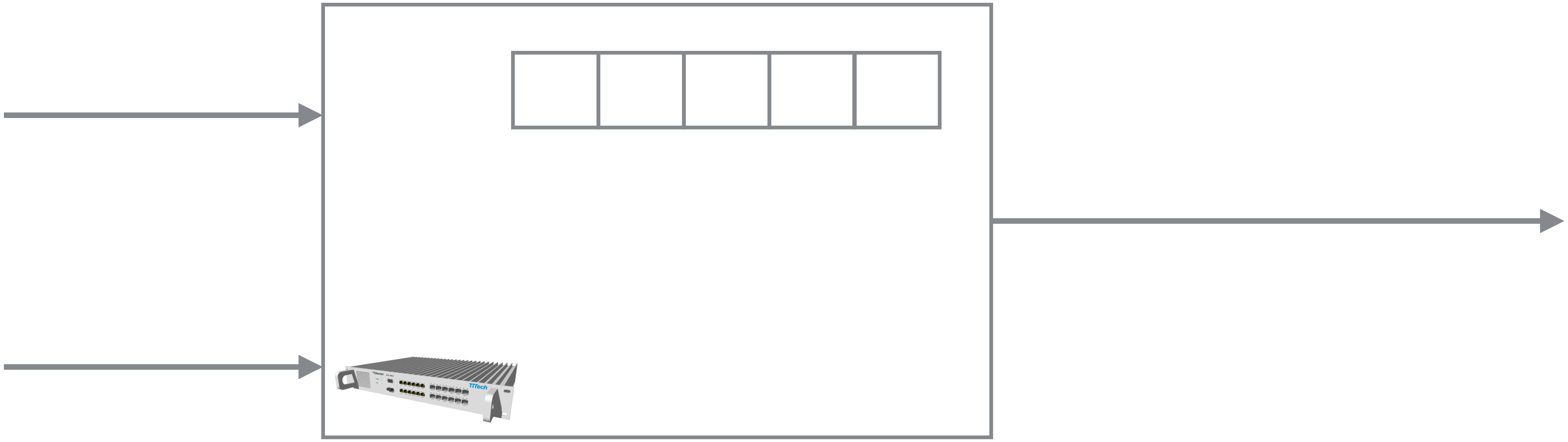


Queue Isolation

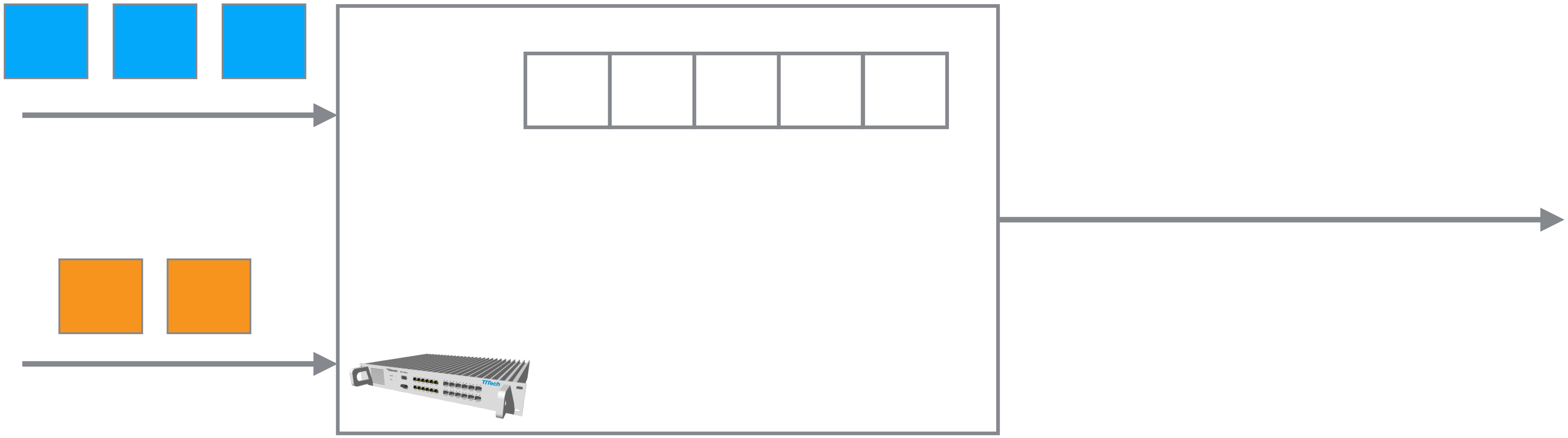


Solves the non-determinism problem but reduces the solution space

Stream (Flow) isolation

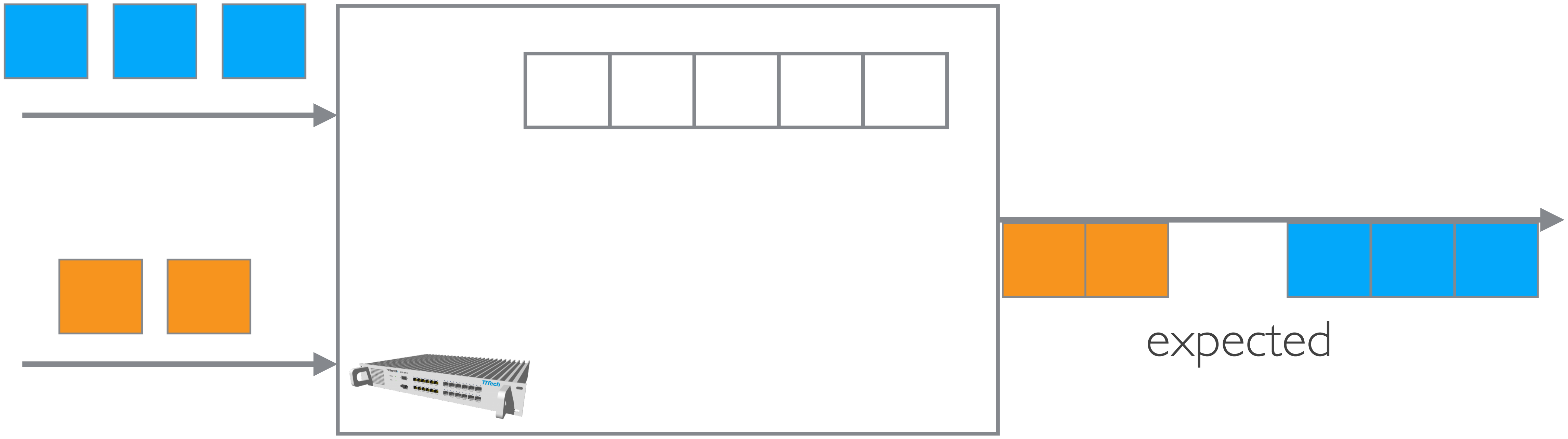


Stream (Flow) isolation

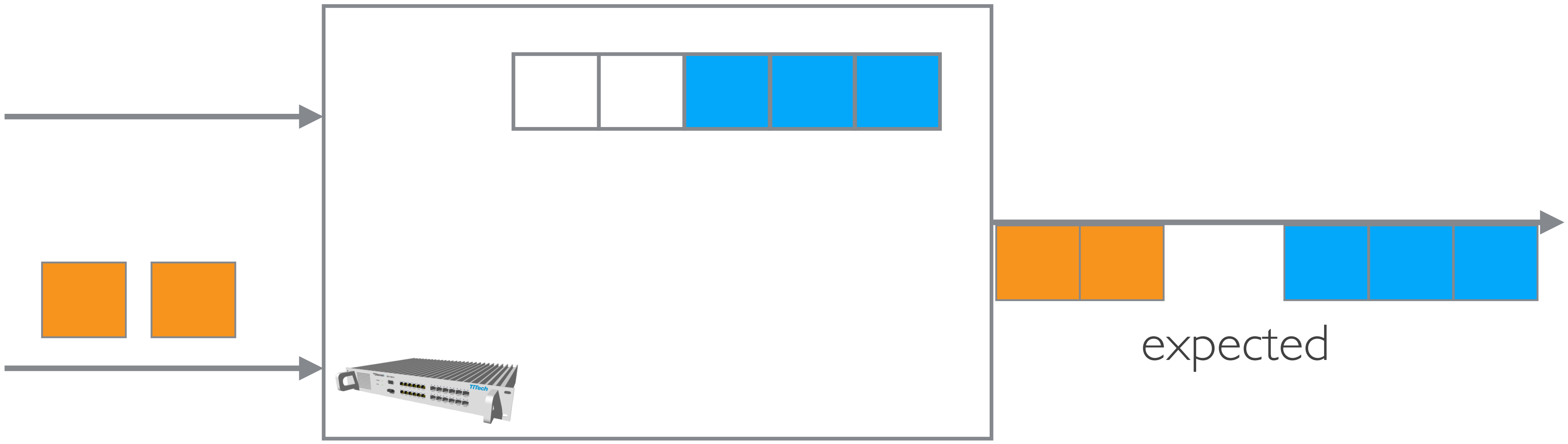


Stream (Flow) isolation

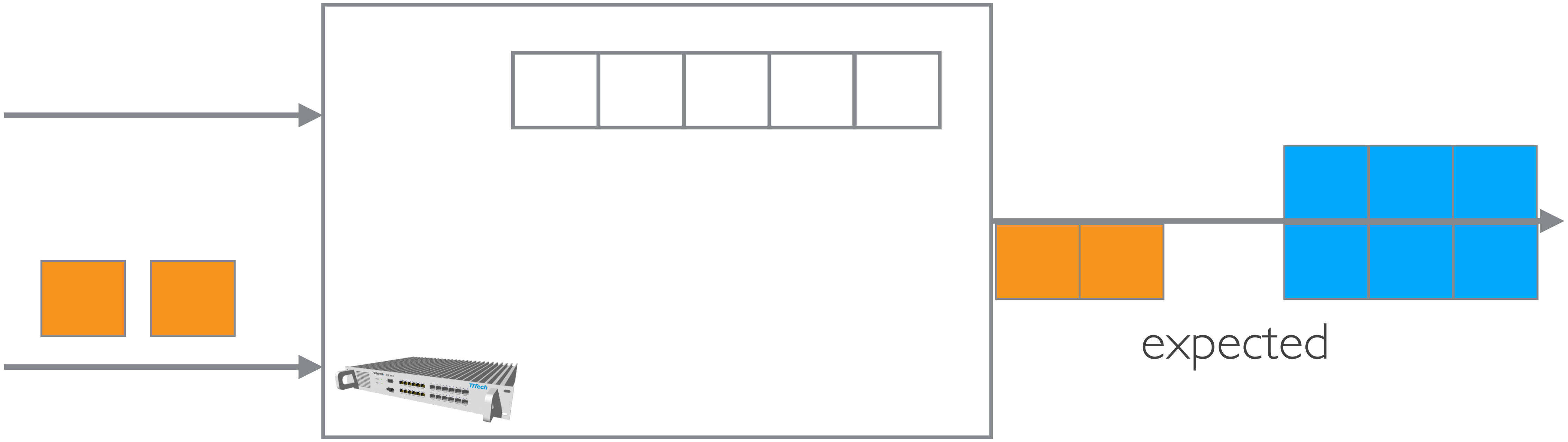
Ensuring Reliable Networks TTTech



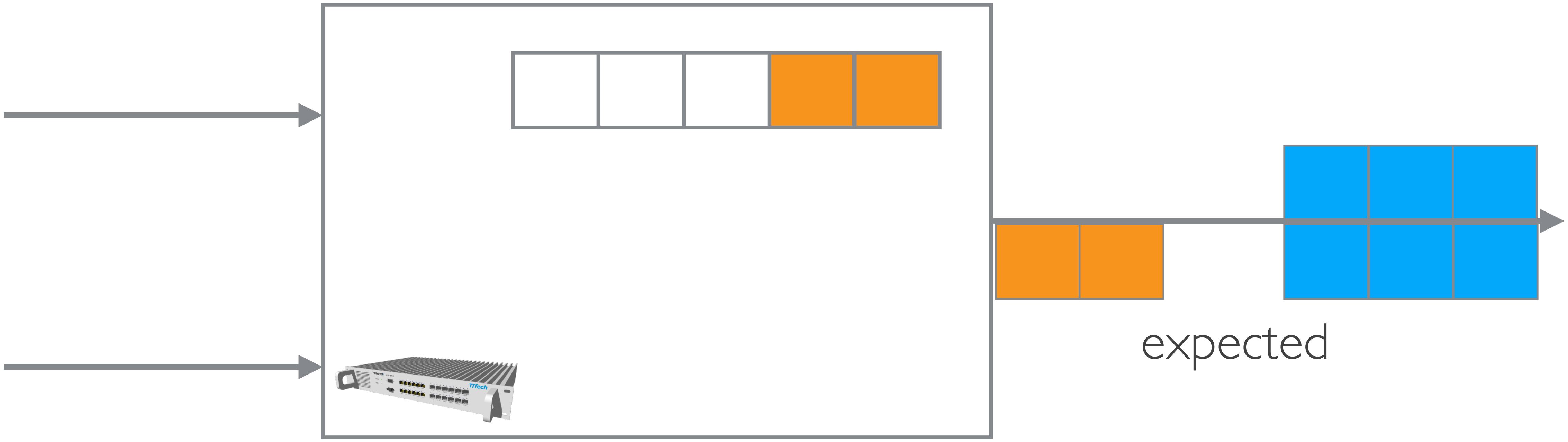
