Ensuring Reliable Networks TTTech

Scheduling Real-Time Communication in IEEE 802.1Qbv Time Sensitive Networks

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TTTech Computertechnik AG

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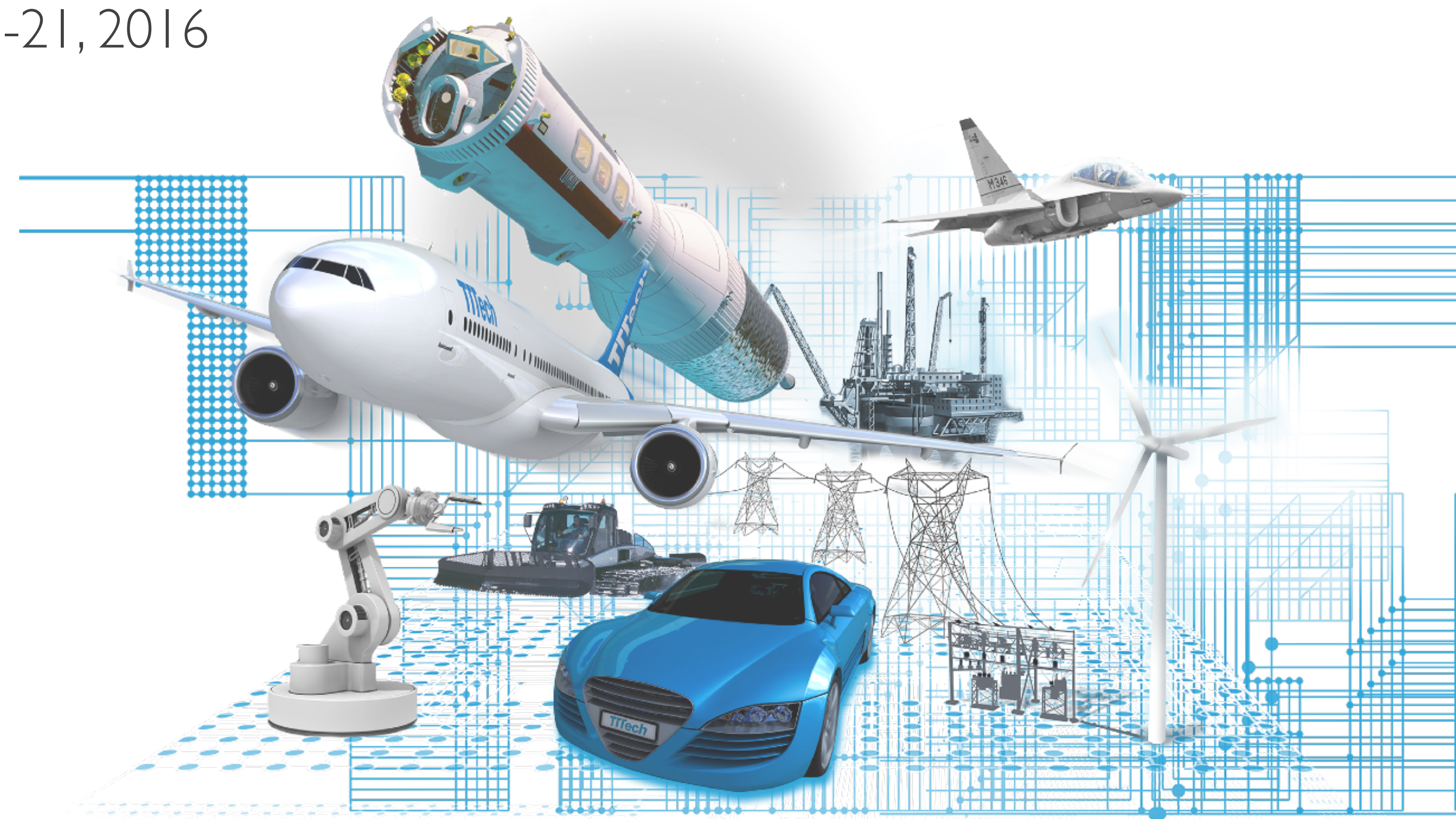

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Why TSN?

Ensuring Reliable Networks

Time-Sensitive Networks

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IEEE TSN task group - collection of sub-standards that enhance 802 Ethernet with fully deterministic 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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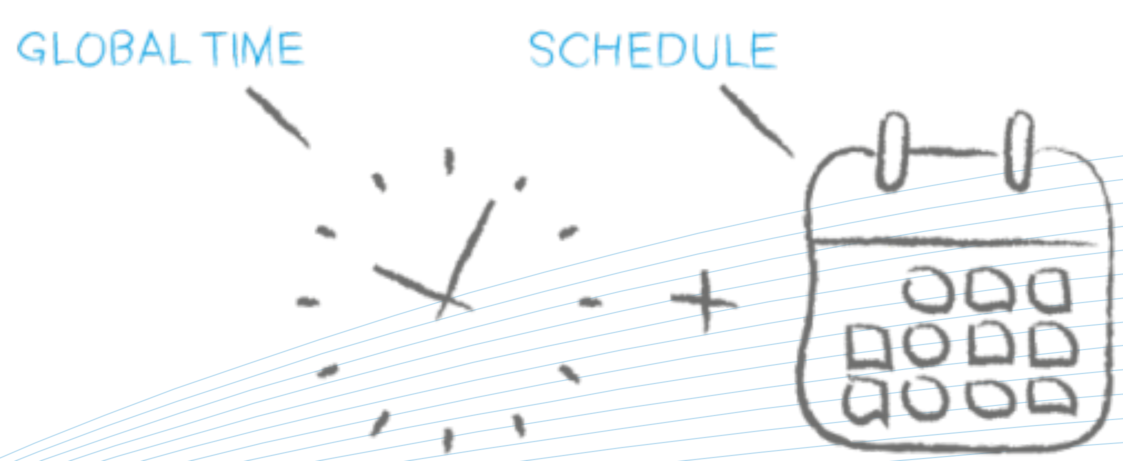

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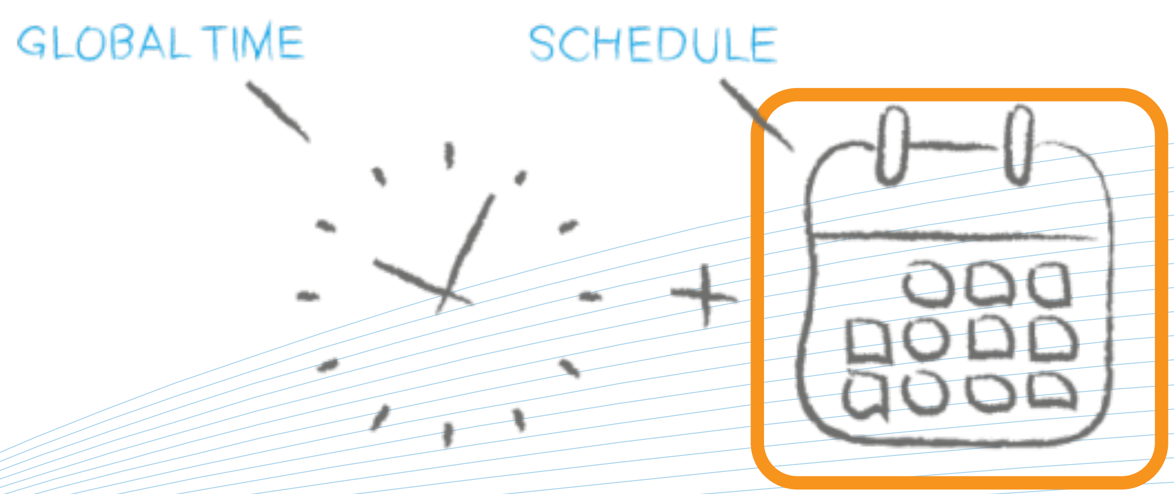
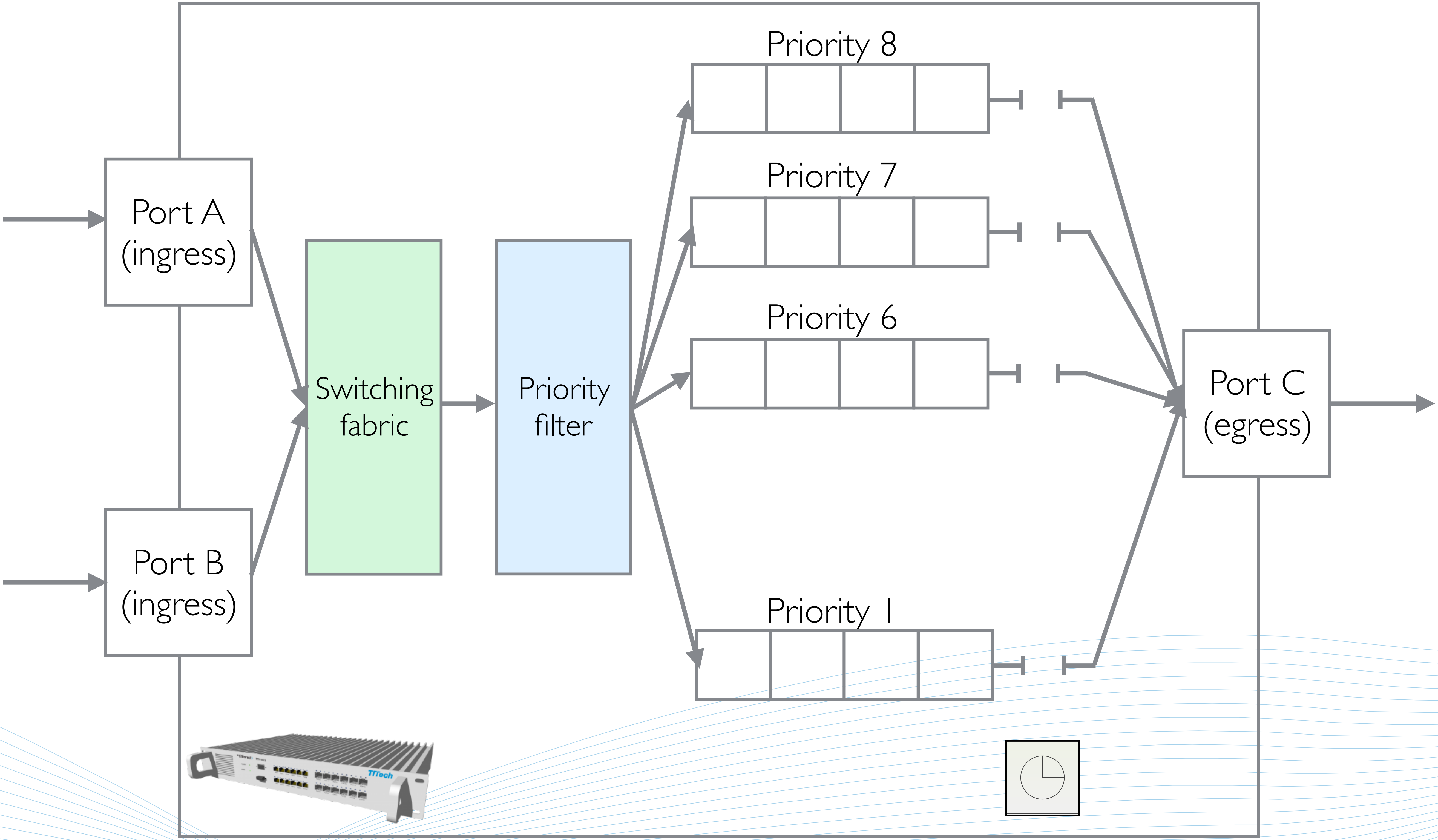


IEEE 802.1Qbv



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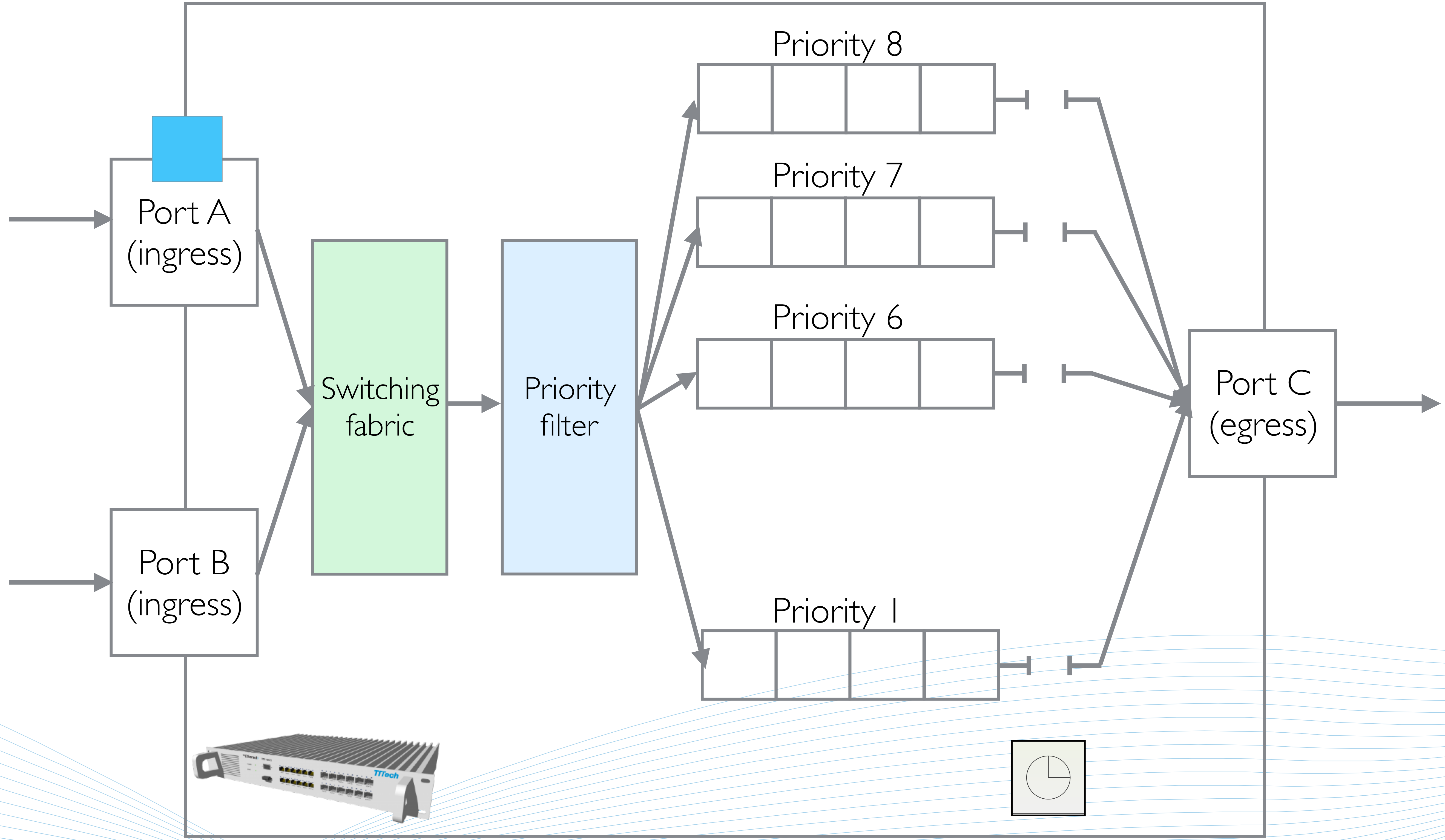