Stream (Flow) isolation



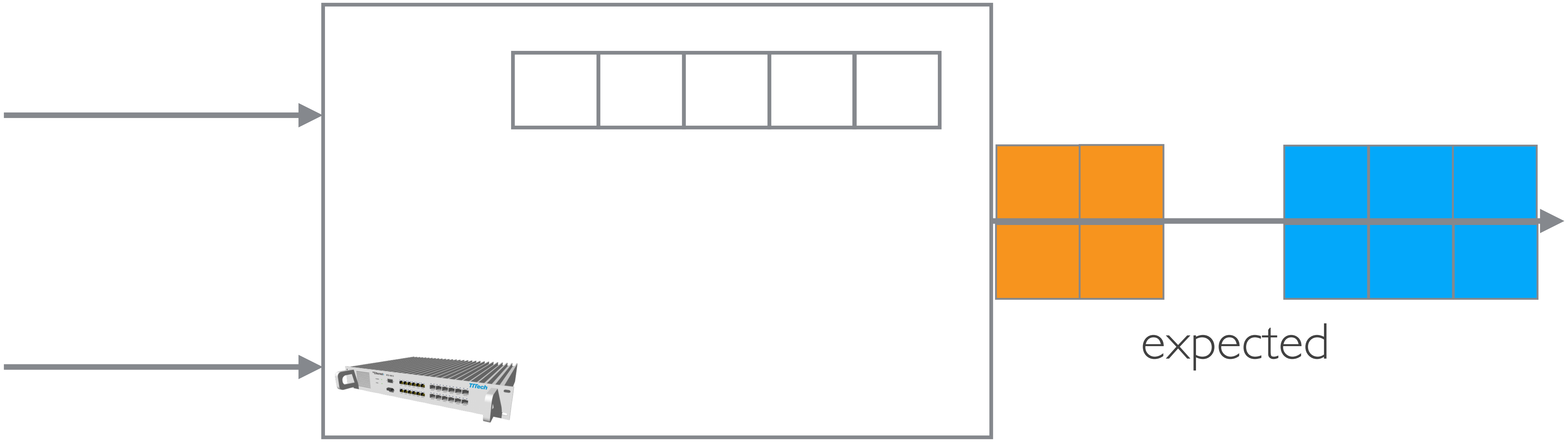
Stream (Flow) isolation



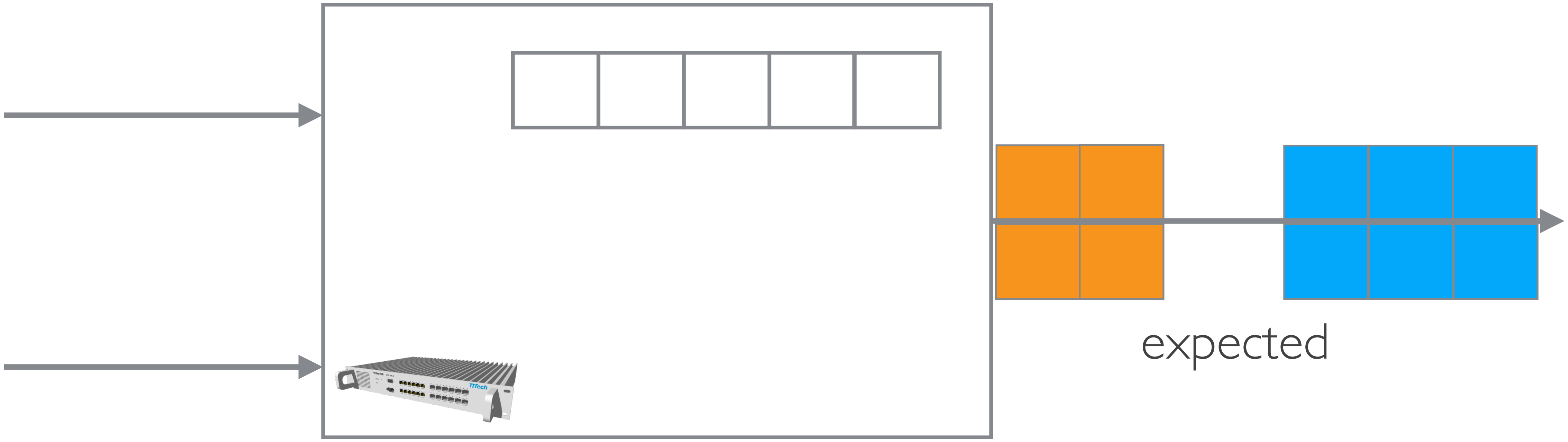
Stream (Flow) isolation



Stream (Flow) isolation

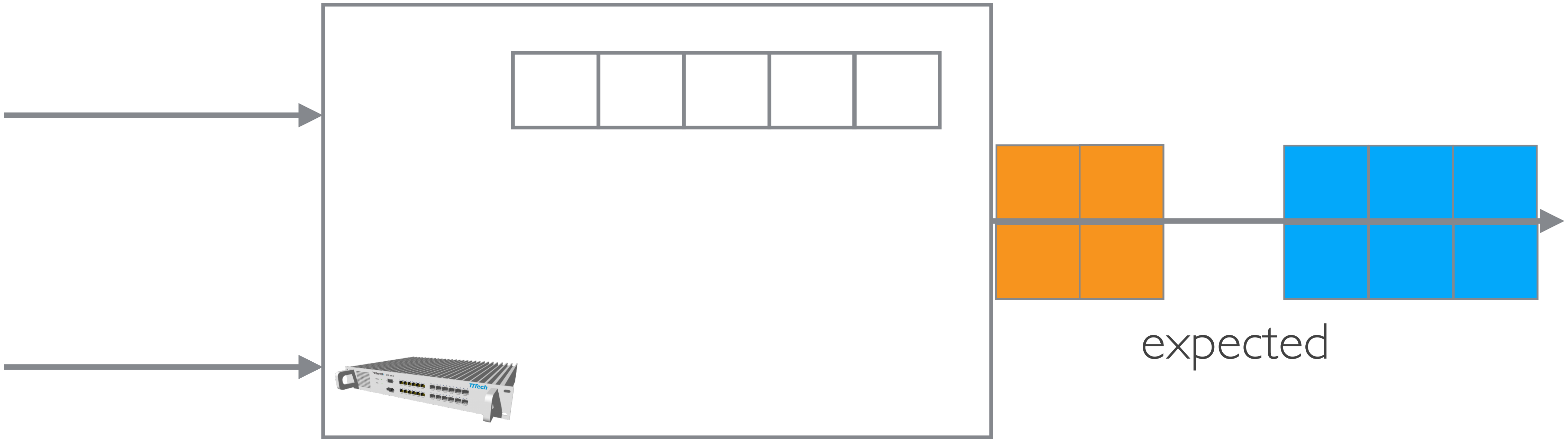


Stream (Flow) isolation

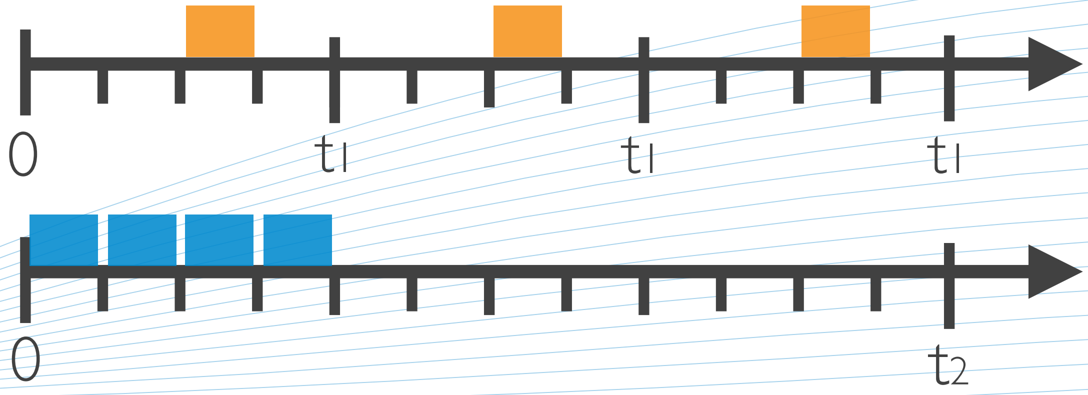


- Once a flow has arrived, no other flow can arrive in the same queue until the first flow has been completely sent
- Better than queue isolation but still restrictive

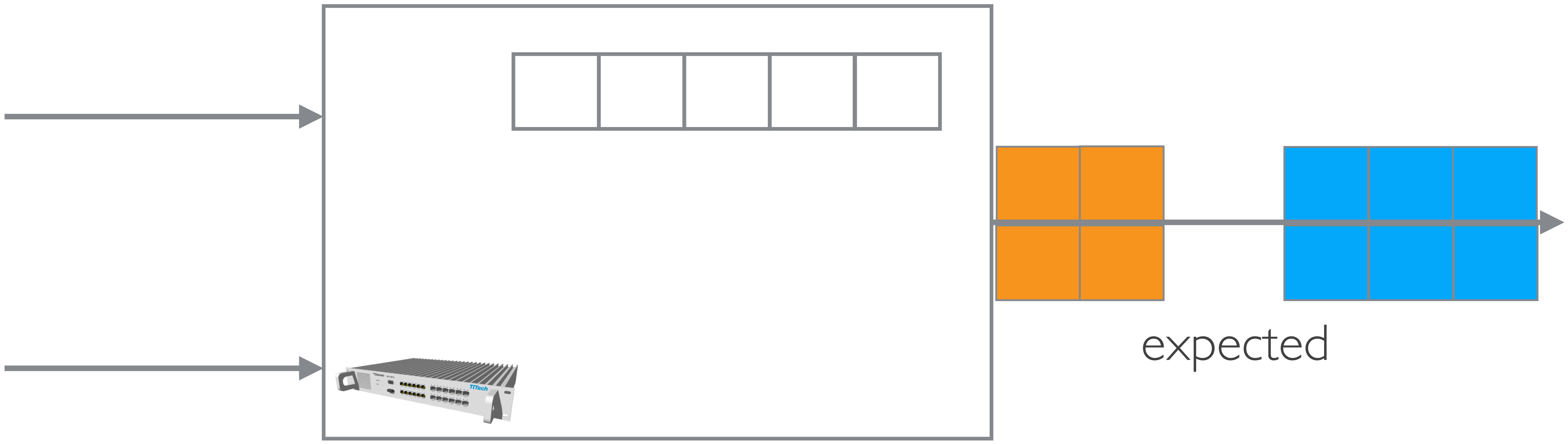
Stream (Flow) isolation



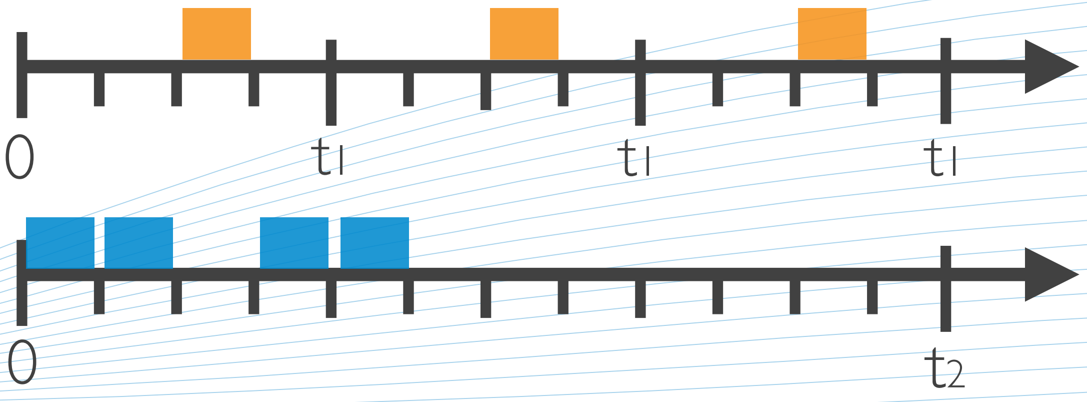
- Once a flow has arrived, no other flow can arrive in the same queue until the first flow has been completely sent
- Better than queue isolation but still restrictive



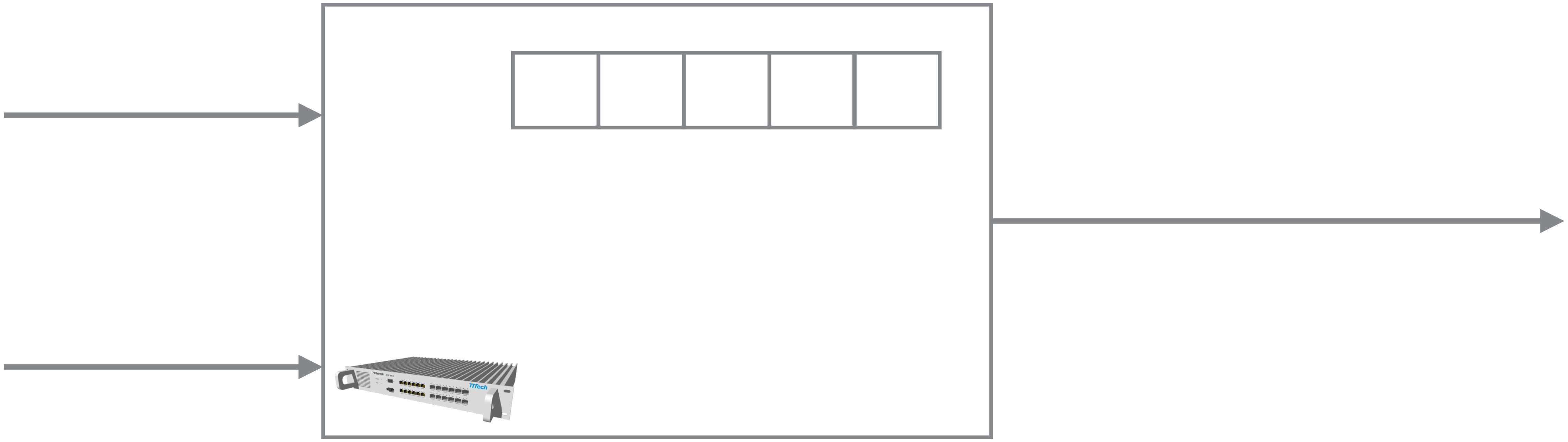
Stream (Flow) isolation



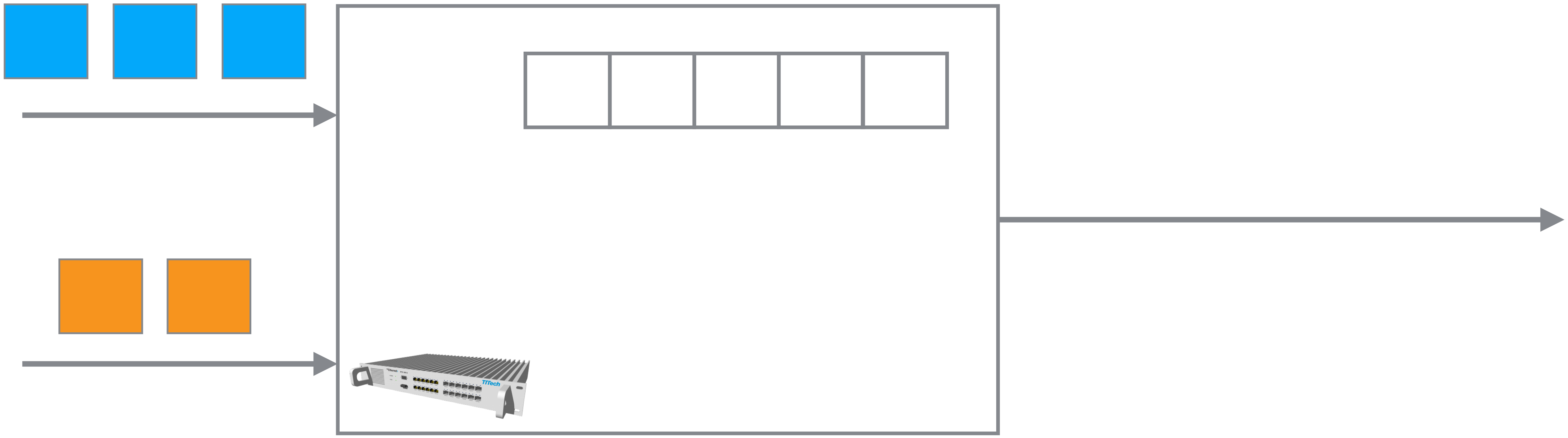
- Once a flow has arrived, no other flow can arrive in the same queue until the first flow has been completely sent
- Better than queue isolation but still restrictive