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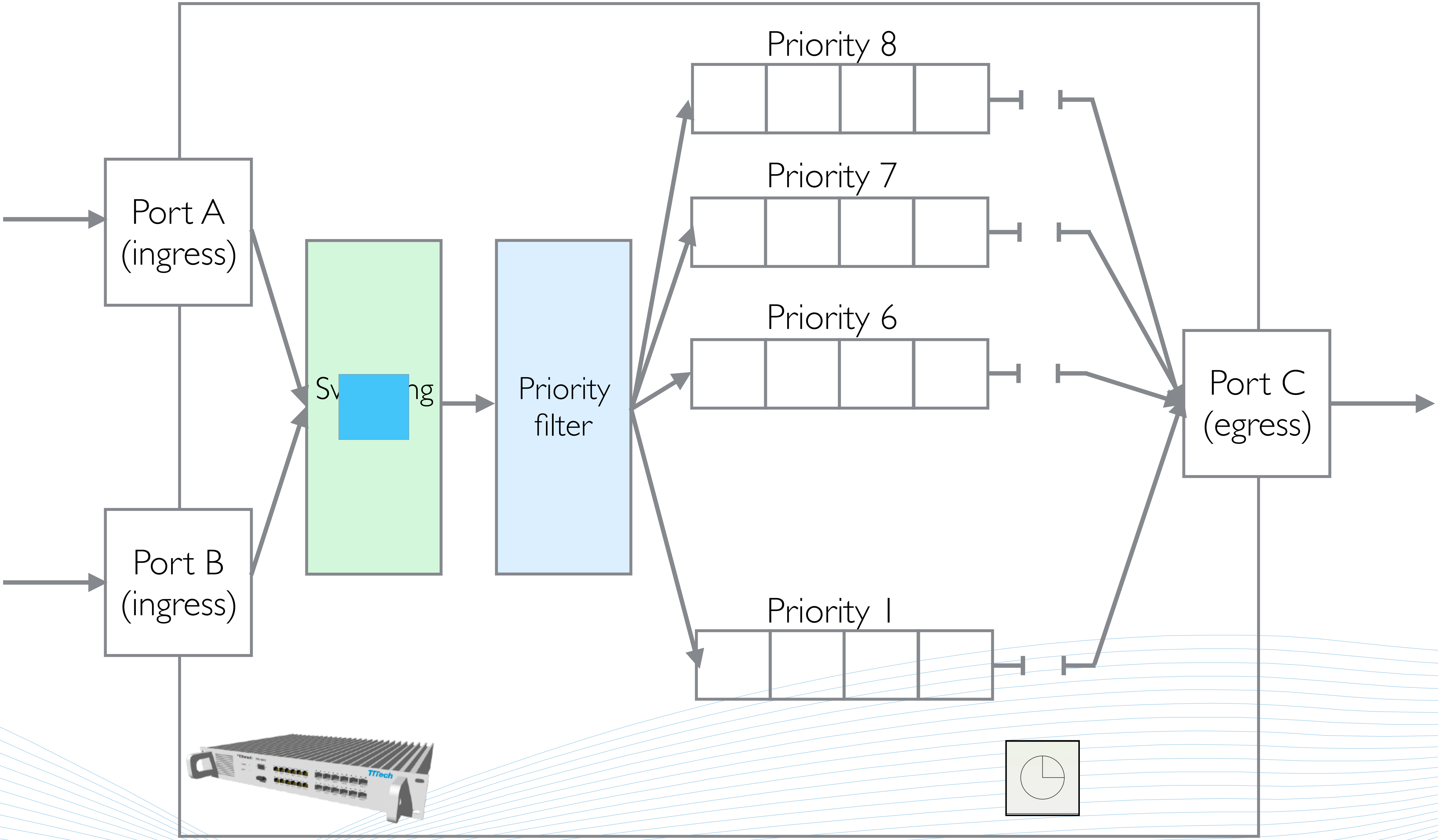

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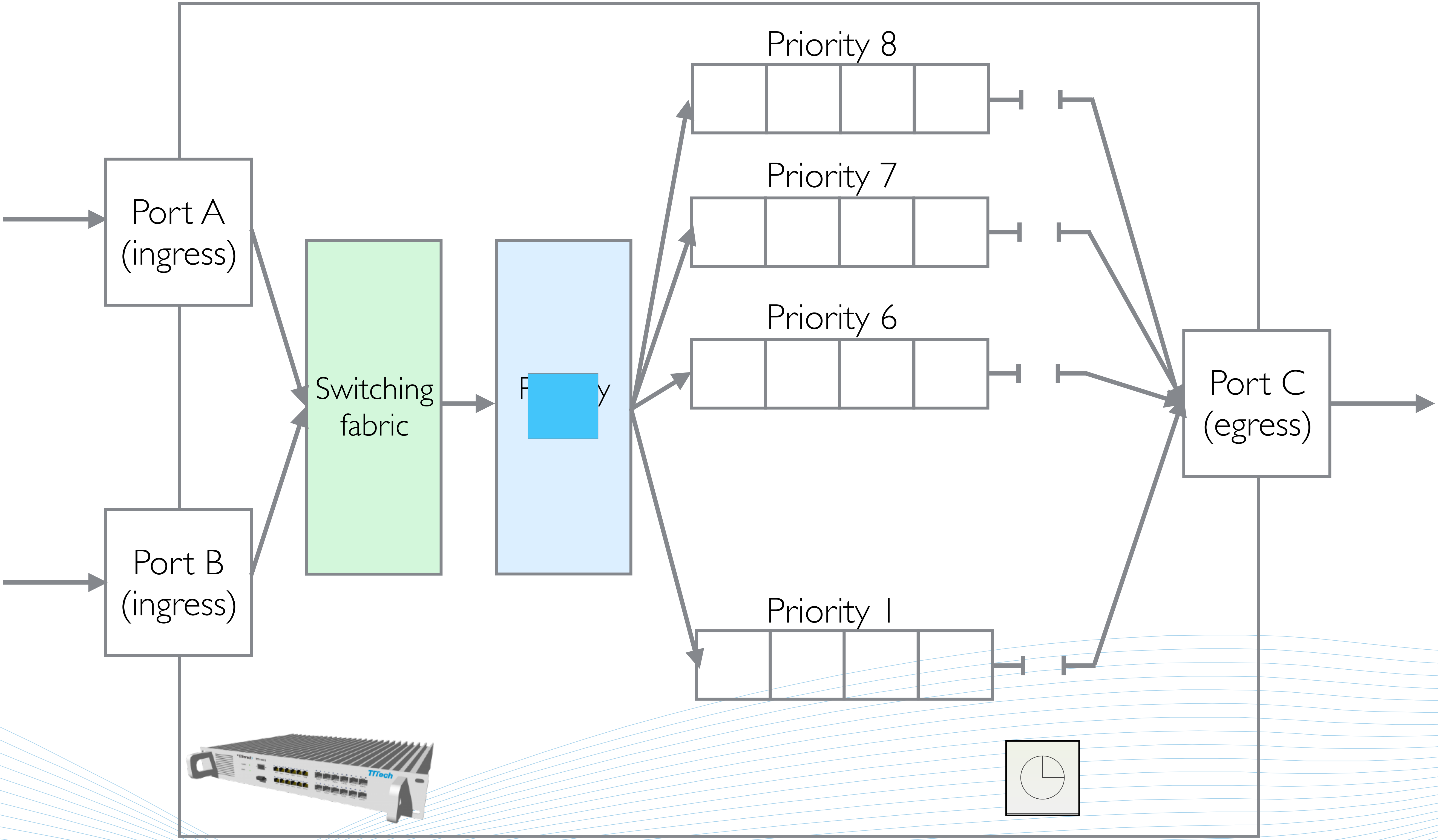

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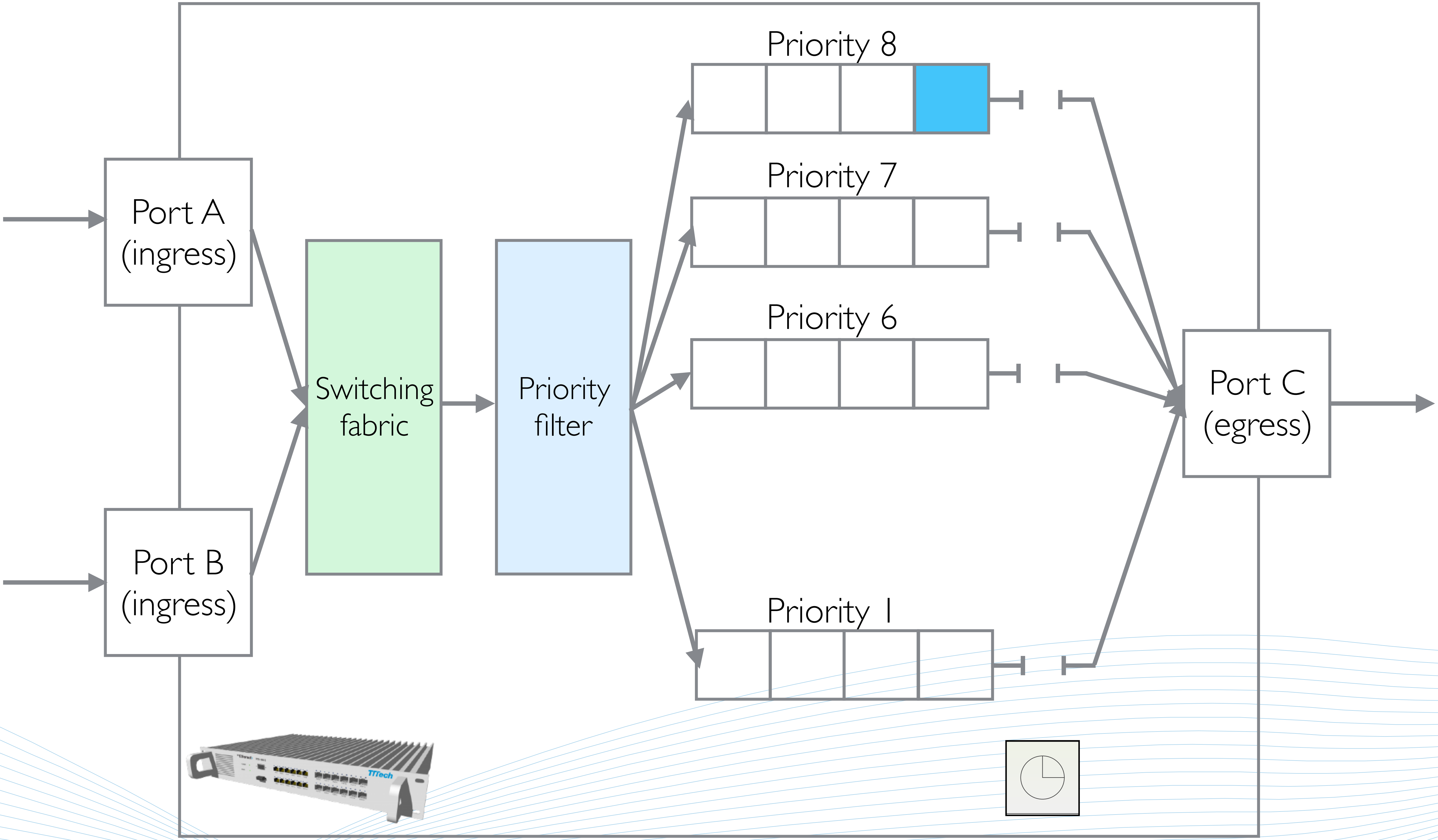

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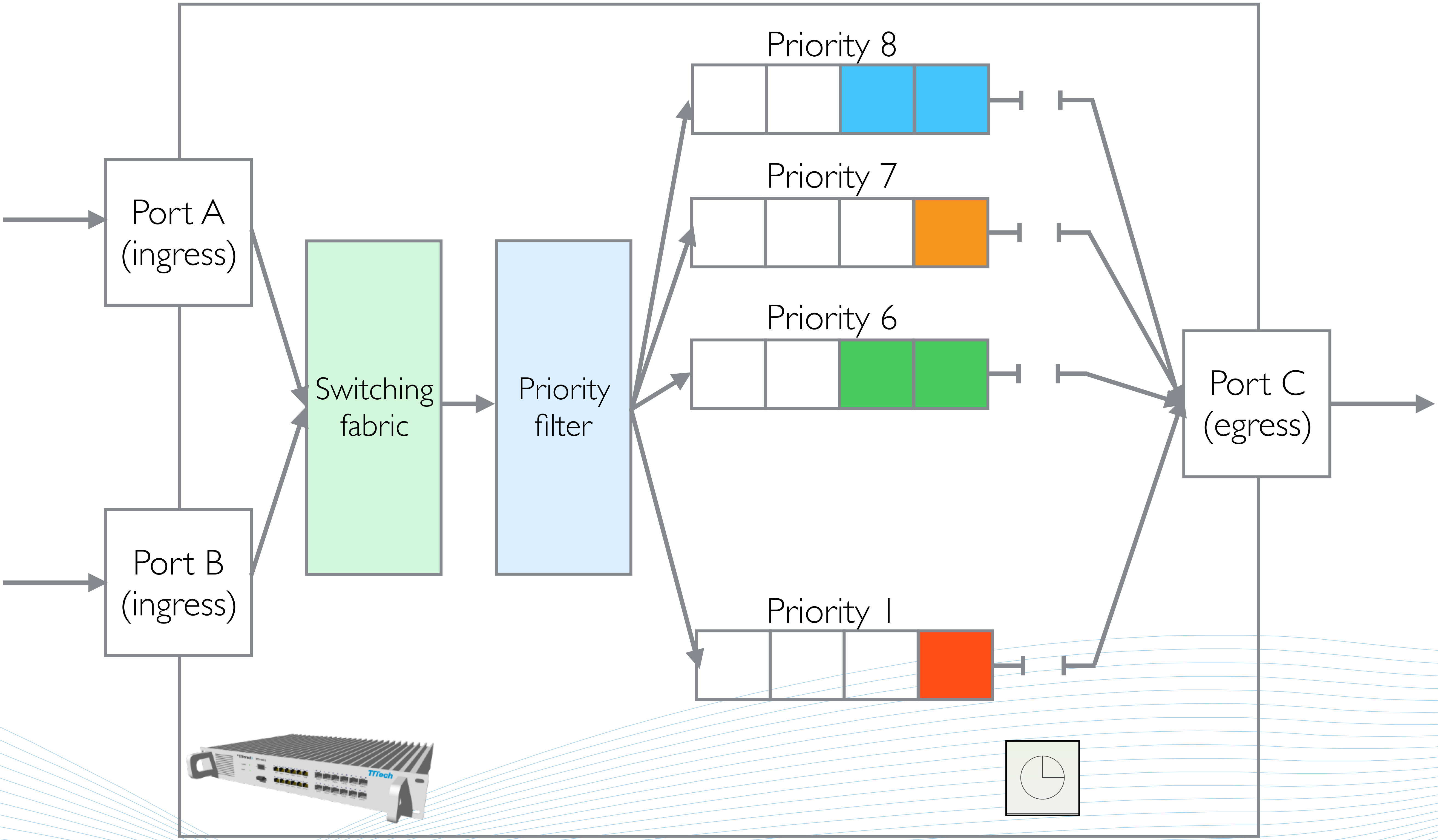

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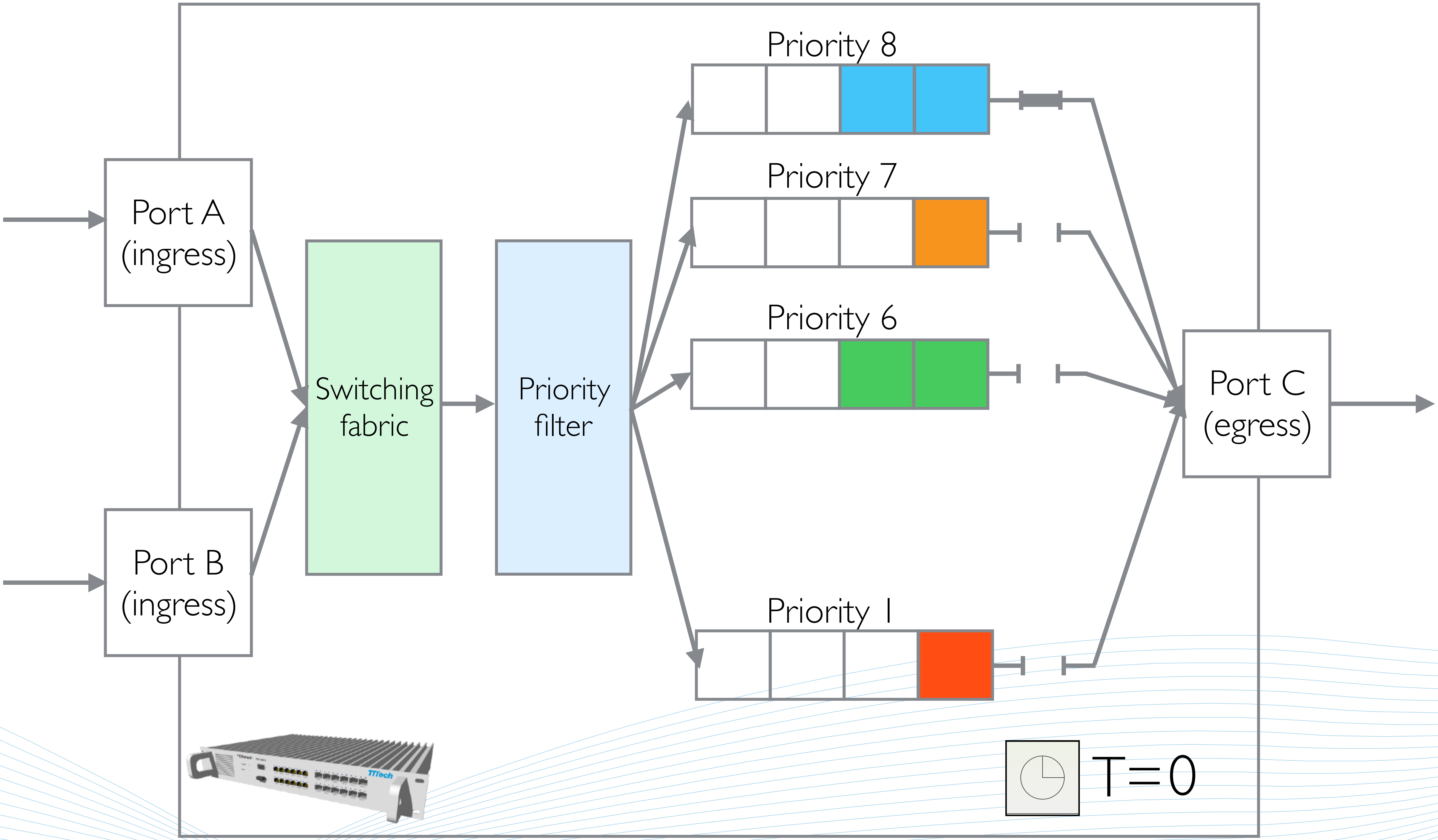