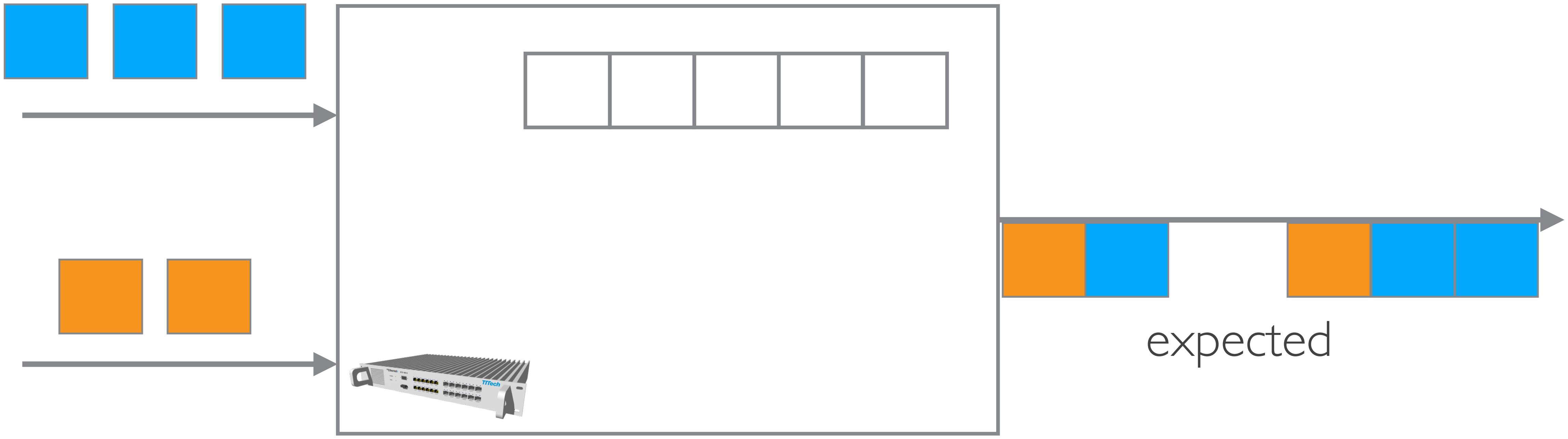
Frame isolation



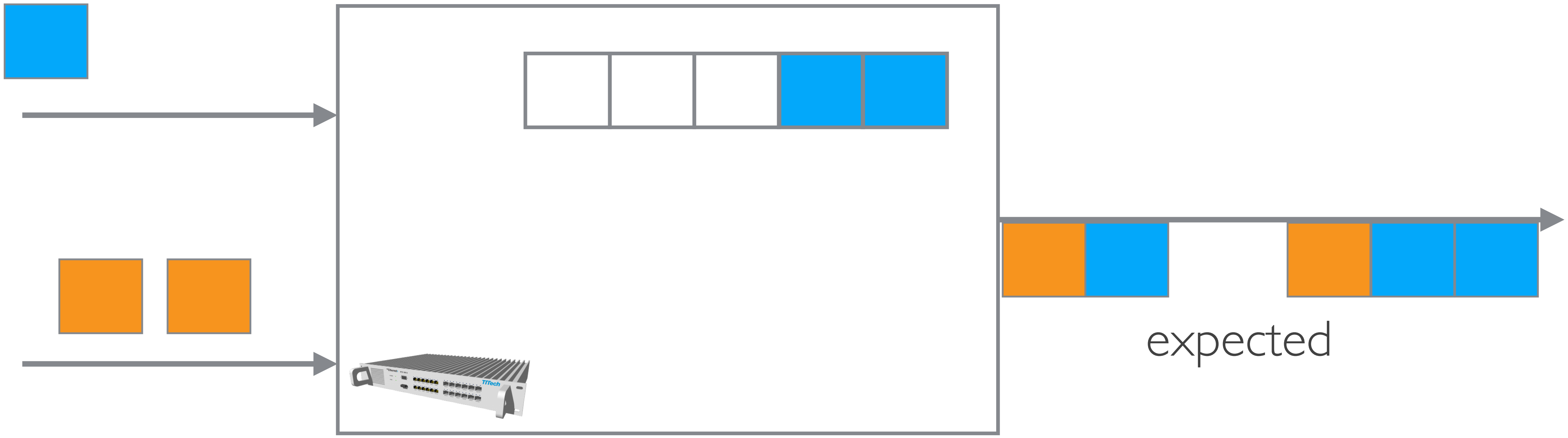
Frame isolation



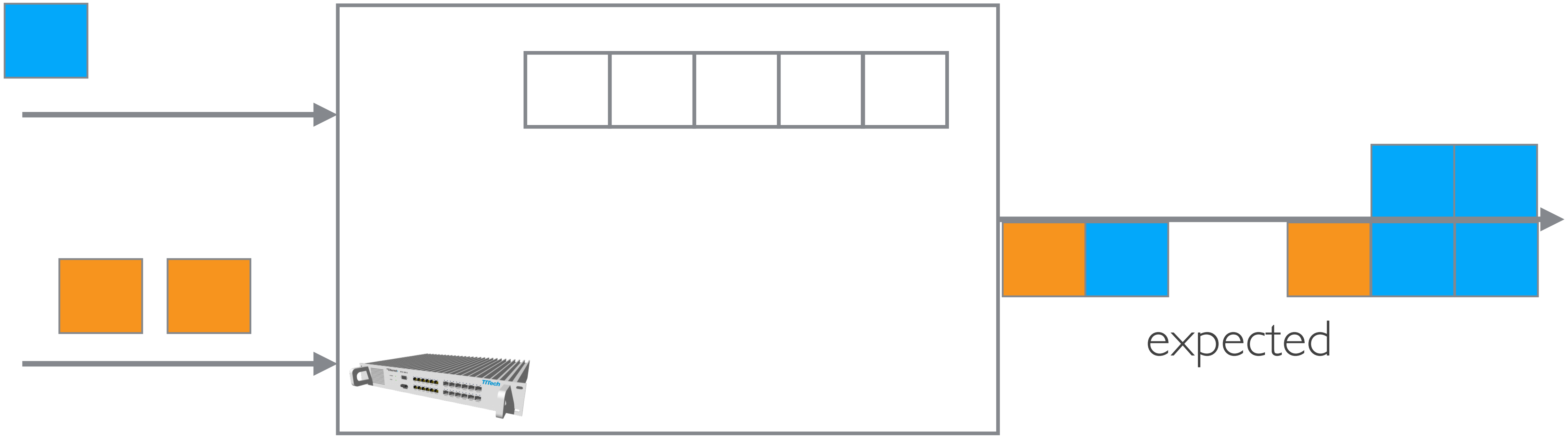
Frame isolation



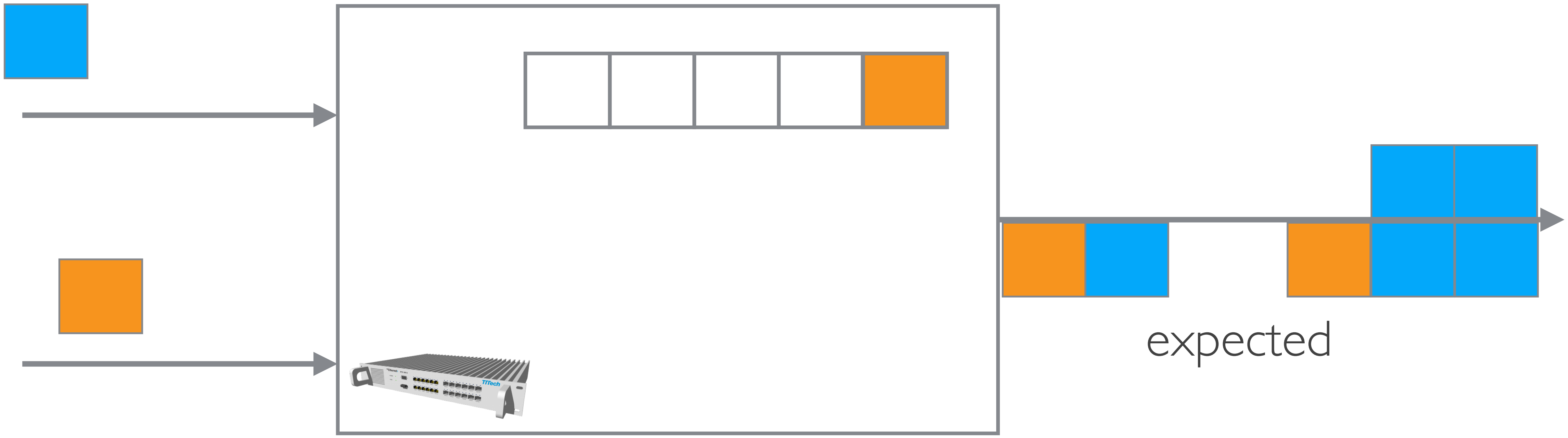
Frame isolation



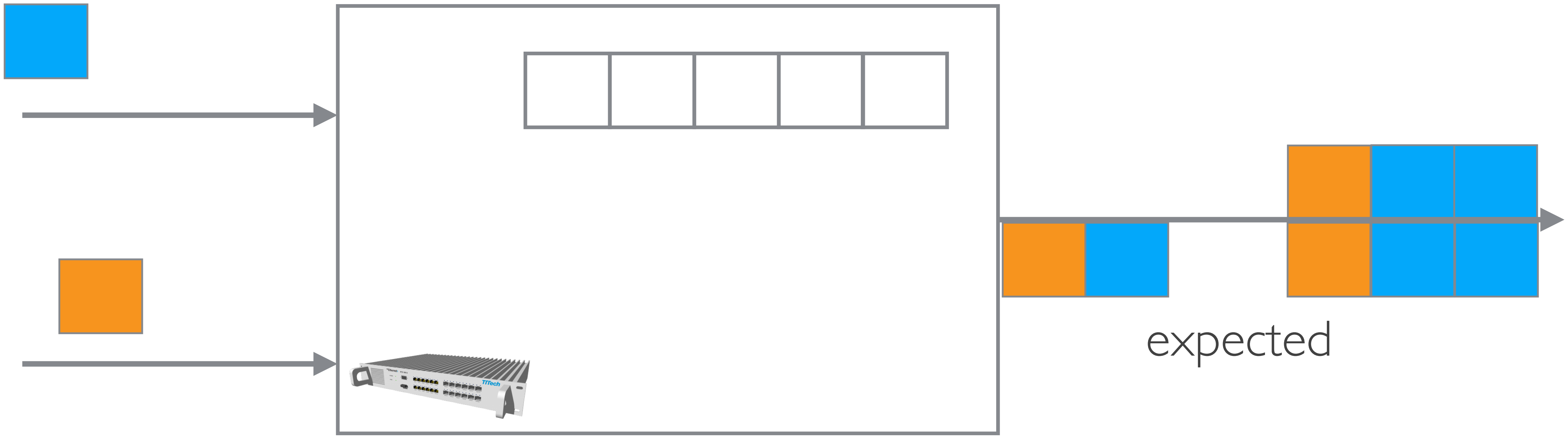
Frame isolation



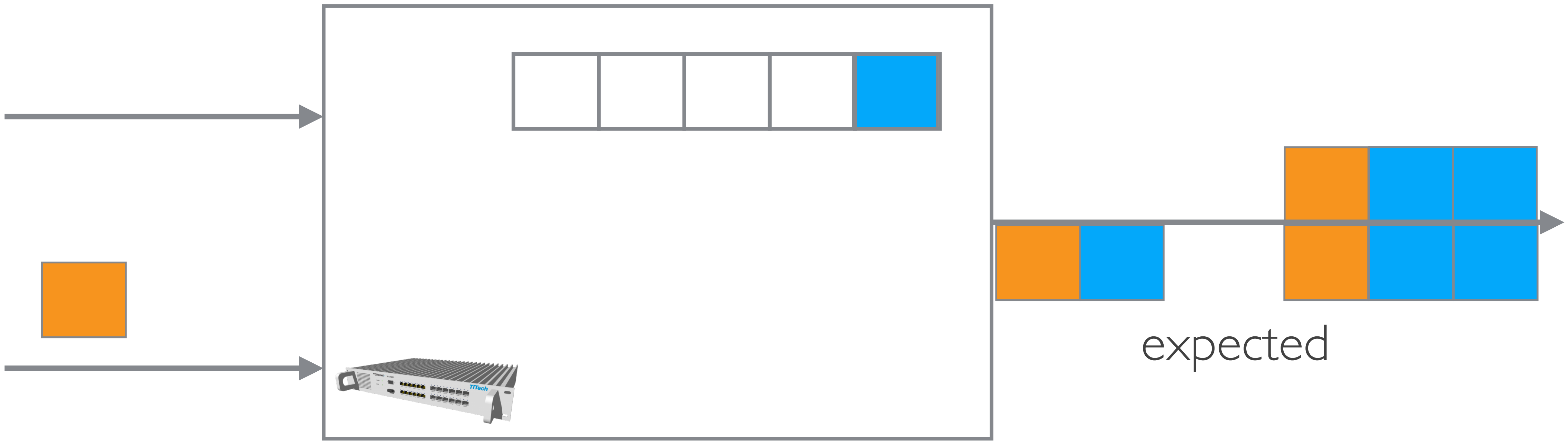
Frame isolation



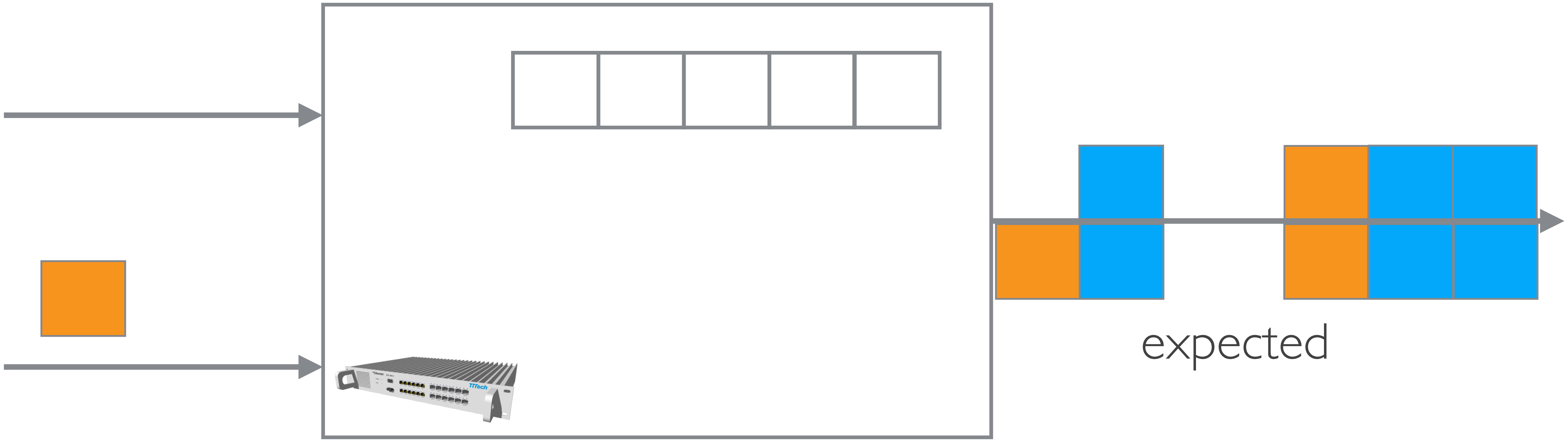
Frame isolation



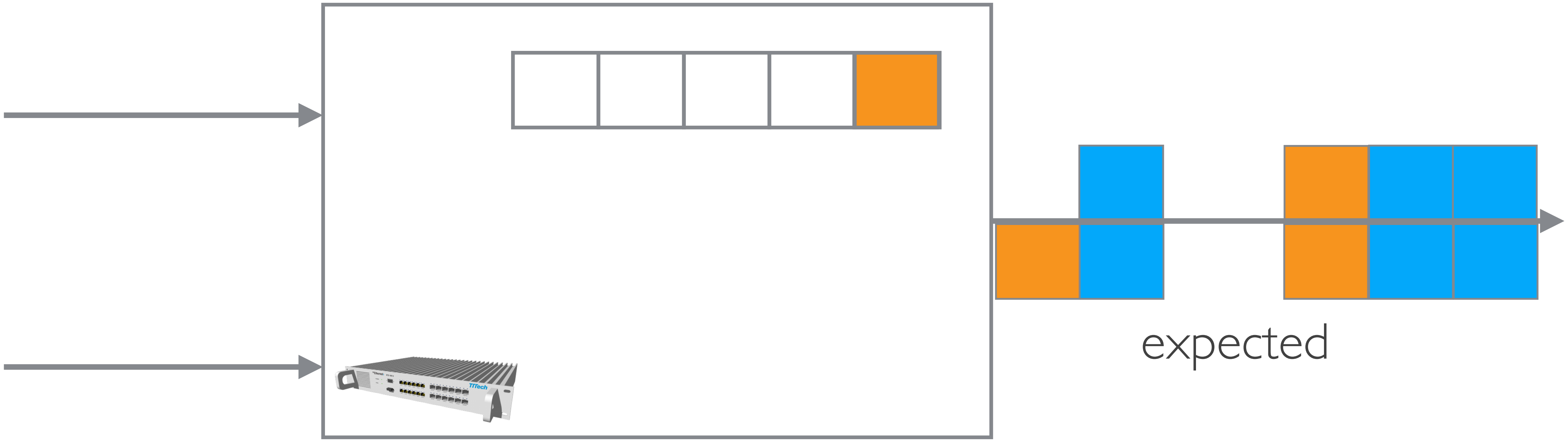
Frame isolation



Frame isolation

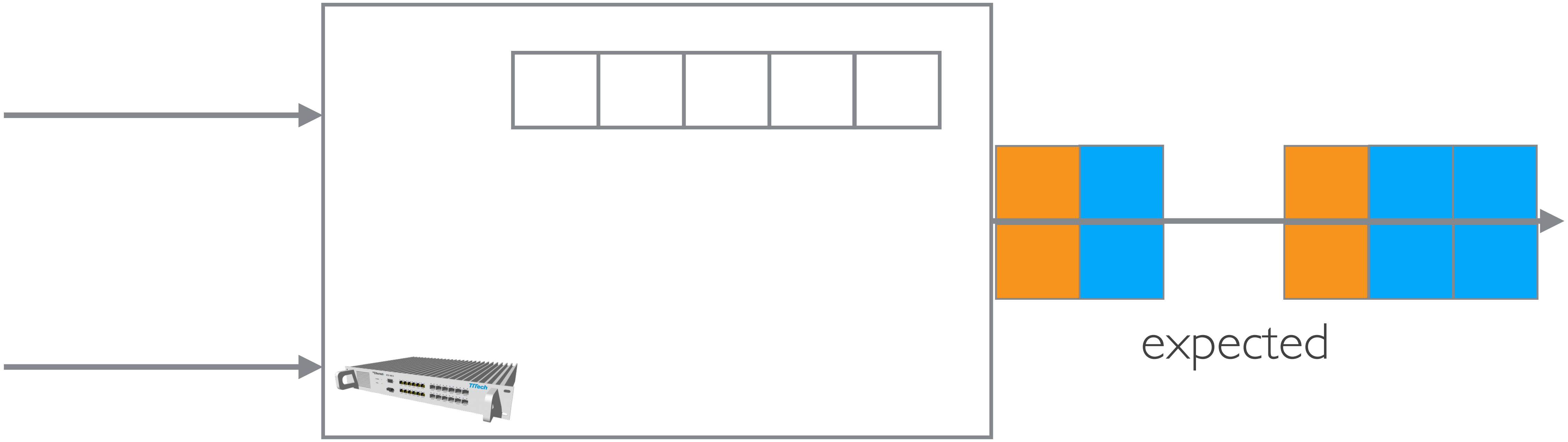


Frame isolation



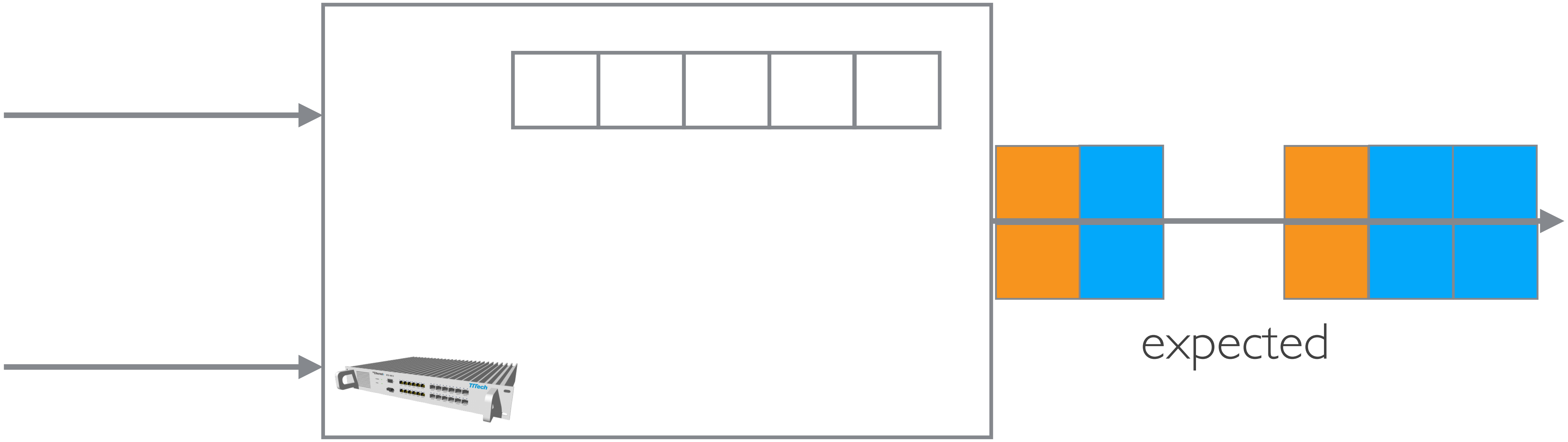
expected

Frame isolation



expected

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 at all frame interleavings

802.1Qbv scheduling constraint

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

isolate frames/streams 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

Scheduling problem

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

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** ⇨ 802.1Qbv

Scheduling problem

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

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** ⇨ 802.1Qbv

NP-complete

Satisfiability Modulo Theories

satisfiability of logical formulas in first-order formulation

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

variables $x_1, x_2, \ldots, x_n$

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]

Satisfiability Modulo Theories

satisfiability of logical formulas in first-order formulation

background theories $\boxed{\mathcal{LA}(\mathbb{Z})}\ \mathcal{BV}$

variables $x_1, x_2, \ldots, x_n$

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

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

quantifiers $\xcancel{\exists, \forall}$

optimization (OMT) [Bjørner@TACAS15]

A lot of solvers and a very active community

OpenSMT [Bruttomesso@TACAS10]

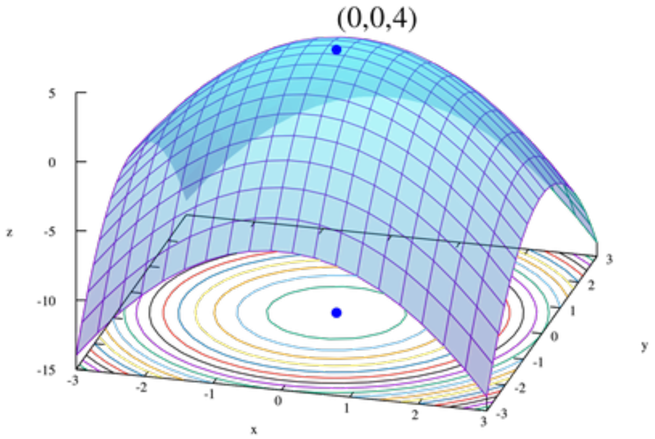
Yices [Dutertre@CAV14]

CVC4 [Barrett@CAV11]

Z3 [de Moura@TACAS08]

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

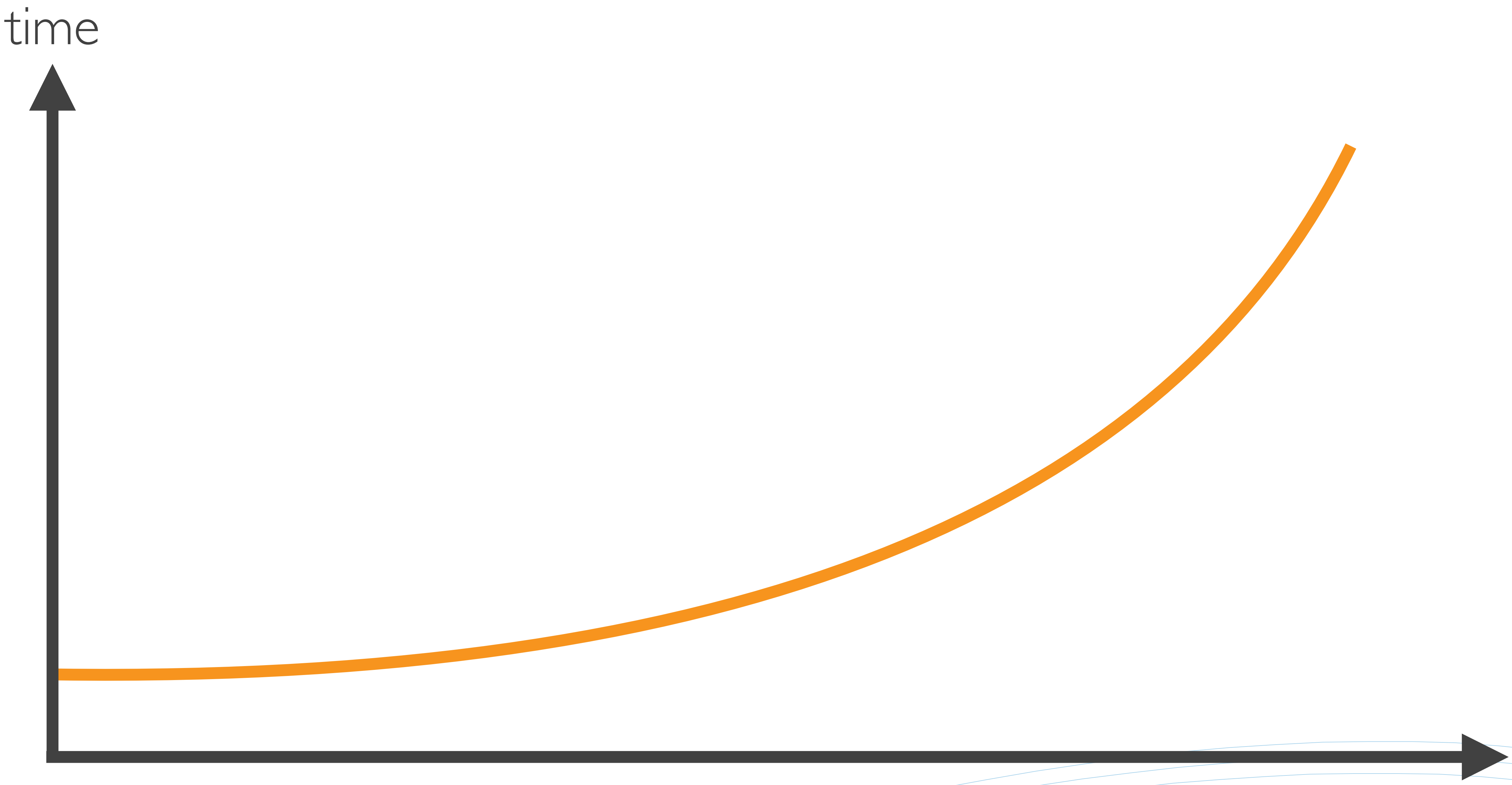
- **Z3** v4.4.1 solver (64bit) (Yices v2.4.2 with quantifier-free linear integer arithmetic)
- 64bit 4-core **3.40GHz** Intel Core-i7 PC with 4GB memory
- 3 predefined topologies ranging from 3 end-systems connected to one switch to 7 end-systems connected through 5 switches via **1Gbit/s** links with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