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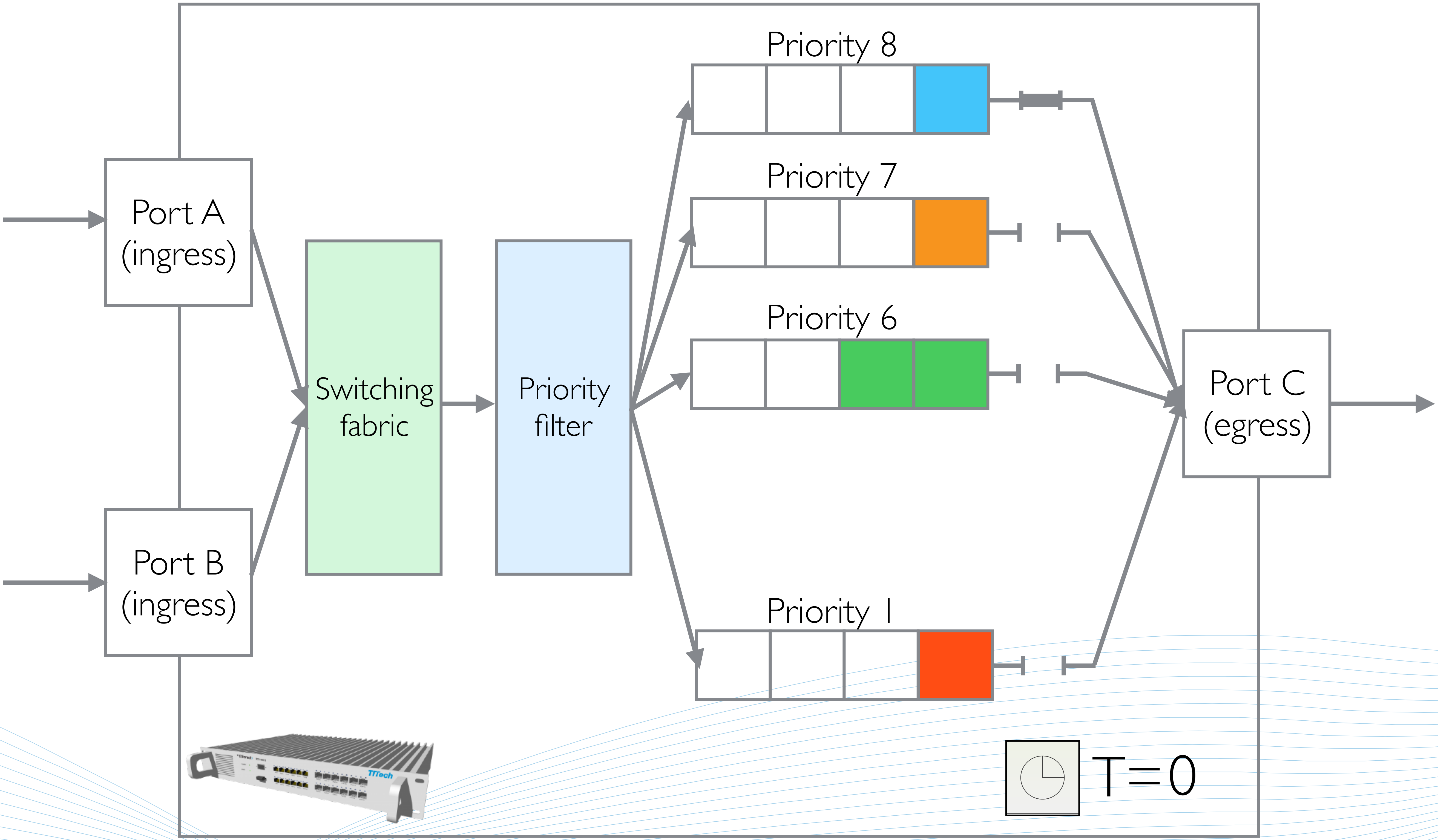

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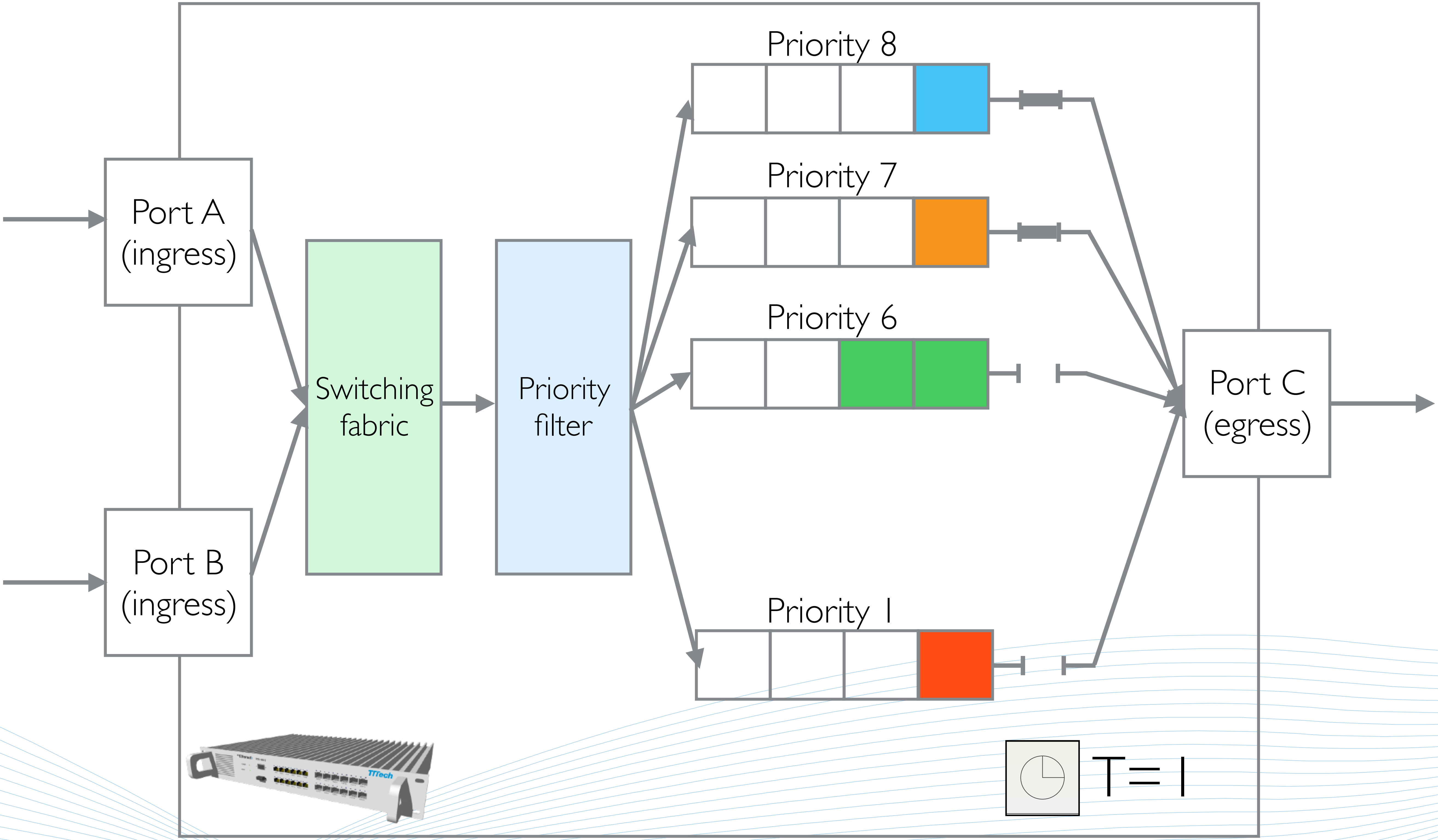

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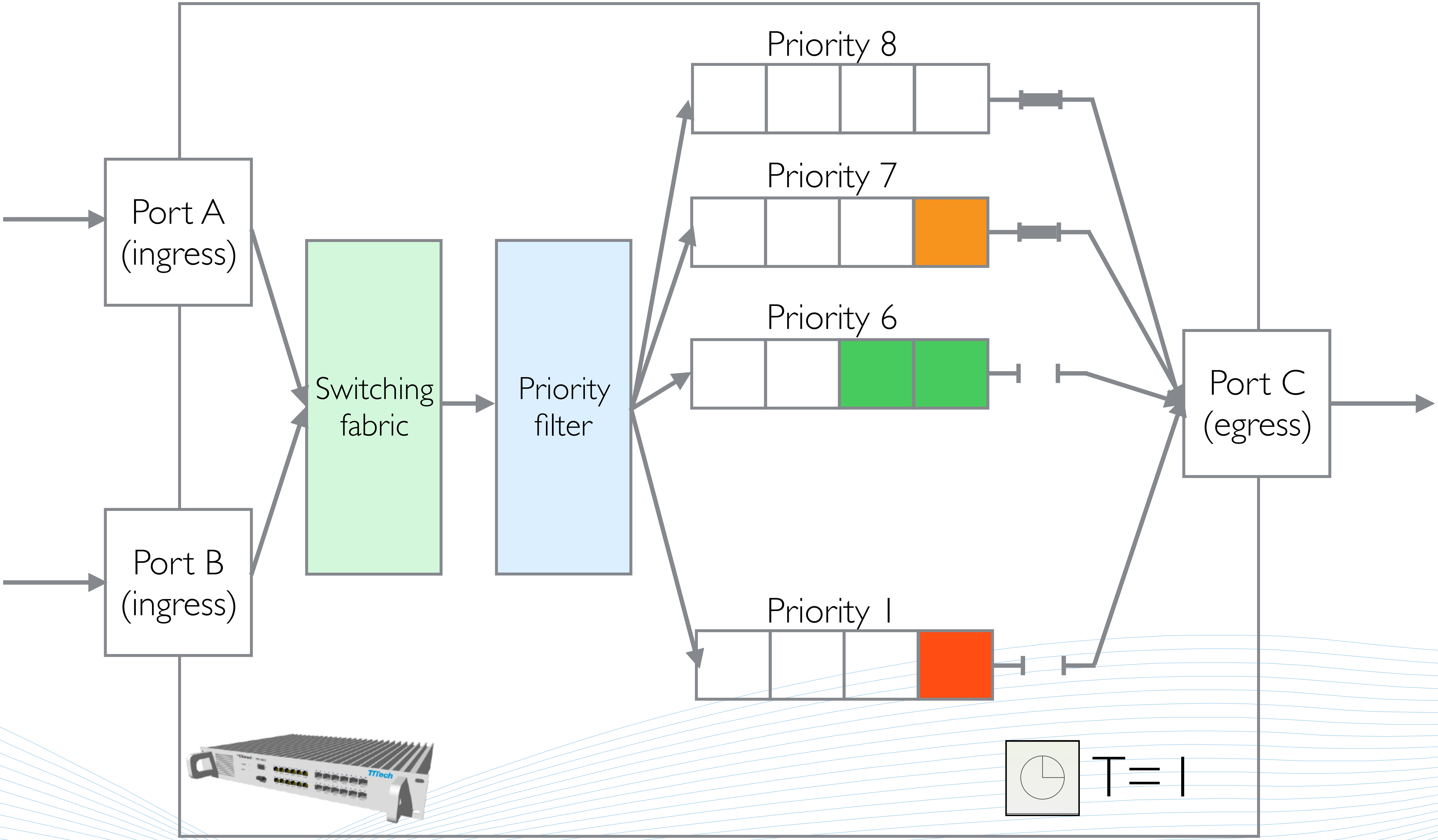

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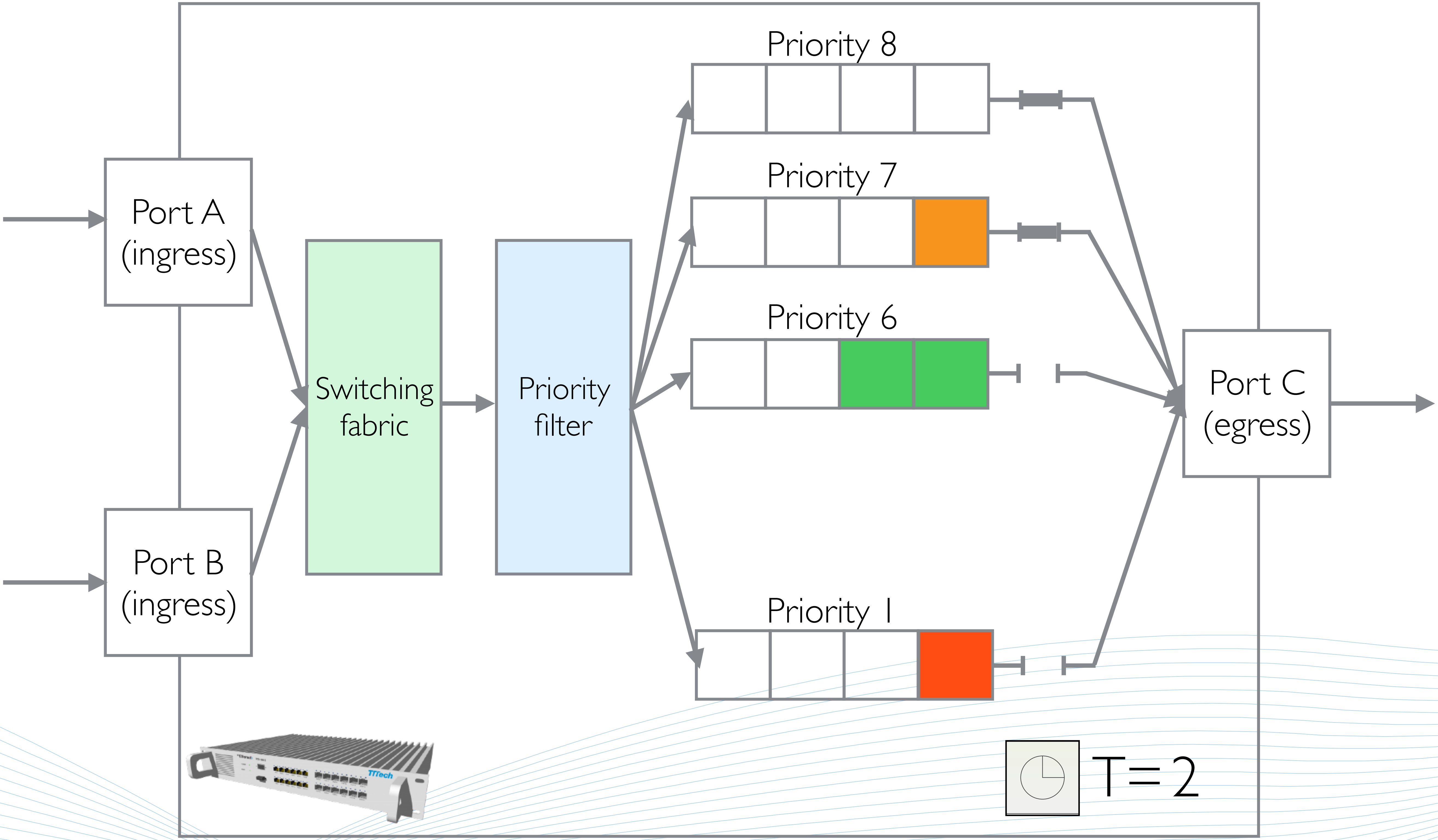