Scalability and schedulability experiments

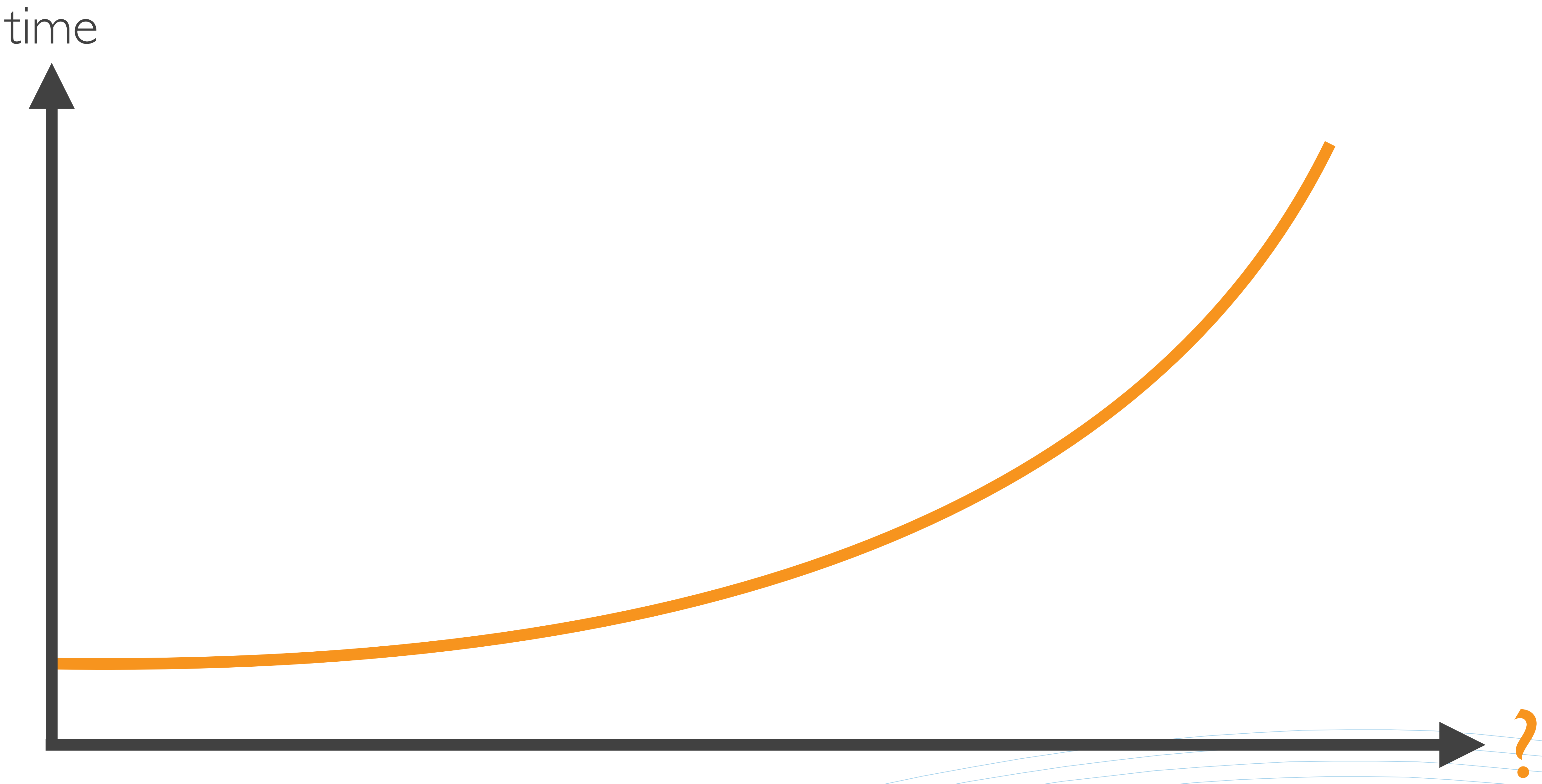
Evaluation

Evaluation

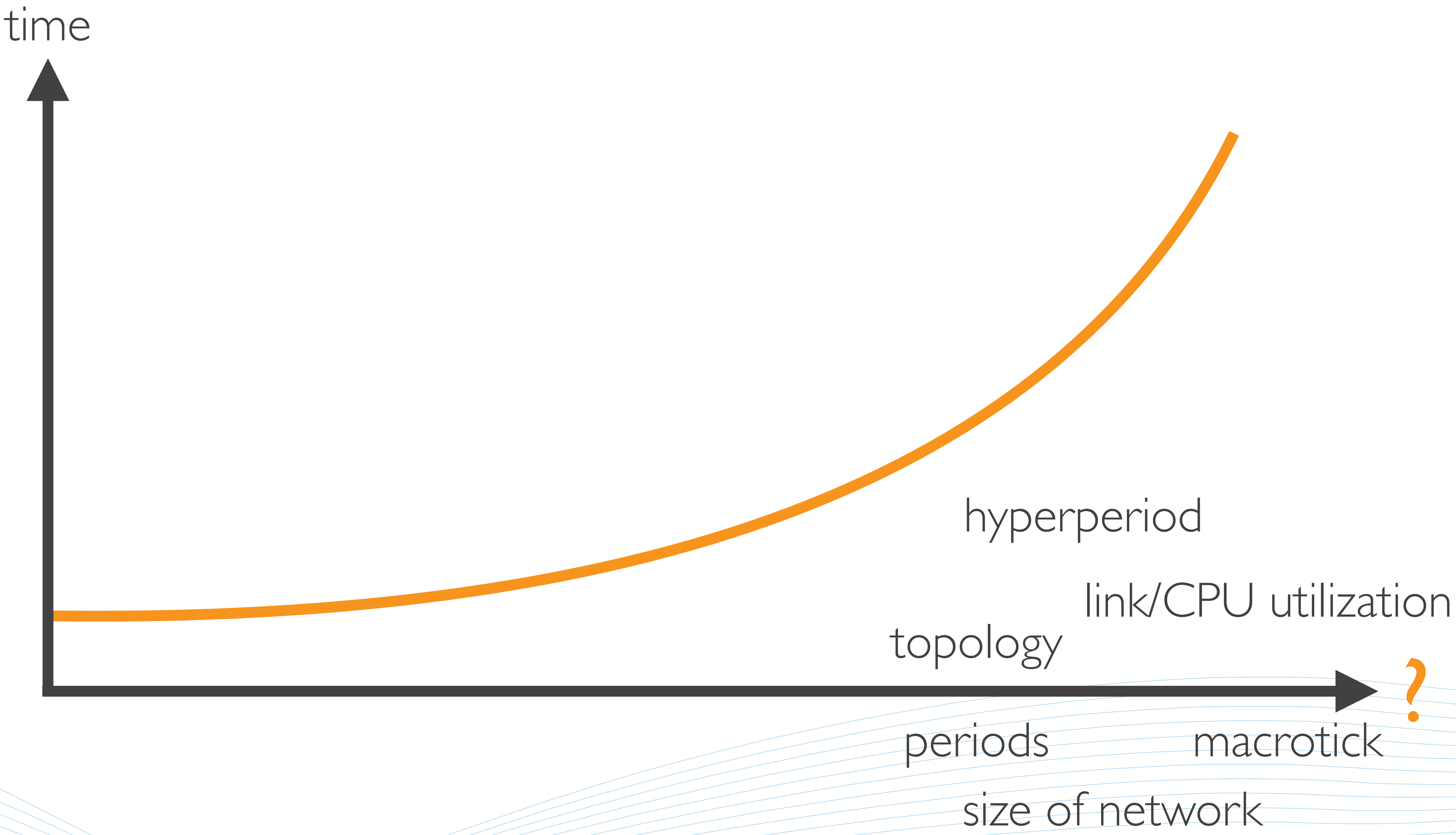
Evaluation



Evaluation



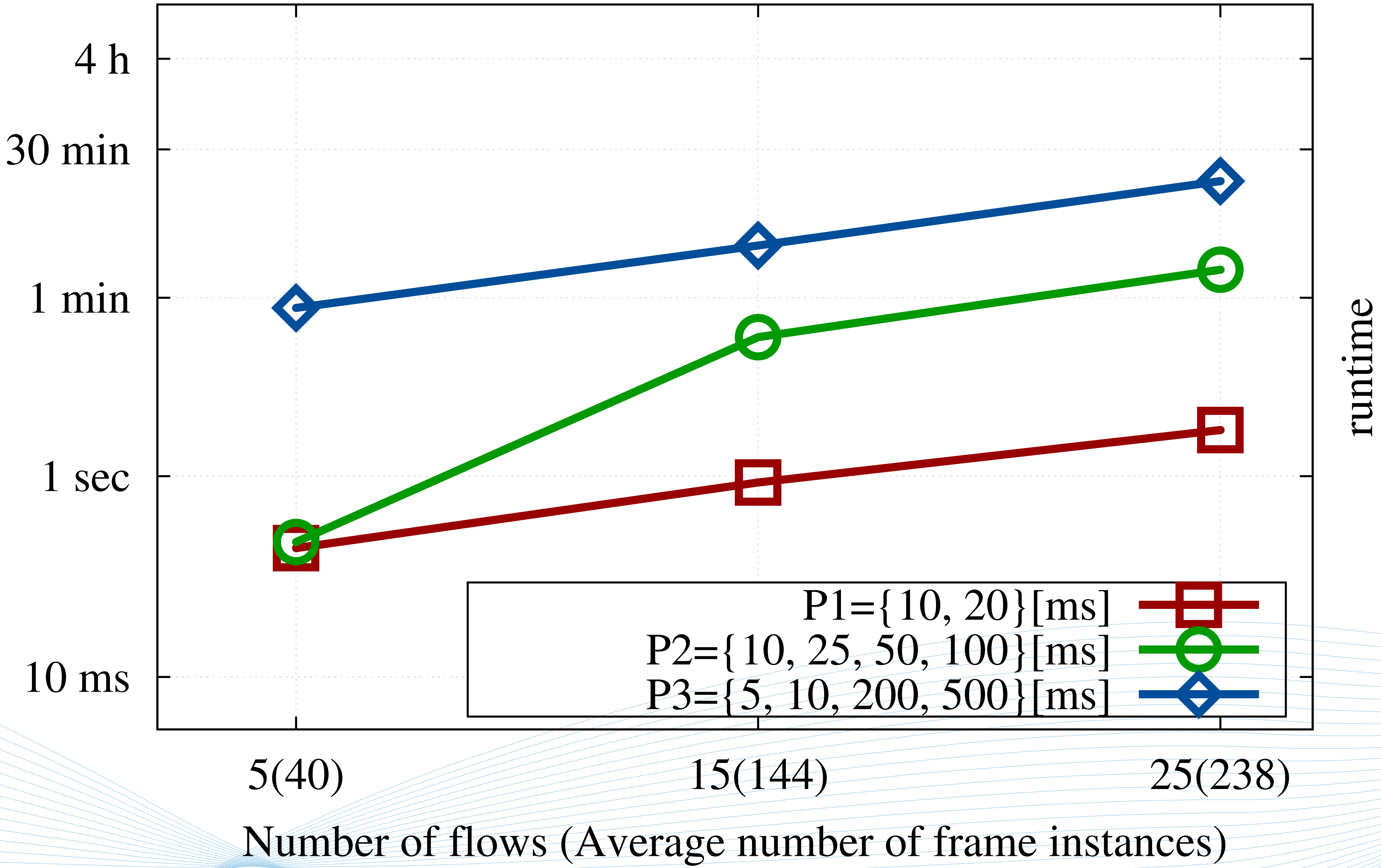
Evaluation


time
hyperperiod
link/CPU utilization
topology
?
periods
macrotick
size of network