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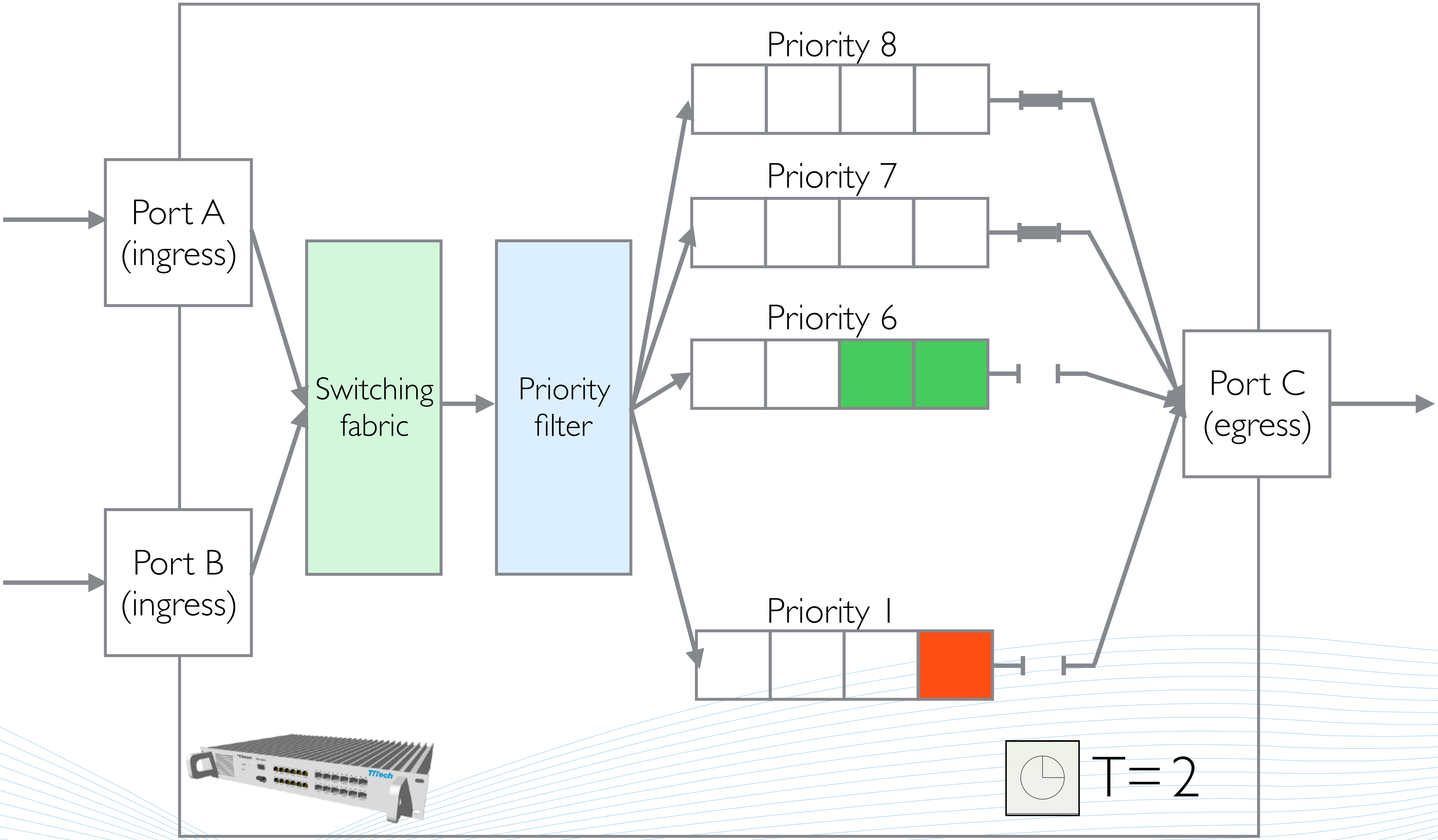

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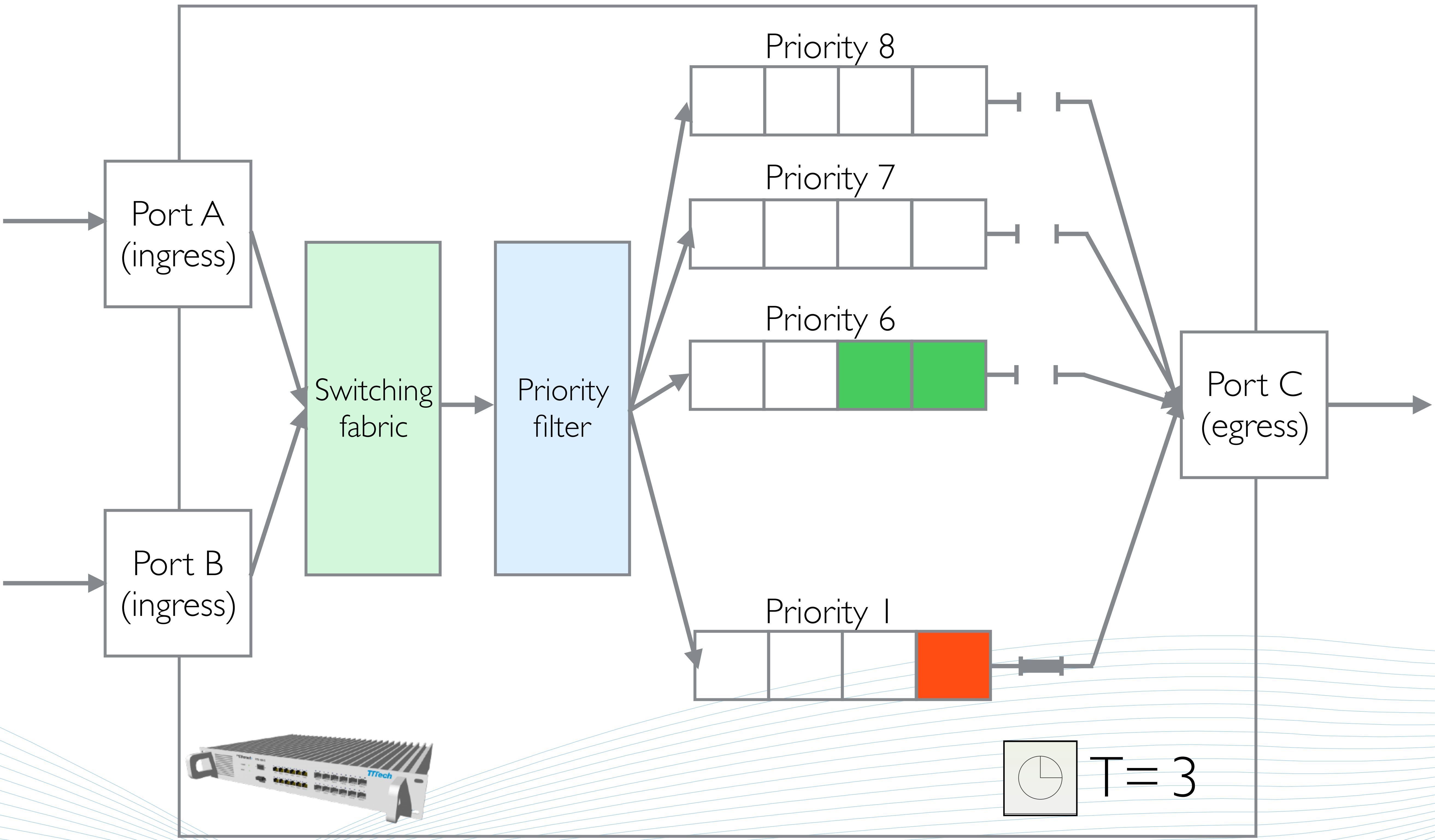

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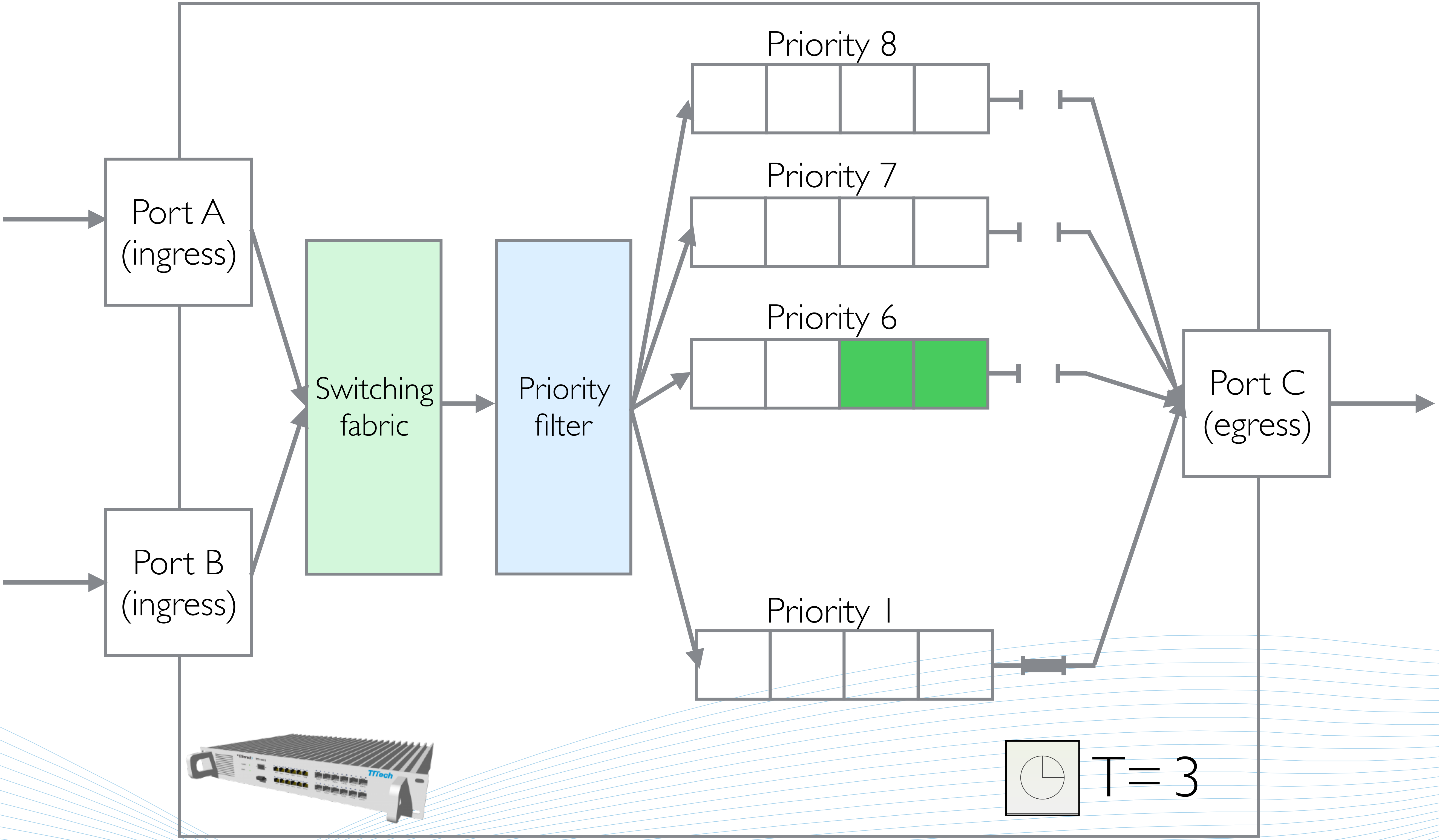

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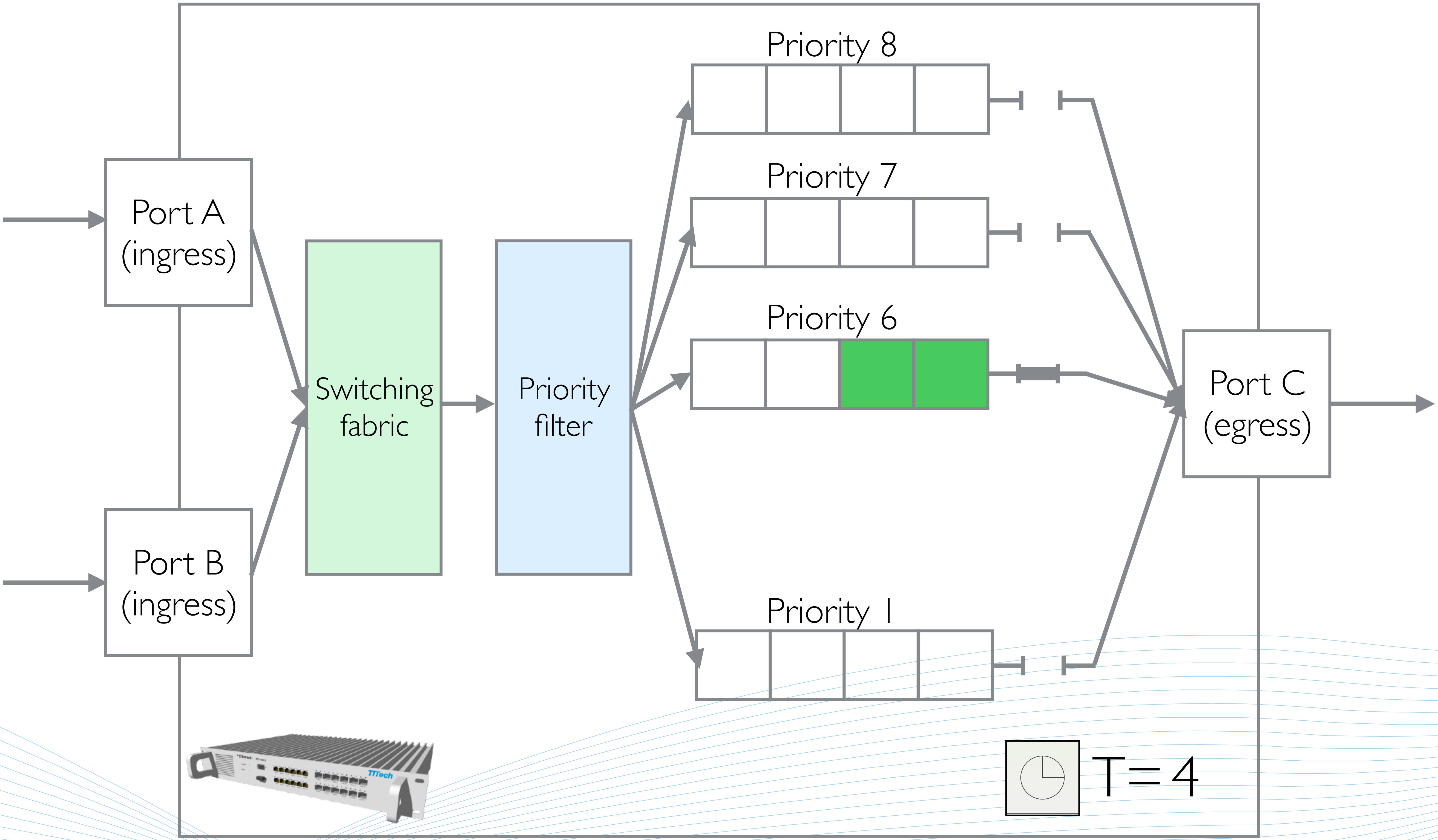