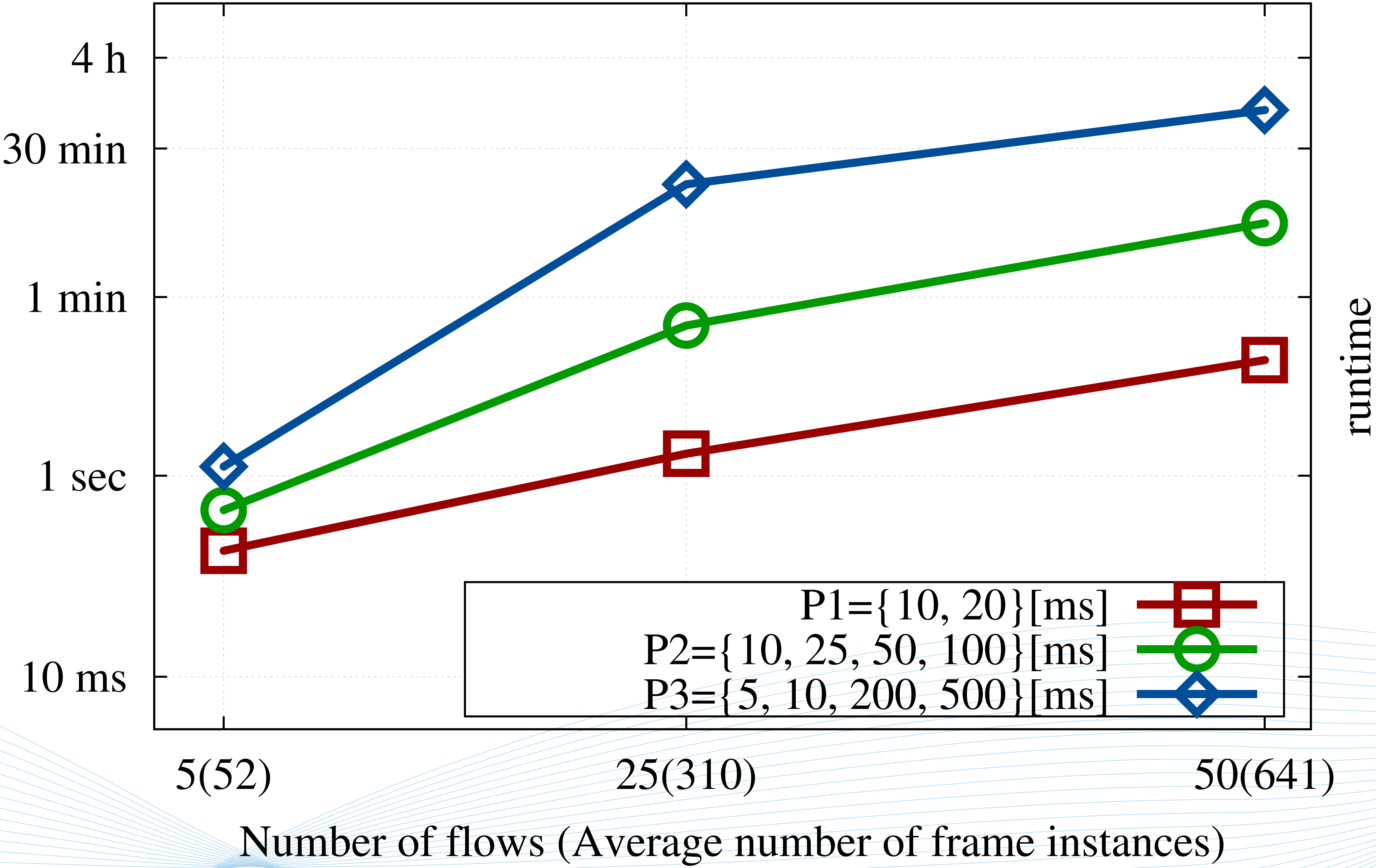
Scalability Experiments

- **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

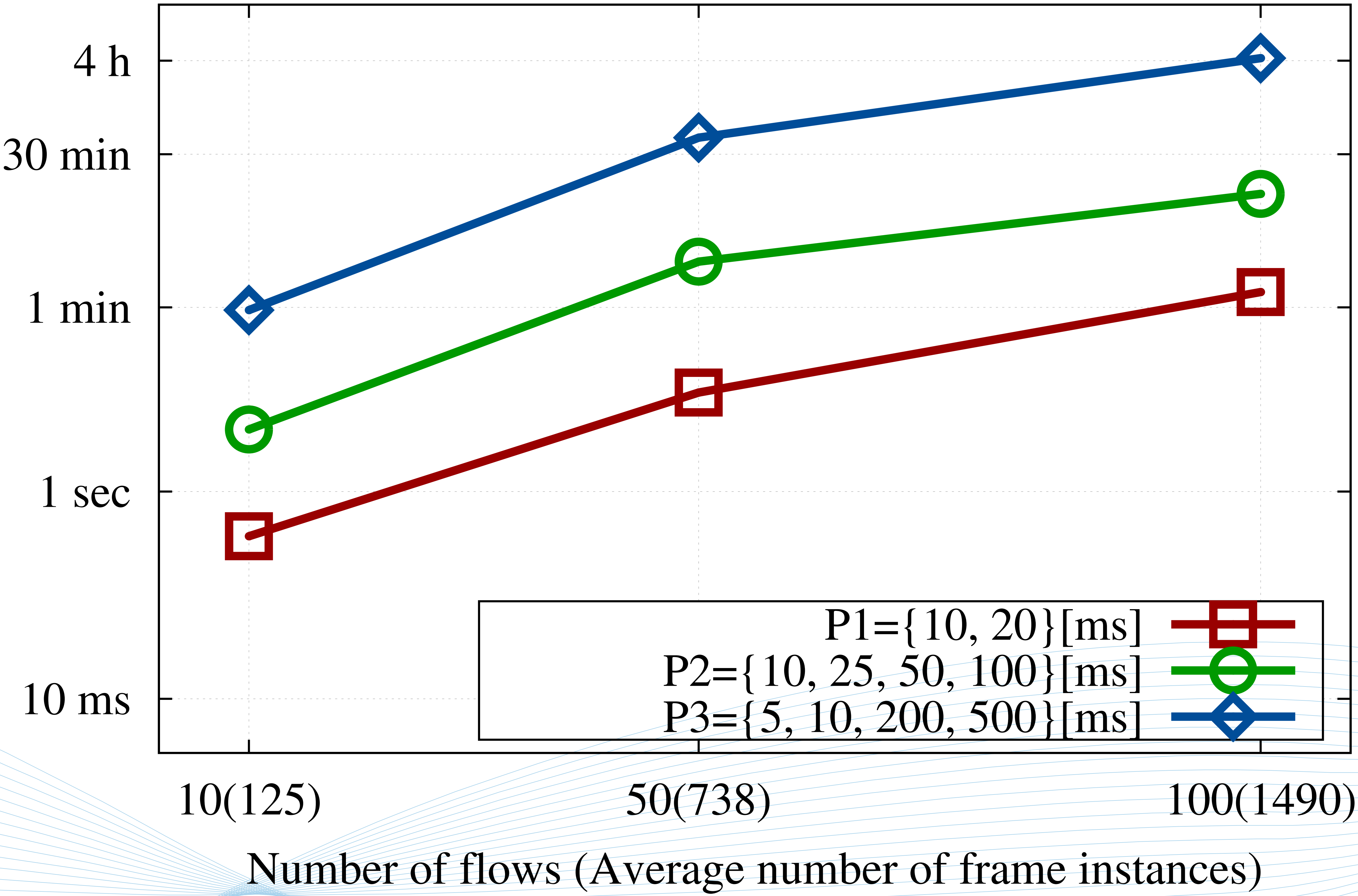


Scalability Experiments



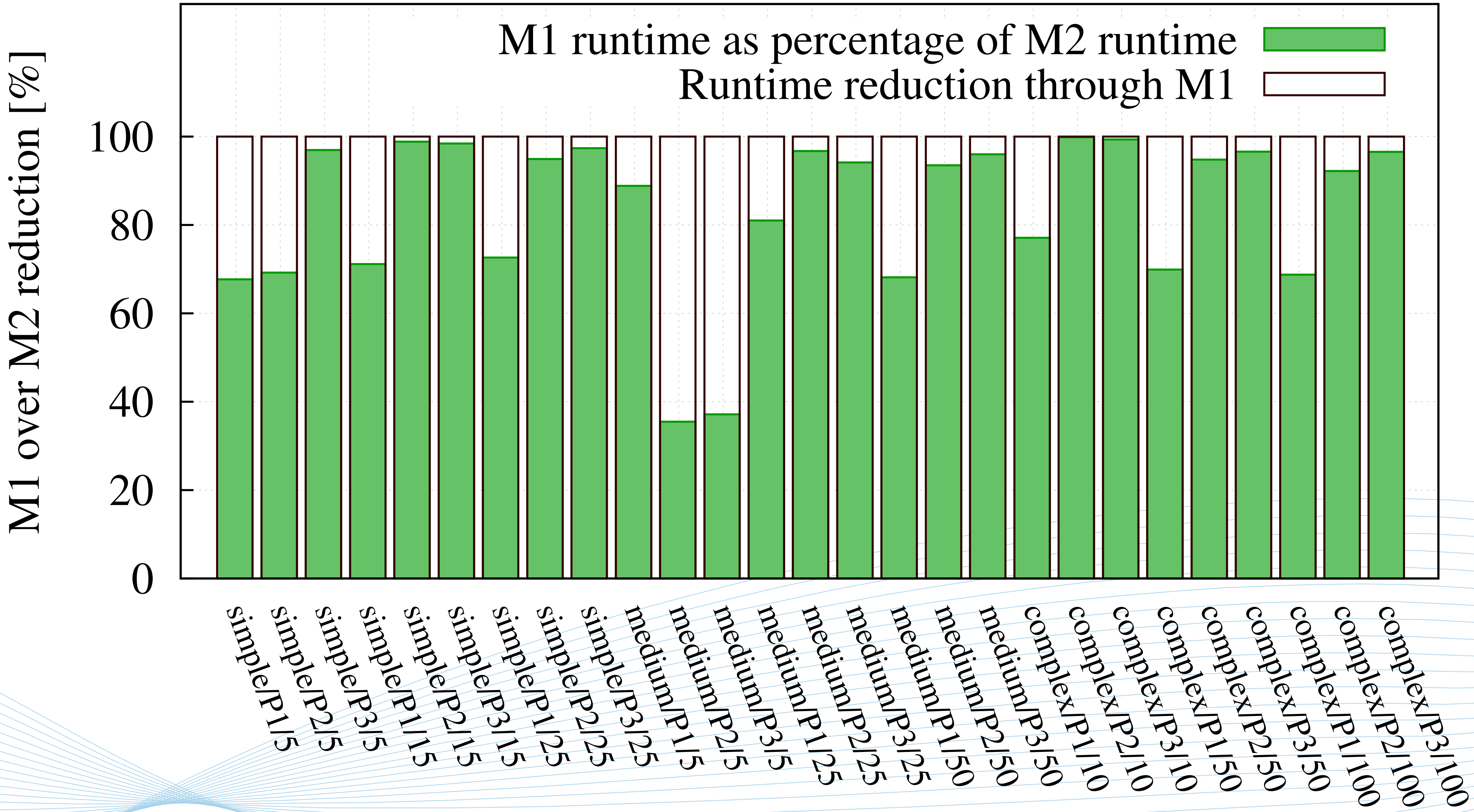
Scalability Experiments

Ensuring Reliable Networks TTTech



Frame vs. Stream Isolation

- **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

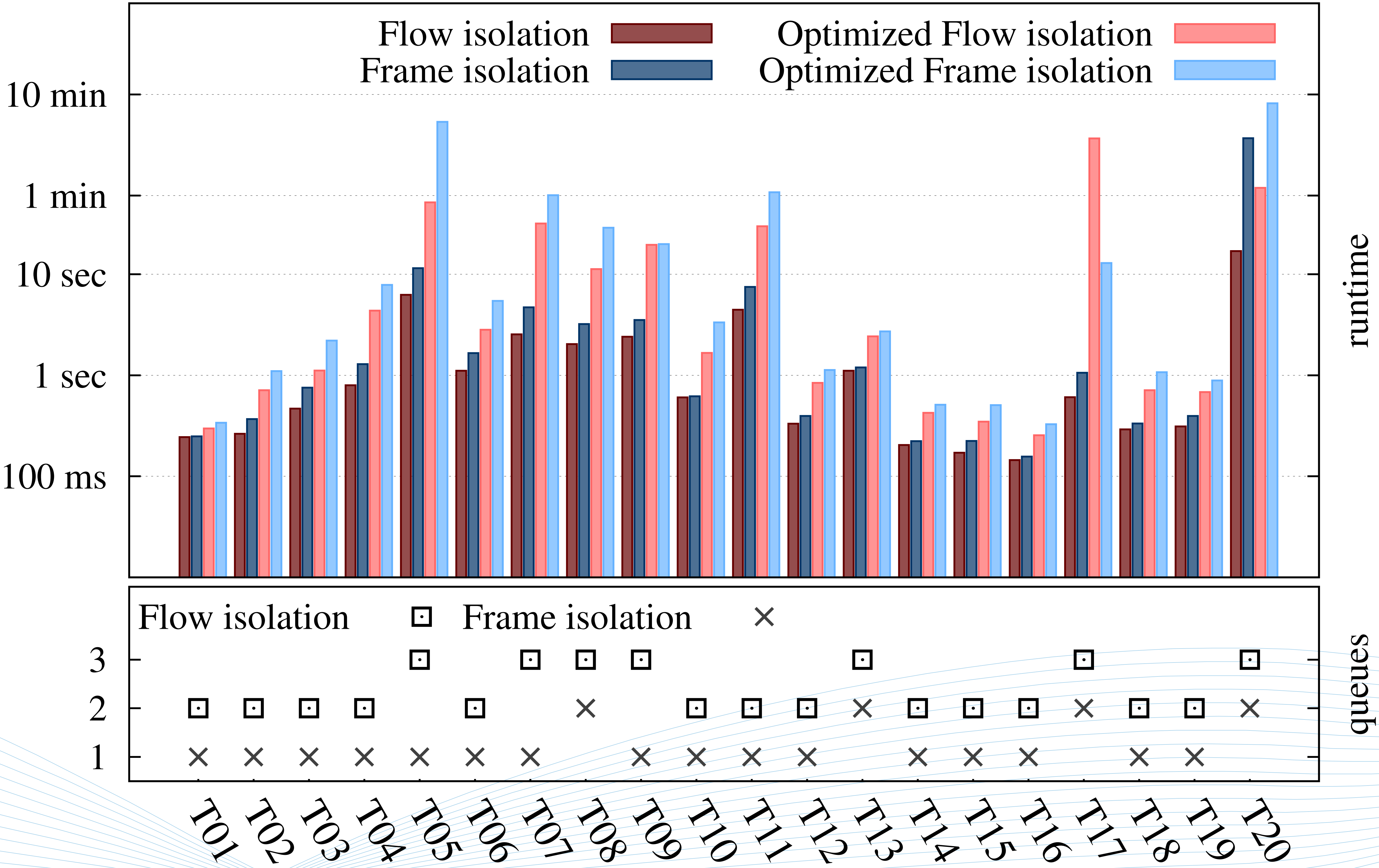


Schedulability Experiments

- 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

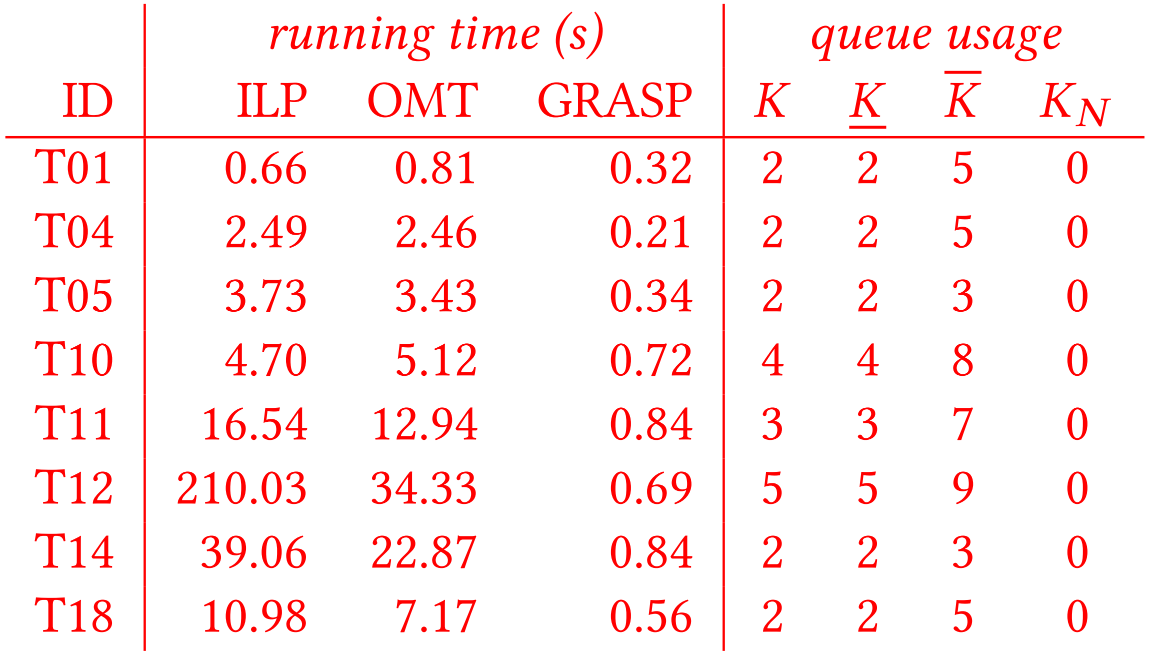
Ensuring Reliable Networks TTTech



Heuristics

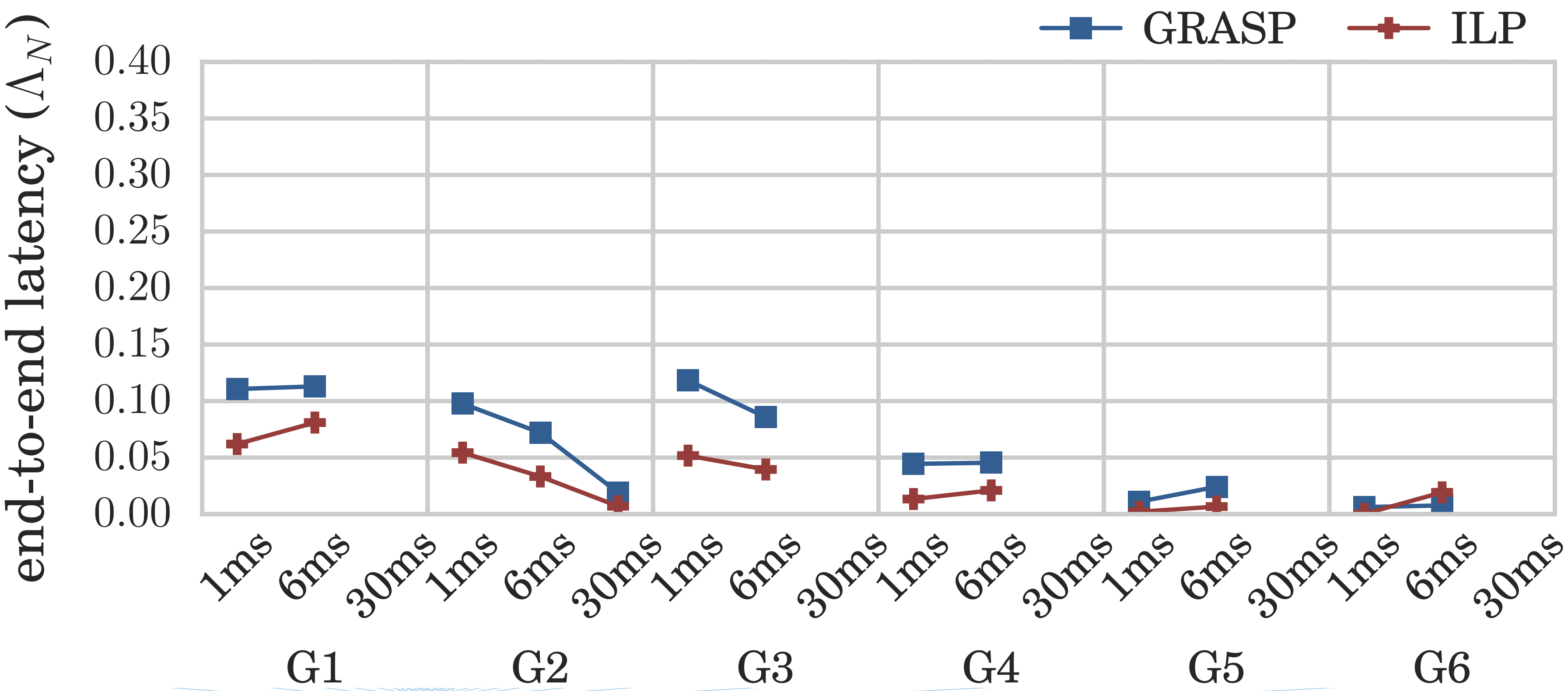
For large networks we have to use heuristics, e.g:

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



	running time (s)			*queue usage*			
ID	ILP	OMT	GRASP	K	$\underline{K}$	$\overline{K}$	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

Conclusions

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

Conclusions

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

- **key functional parameters** affecting the behaviour of 802.1Qbv networks

Conclusions

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

- **key functional parameters** affecting the behaviour of 802.1Qbv networks
- **802.1Qbv-specific constraints** for creating correct offline schedules guaranteeing **low and bounded jitter** as well as **deterministic end-to-end latencies** for critical traffic

Conclusions

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

- **key functional parameters** affecting the behaviour of 802.1Qbv networks
- **802.1Qbv-specific constraints** for creating correct offline schedules guaranteeing **low and bounded jitter** as well as **deterministic end-to-end latencies** for critical traffic
- use **SMT/OMT** solvers to create static schedules for 802.1Qbv devices

Conclusions

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

- **key functional parameters** affecting the behaviour of 802.1Qbv networks