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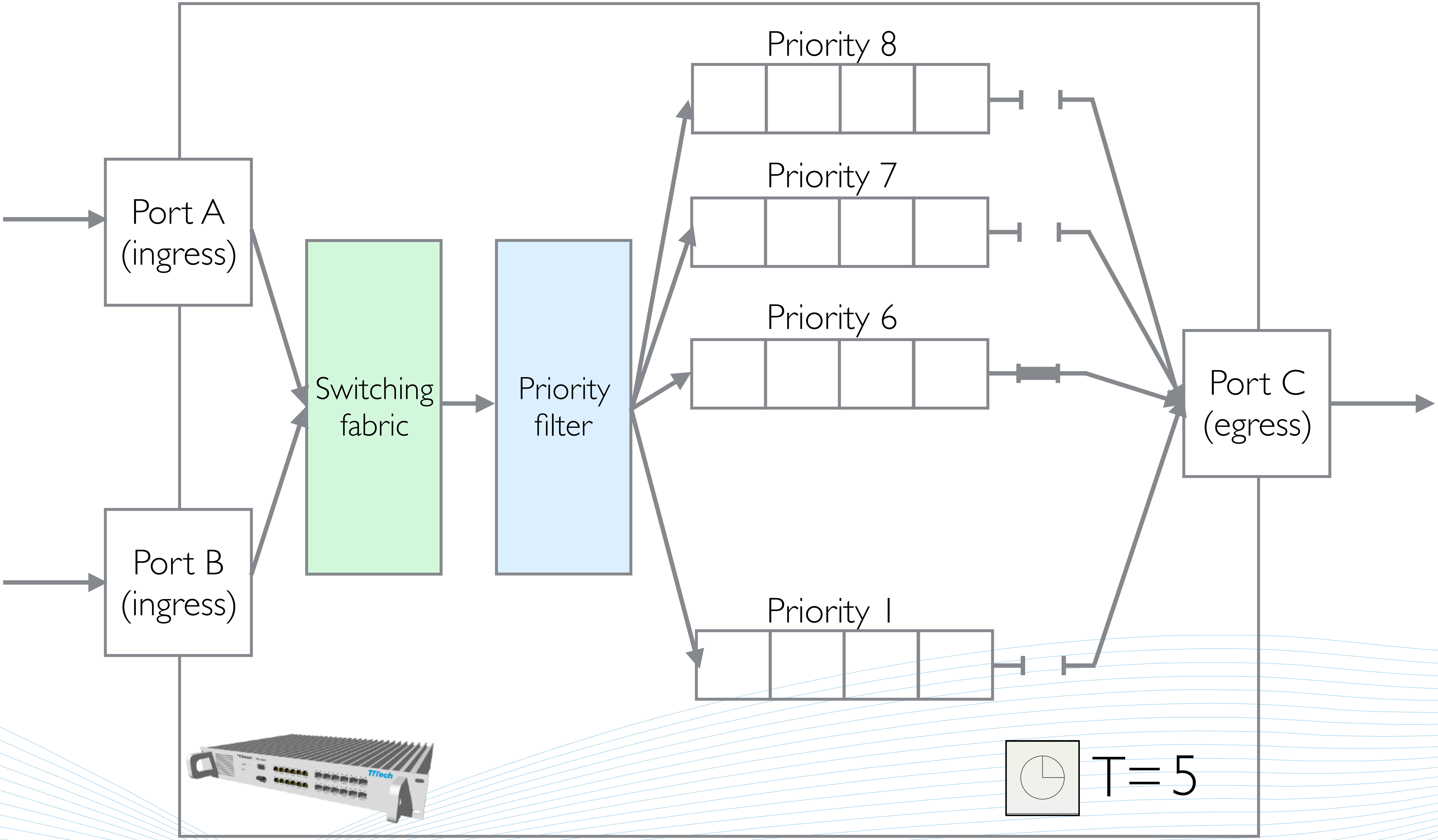

Functional parameters

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

Device capabilities

$$G(E)$$

V_e Scheduled Es

V_s Scheduled Sw

V_{e+s} Scheduled Es+Sw

Queue configuration

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

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

- 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)

Network & traffic model

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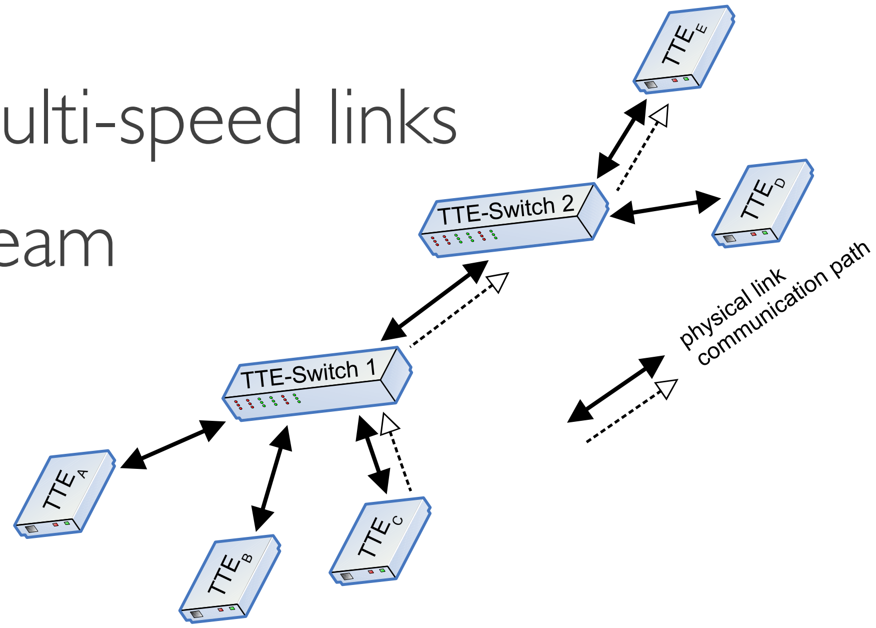
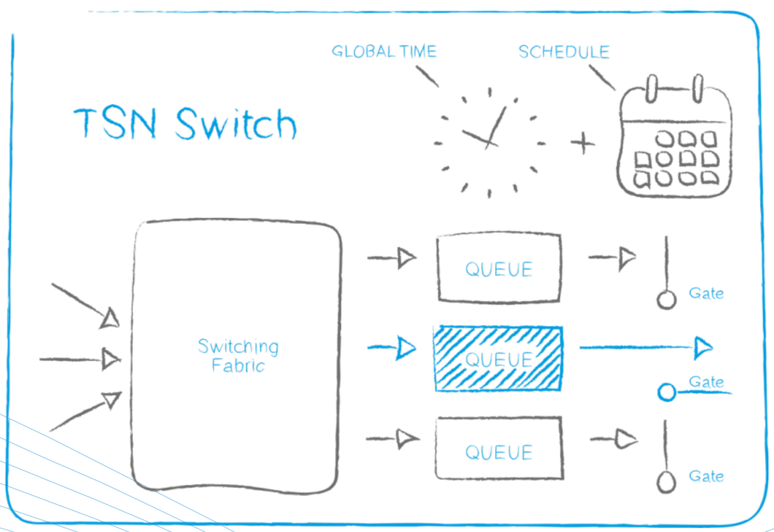
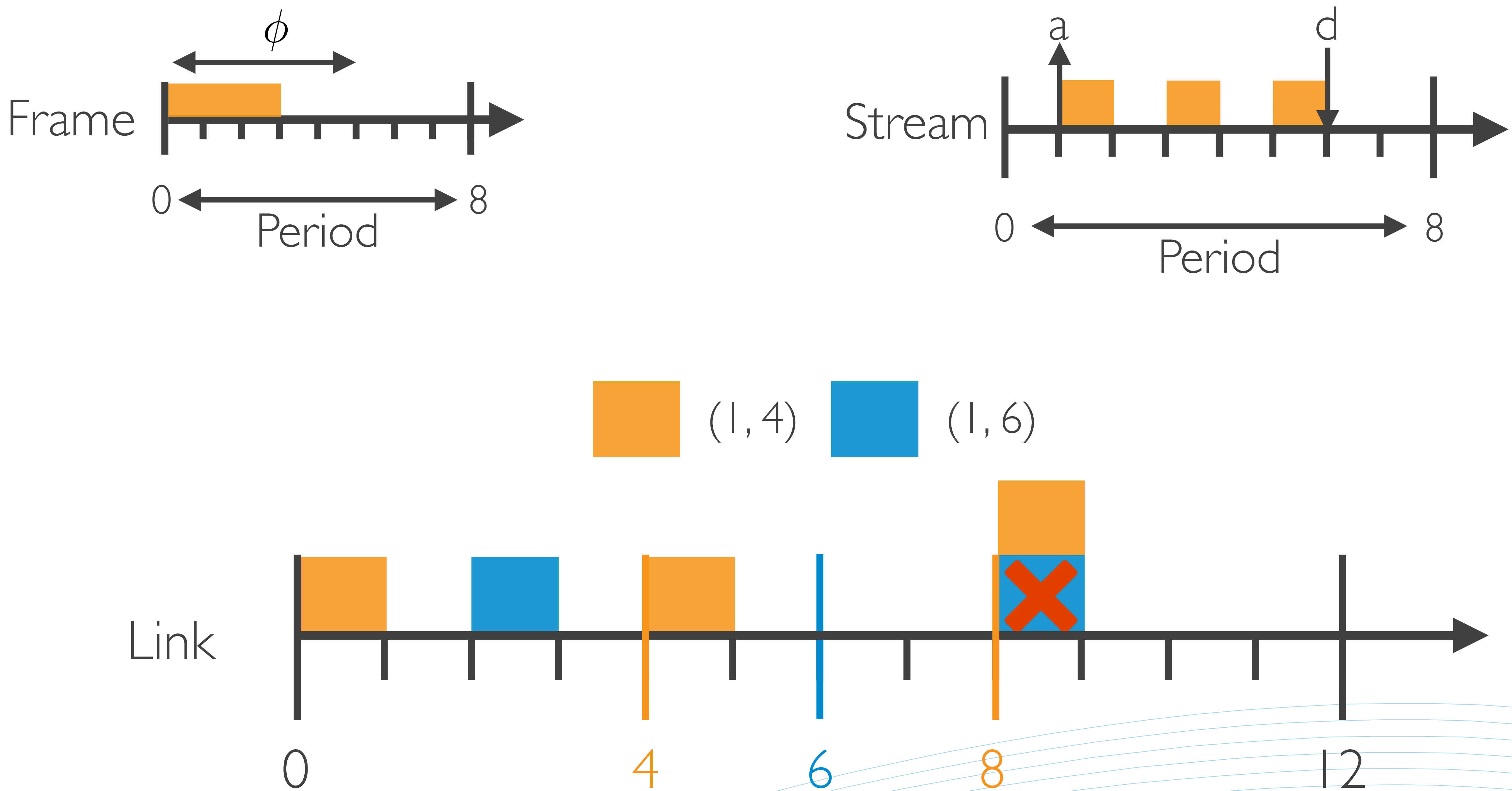
- multi-hop layer 2 switched network via full-duplex multi-speed links
- (multicast) TSN streams with multiple frames per stream
- synchronised time (<1 usec precision)
- wire and device delays





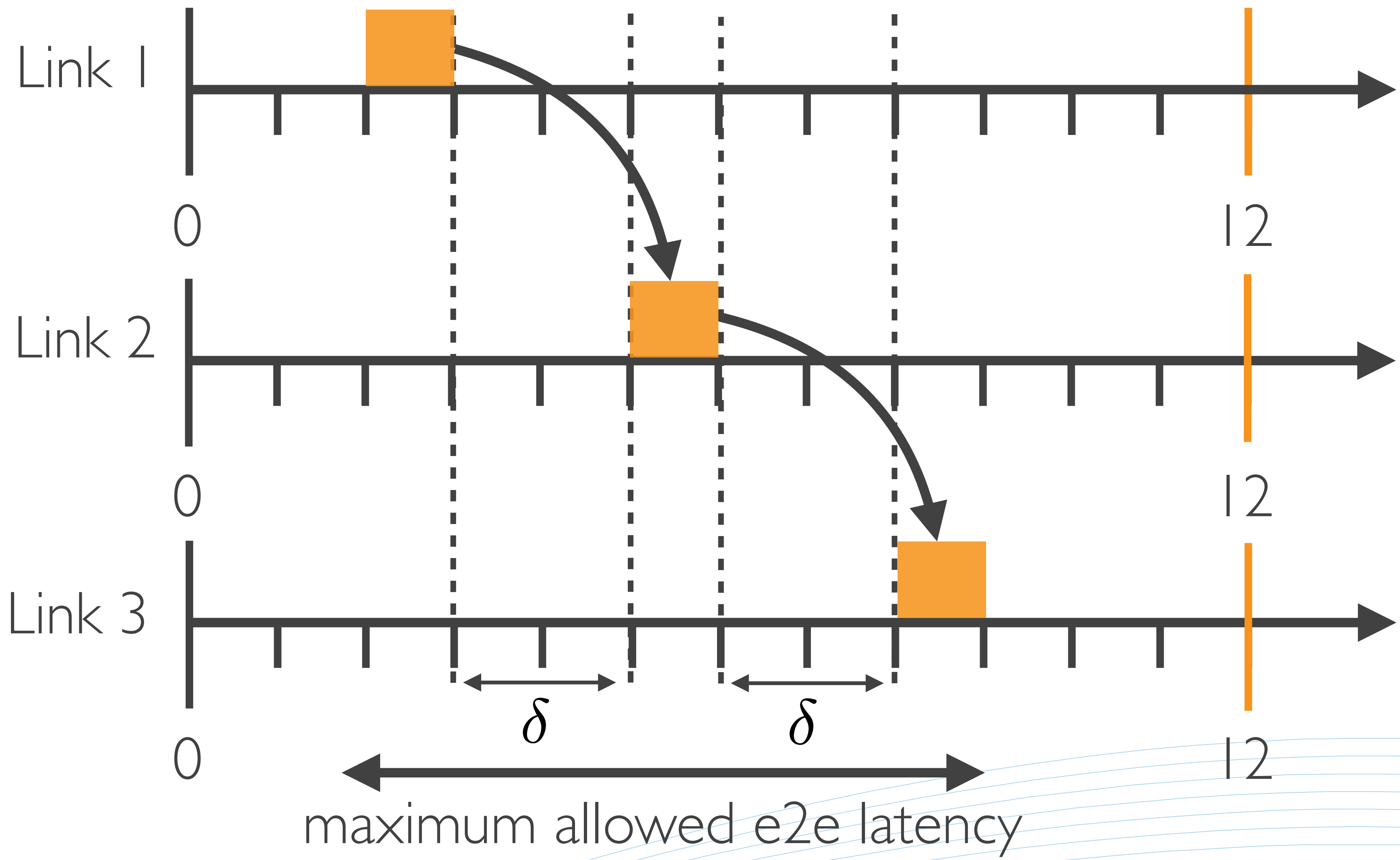
- Scheduled 802.1Qbv-compatible devices (Sw + Es)
- Scheduled (mutually exclusive) & priority queues
- Guaranteed delivery of critical traffic with known latency, small & bounded jitter

Deterministic Ethernet Constraints



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

Stream and e2e latency constraints



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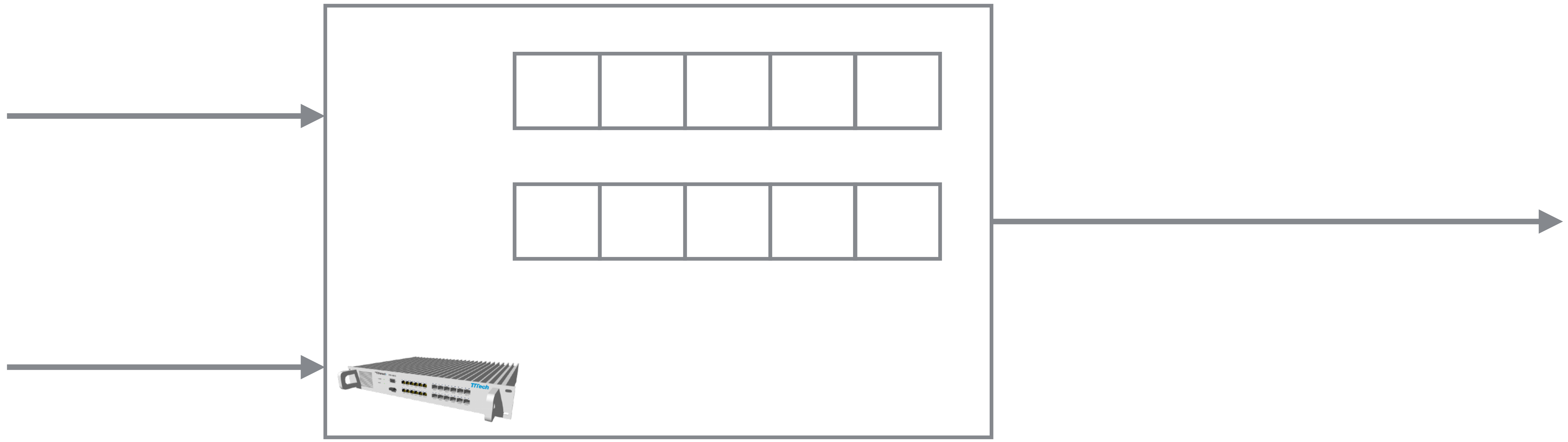
Queue Interleaving