- **802.1Qbv-specific constraints** for creating correct offline schedules guaranteeing **low and bounded jitter** as well as **deterministic end-to-end latencies** for critical traffic
- use **SMT/OMT** solvers to create static schedules for 802.1Qbv devices
- **optimization** directions & system **configurations** and their **trade-offs**

Conclusions

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

- **key functional parameters** affecting the behaviour of 802.1Qbv networks
- **802.1Qbv-specific constraints** for creating correct offline schedules guaranteeing **low and bounded jitter** as well as **deterministic end-to-end latencies** for critical traffic
- use **SMT/OMT** solvers to create static schedules for 802.1Qbv devices
- **optimization** directions & system **configurations** and their **trade-offs**
- **evaluation** in terms of scalability and schedulability

References and further reading

[1] S.S. Craciunas, R. Serna Oliver, M. Chmelík, and W. Steiner - Scheduling Real-Time Communication in IEEE 802.1Qbv Time Sensitive Networks. In Proc. RTNS 2014

[2] M.L. Raagaard, P. Pop, S.S. Craciunas - GRASP-based Gate-Control List Synthesis for IEEE Time-Sensitive Networks (TSN). (to be published)

[3] S.S. Craciunas and R. Serna Oliver - Combined task- and network- level scheduling for distributed time-triggered systems. Real-Time Systems 52, no 2, 2016, 161–200.

[4] P. Pop, M.L. Raagaard, S.S. Craciunas, and W. Steiner - Design Optimization of Cyber-Physical Distributed Systems using IEEE time- sensitive Networks (TSN). IET Cyber-Physical Systems: Theory & Applications 1, 1 (2016), 86–94.

[5] W. Steiner - An evaluation of SMT-based schedule synthesis for time-triggered multi-hop networks. In Real-Time Systems Symposium. 375–384. 2010

[6] D. Tamas-Selicean, P. Pop, and W. Steiner - Design optimization of TTEthernet-based distributed real-time systems. Real-Time Systems 51, (2015), 1–35.

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

Thank you!

TTTech

Ensuring Reliable Networks

www.tttech.com