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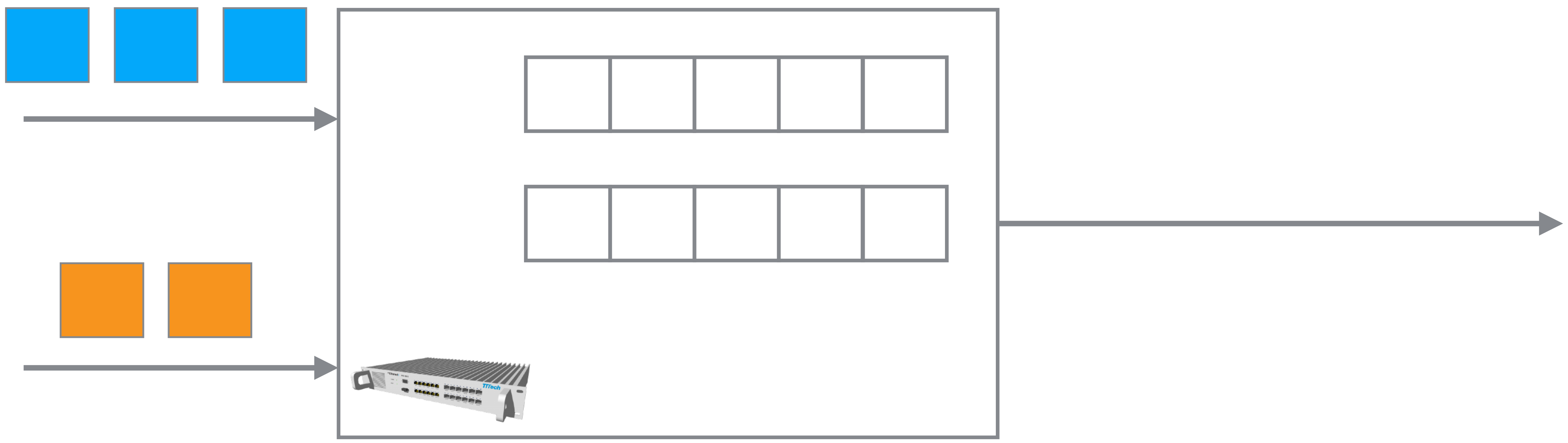

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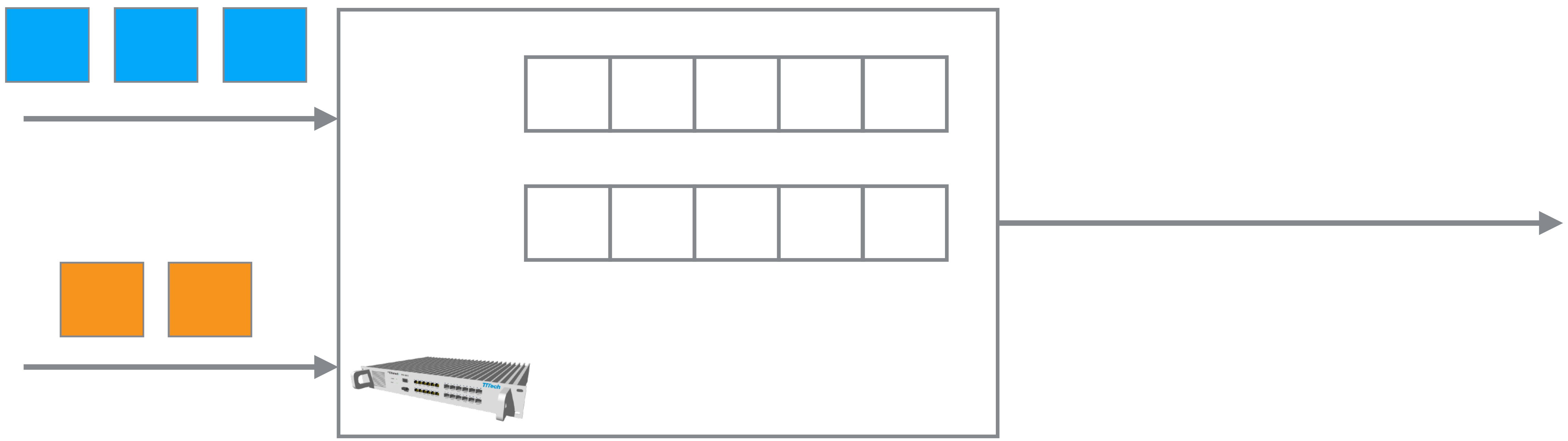

In order to maintain jitter and latency requirements we expect at each device a certain timely order of frames

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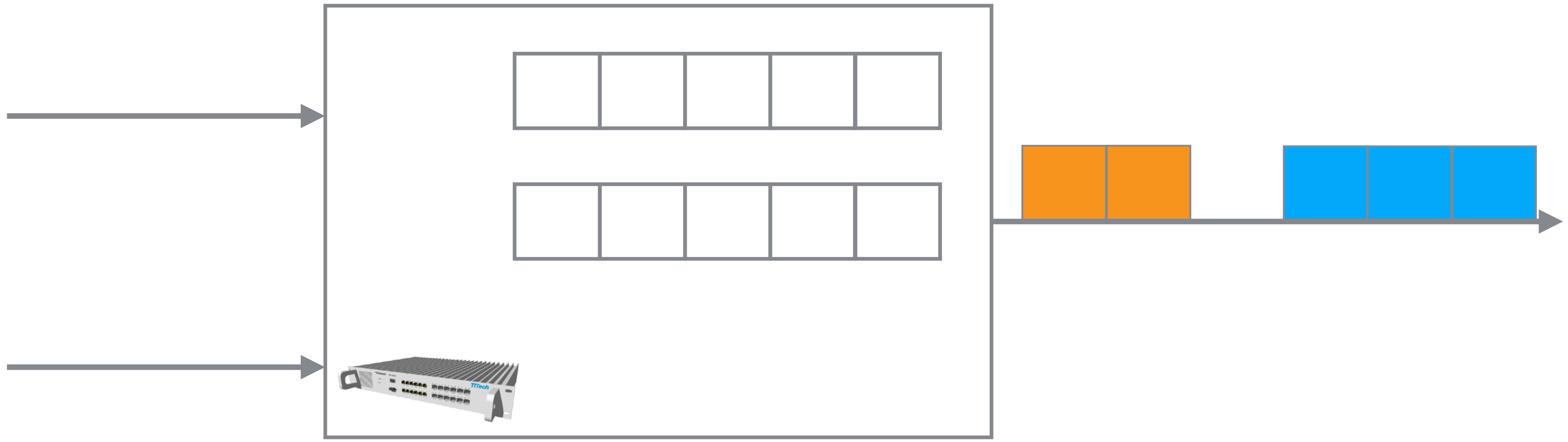

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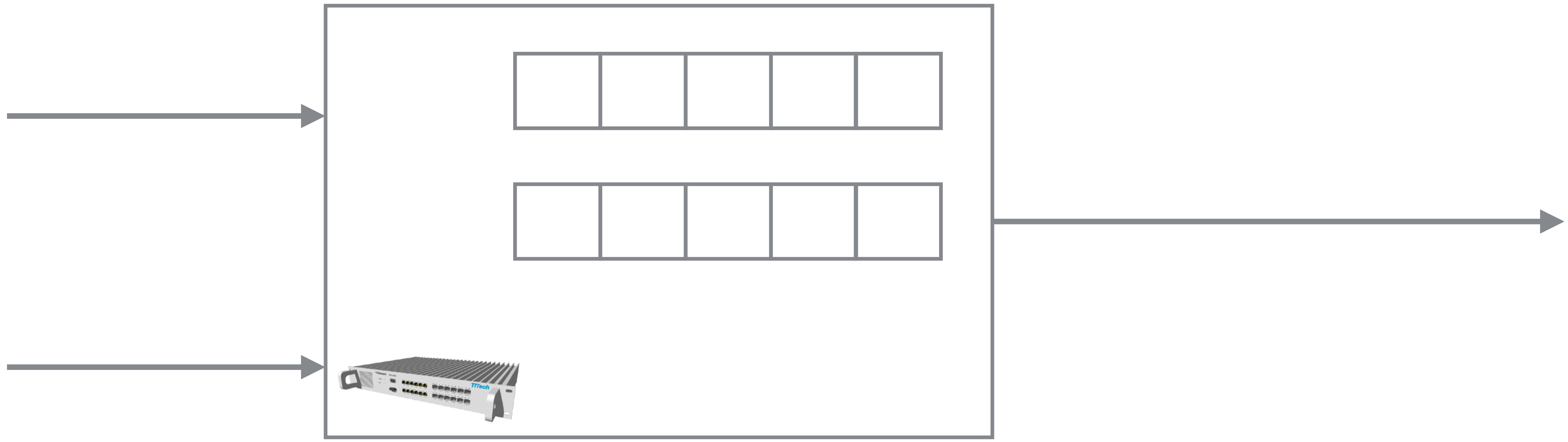

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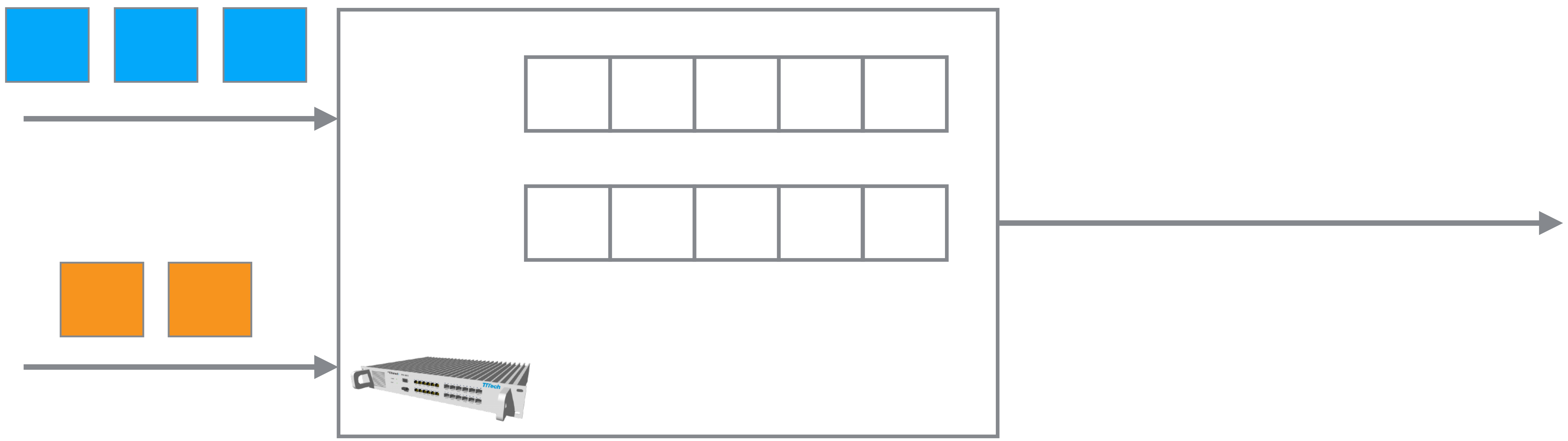

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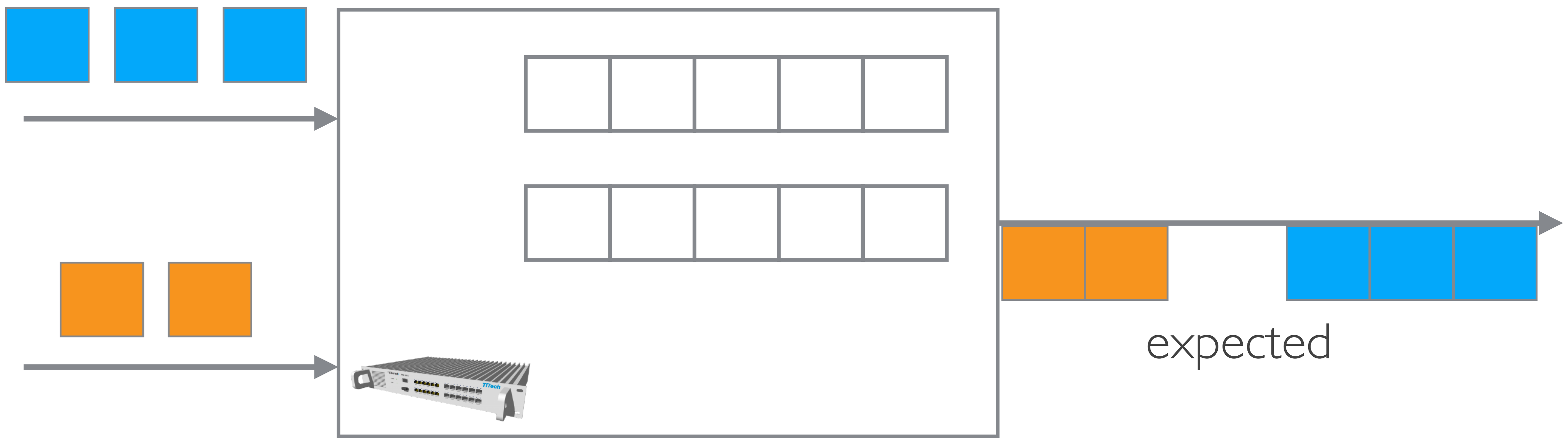

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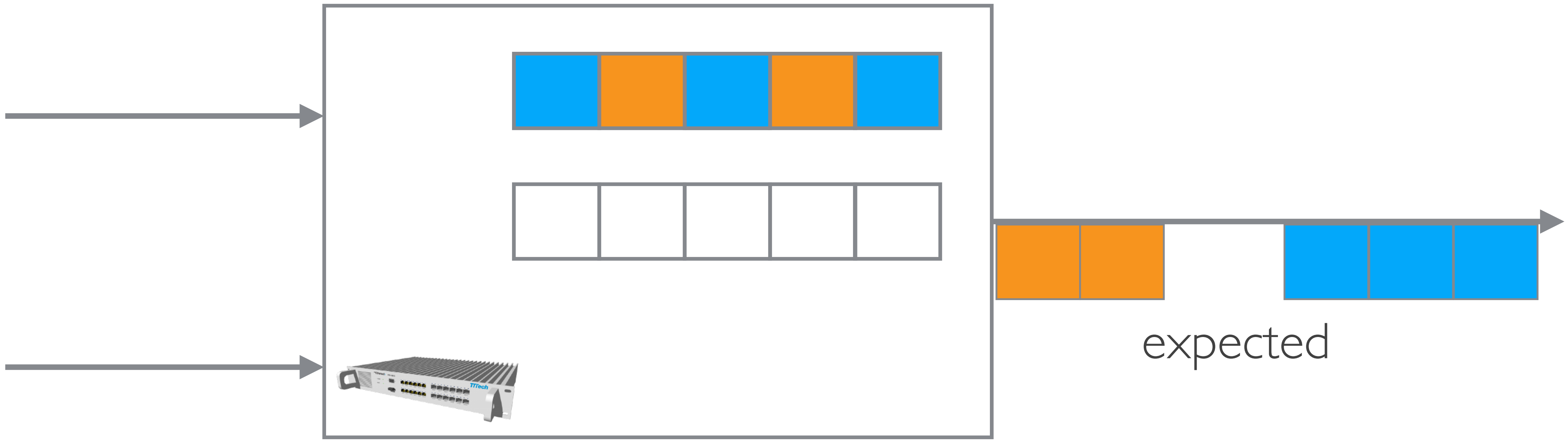

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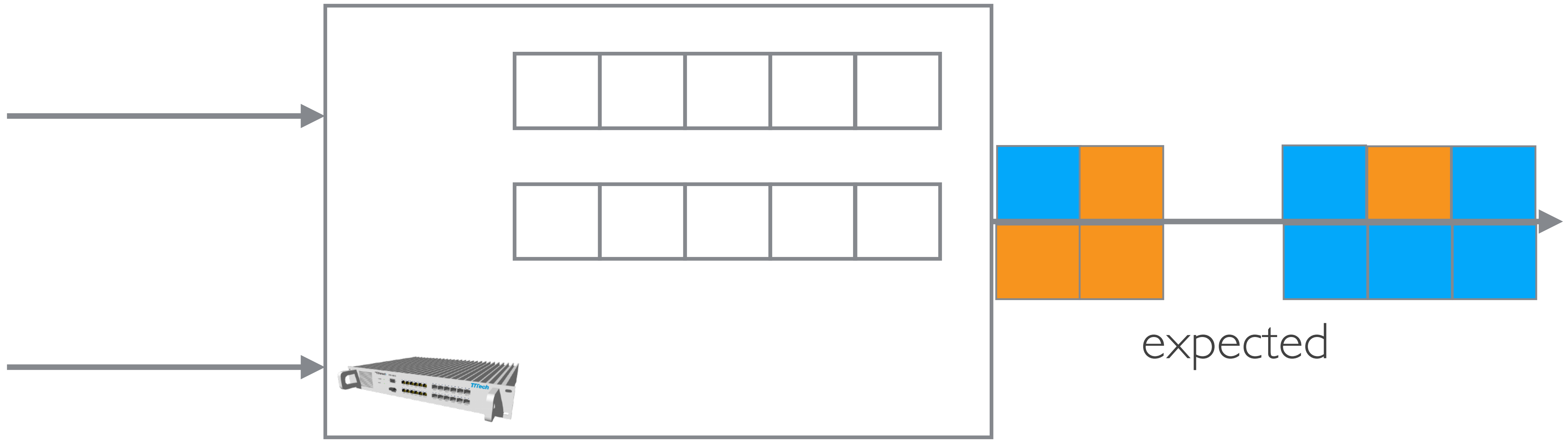

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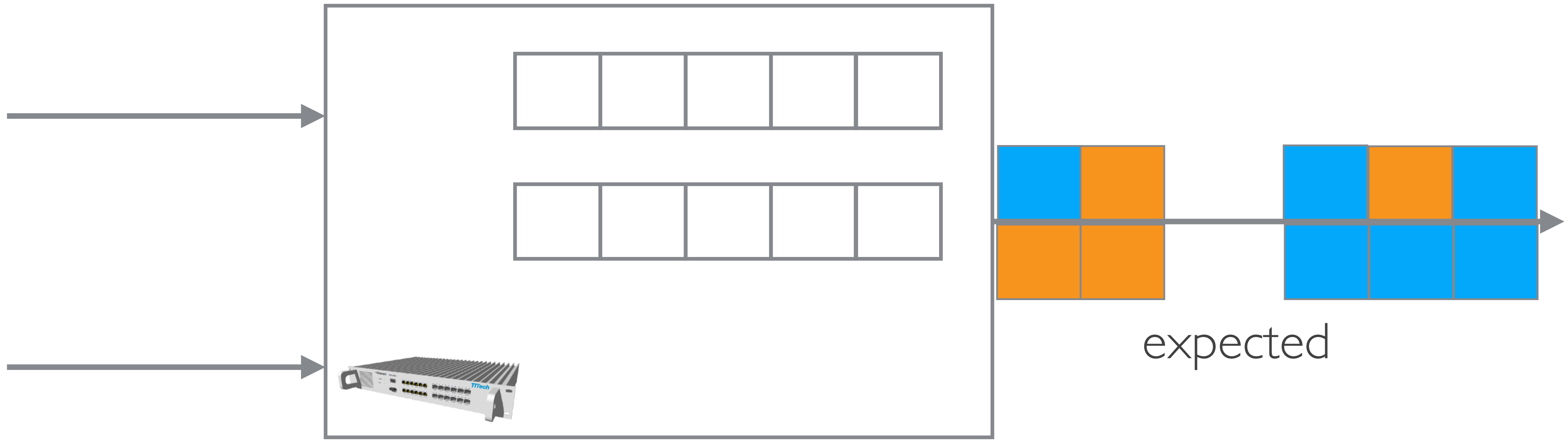

- synchronization errors, frame loss, time-based ingress policing (e.g. IEEE 802.1Qci) may lead to non-deterministic placement in queues during runtime
- timed gates control events on the egress port, not the order of frames in the queue
- placing of frames in the scheduled queues at runtime may be non-deterministic

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

Queue Isolation

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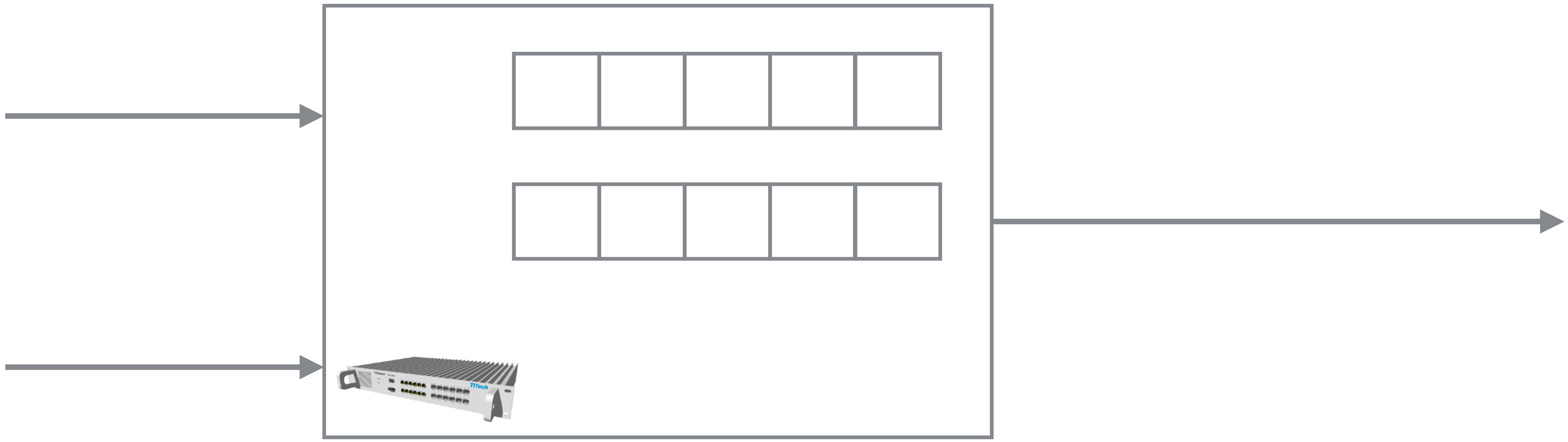

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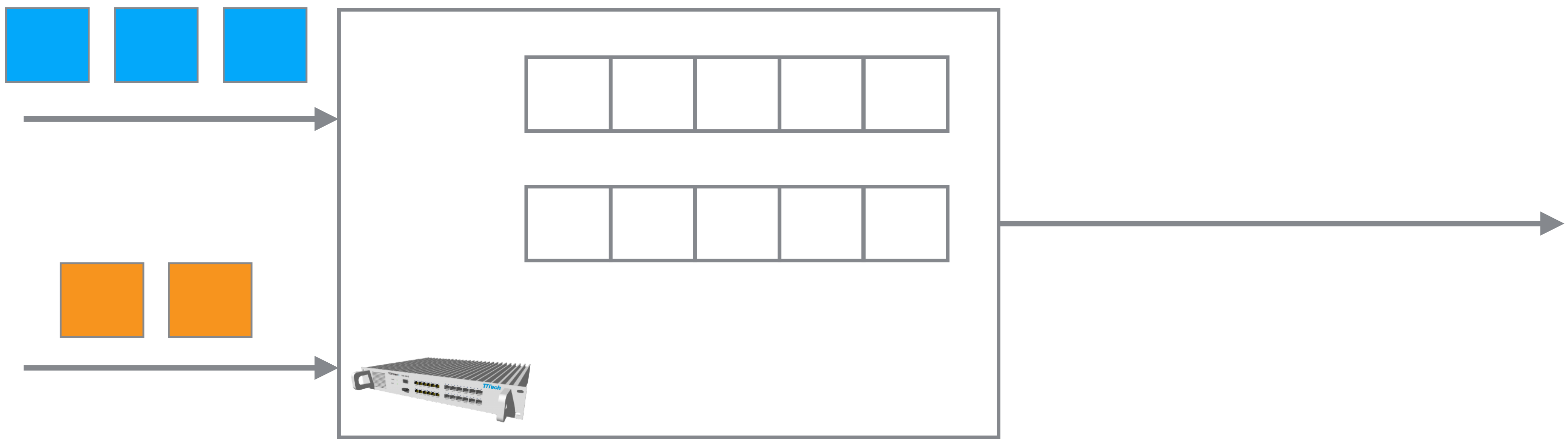

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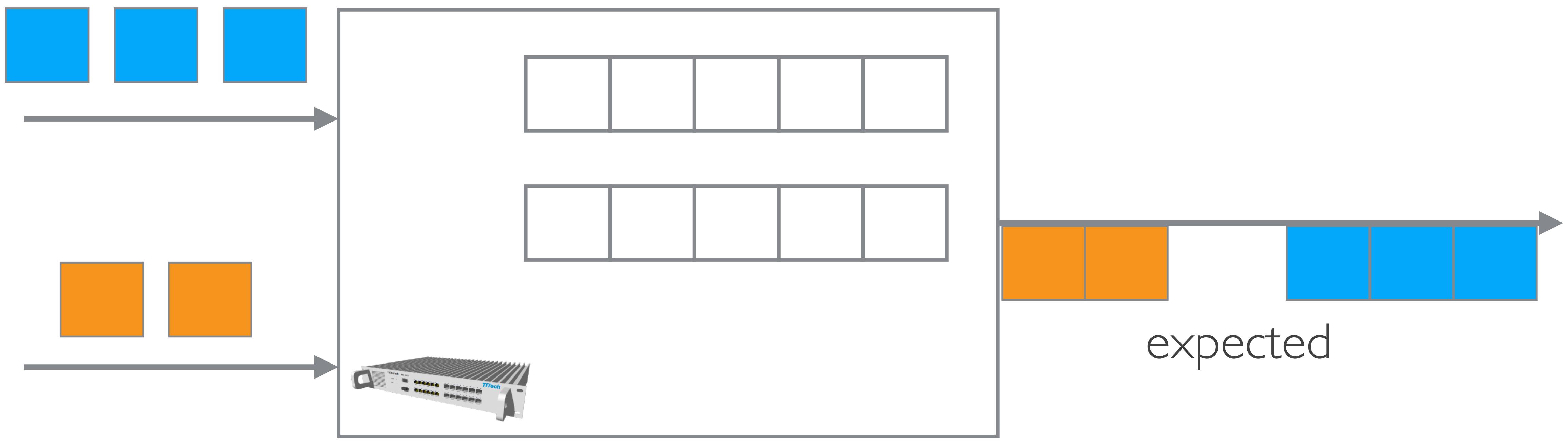

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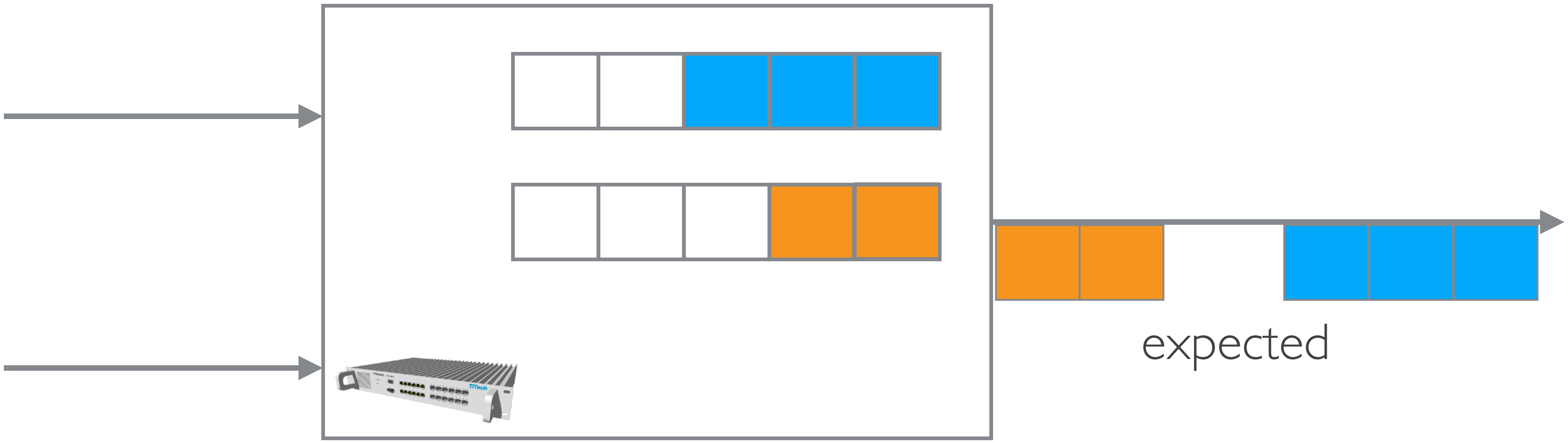

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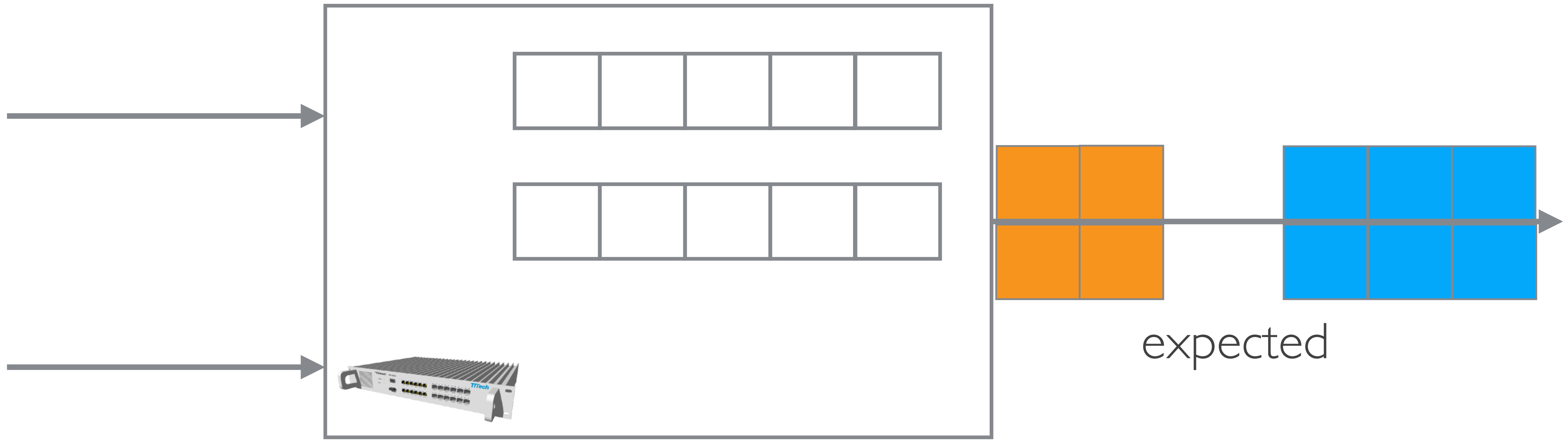

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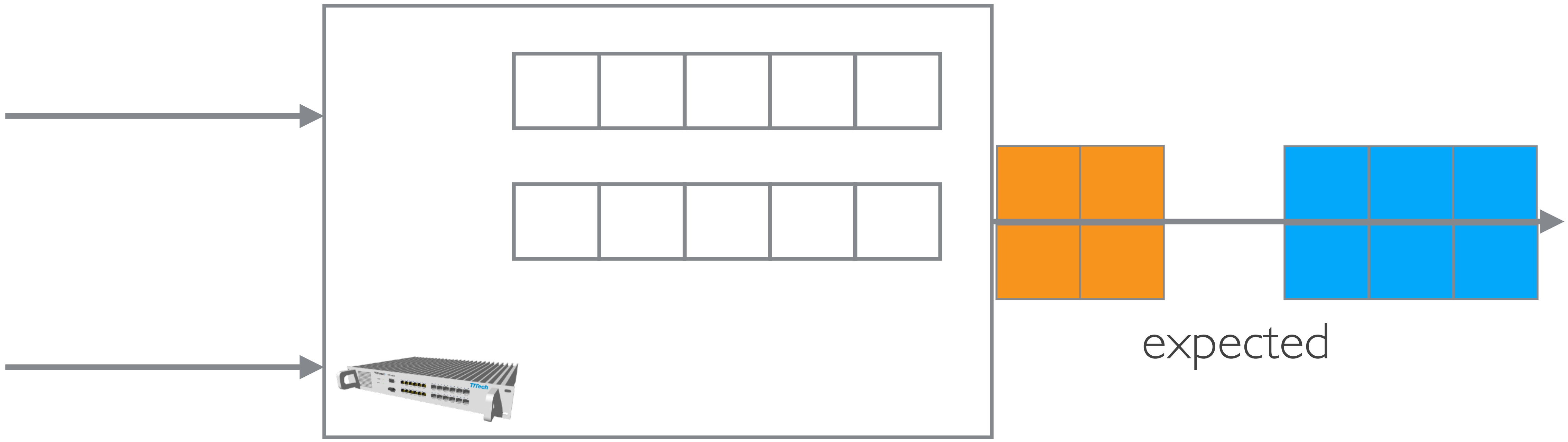

Solves the non-determinism problem but reduces the solution space

Stream (Flow) isolation

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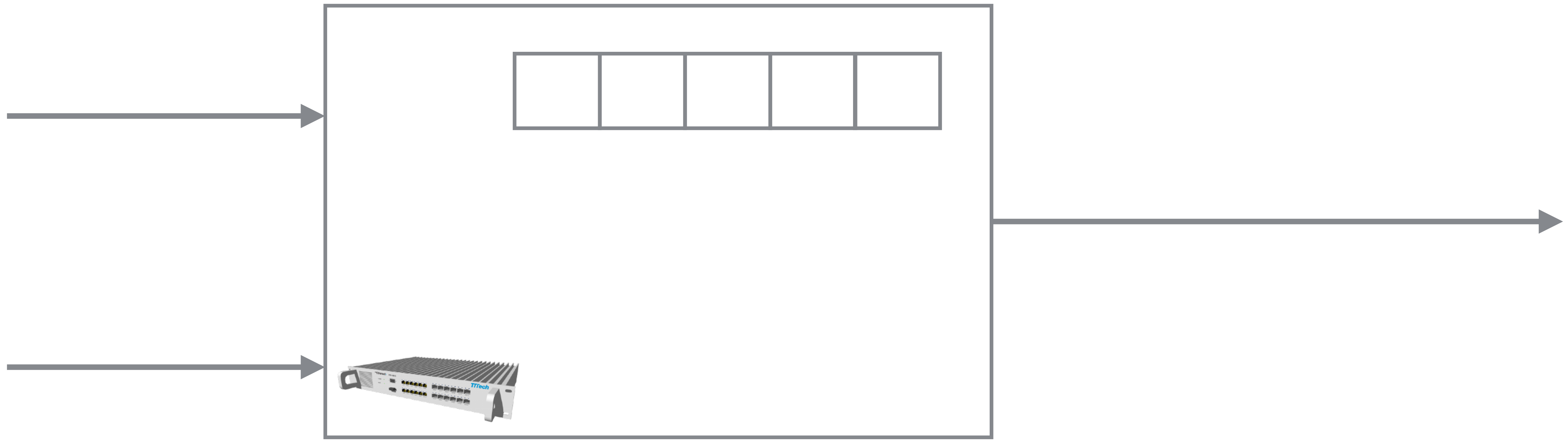

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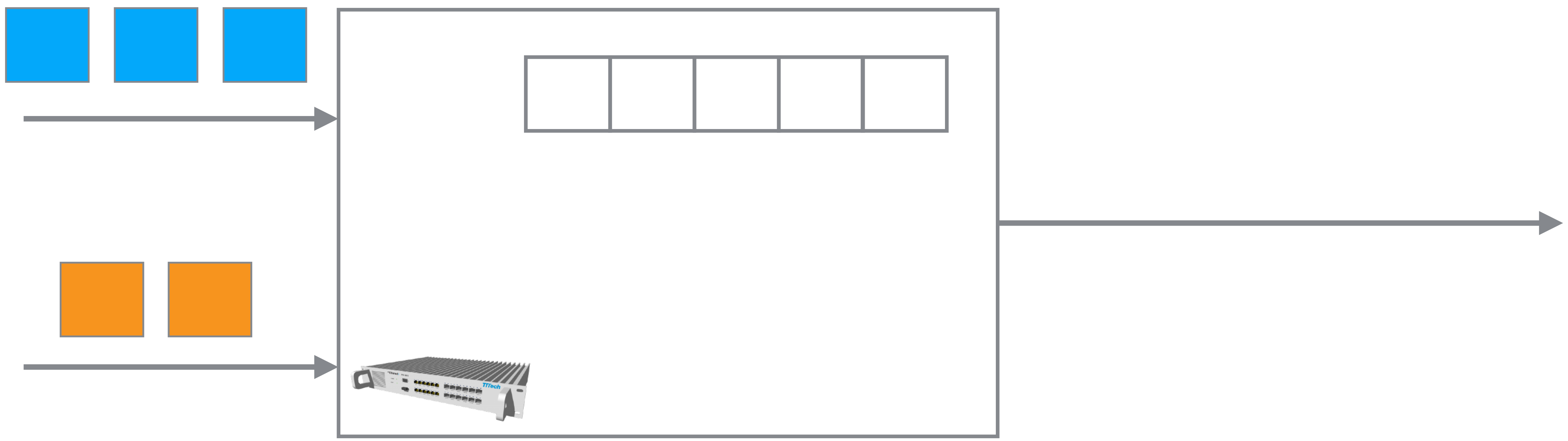

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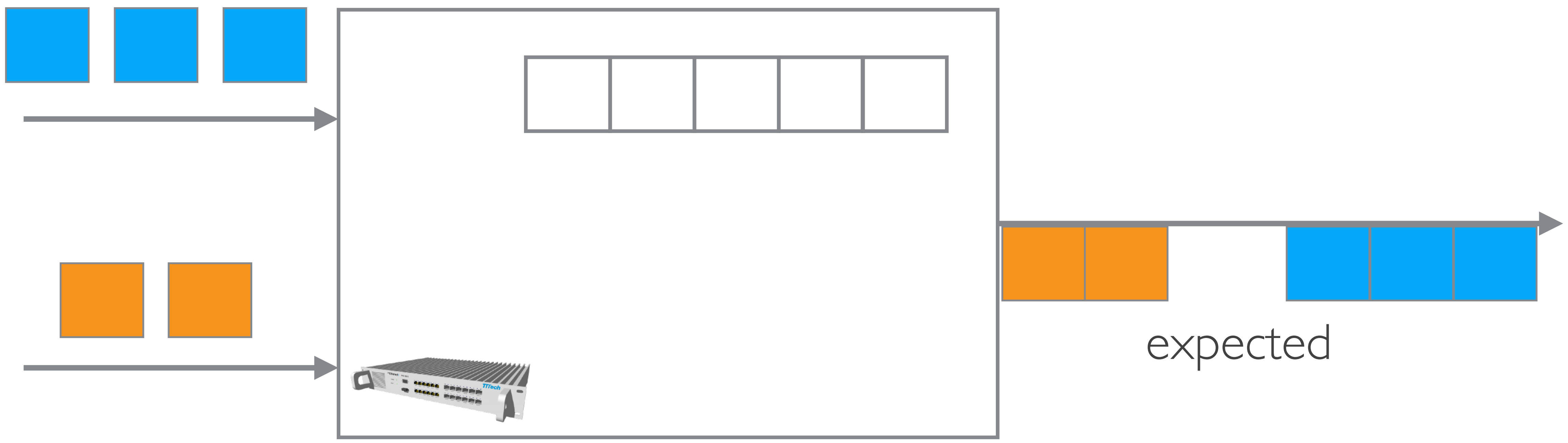

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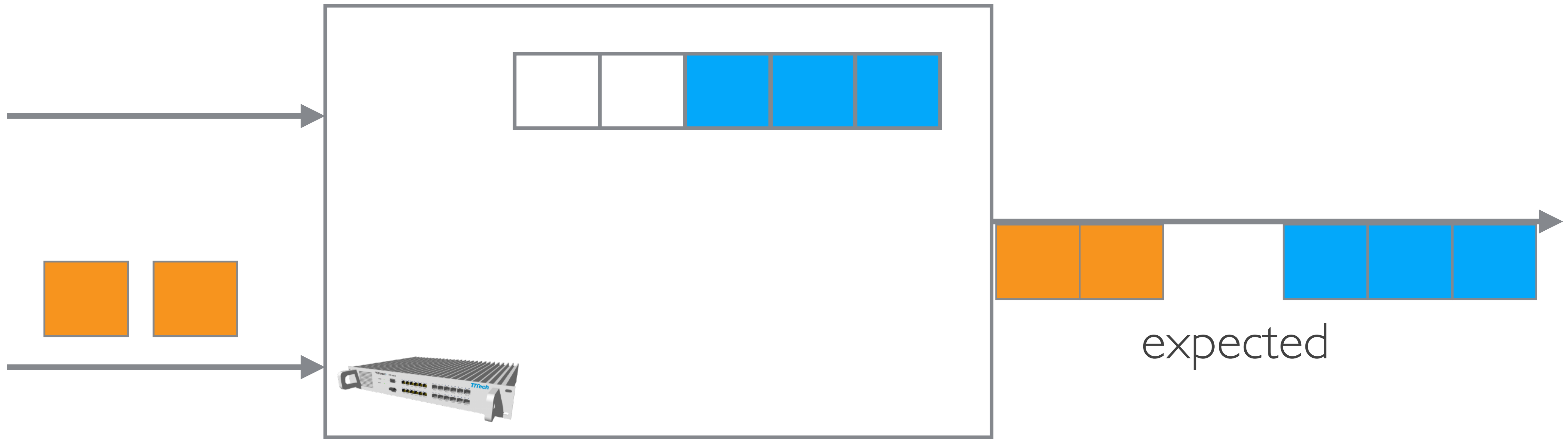

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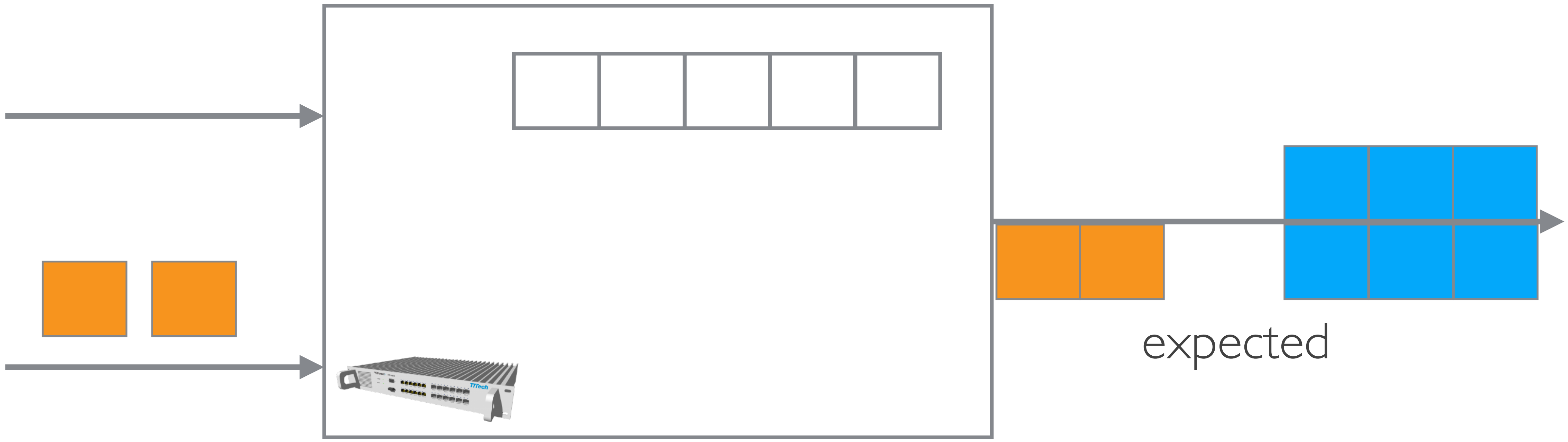

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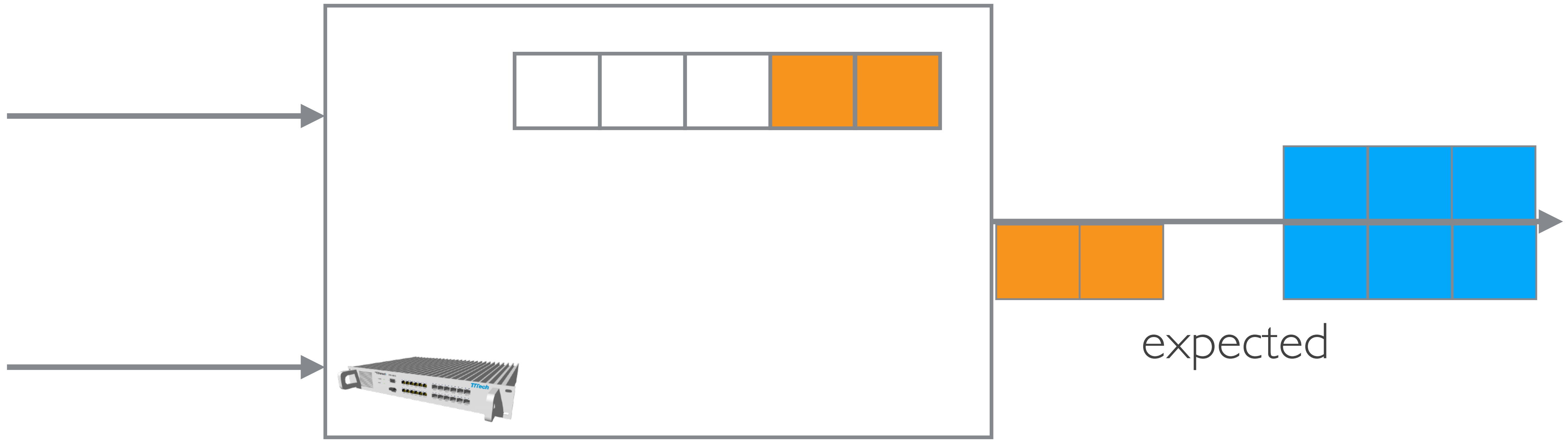

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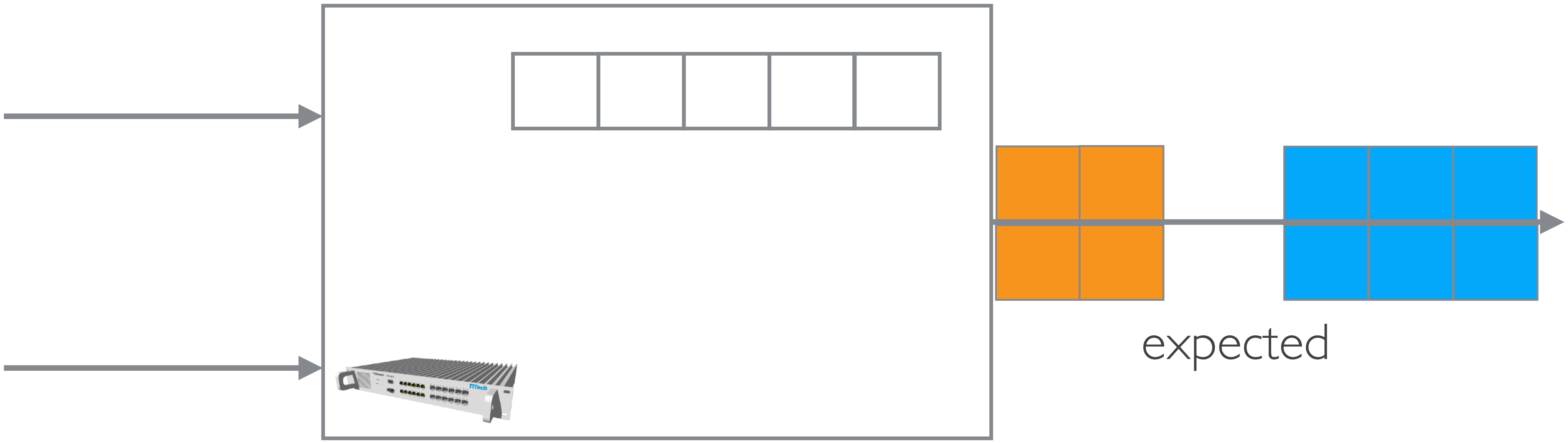

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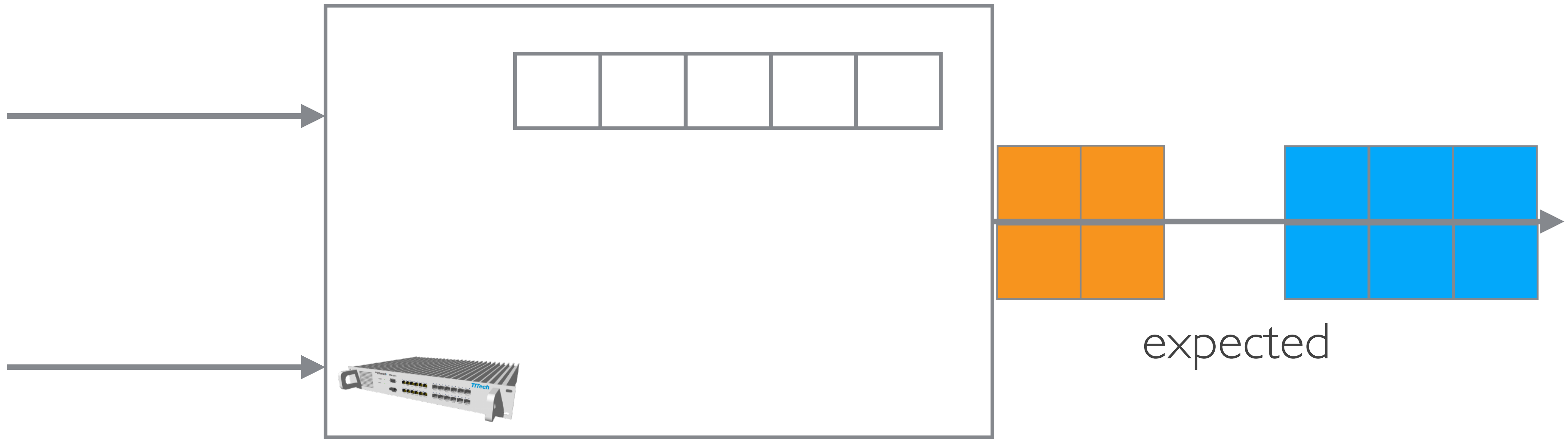

- Once a flow has arrived, no other flow can arrive in the same queue until the first flow has been completely sent
- Better than queue isolation but still restrictive

Stream (Flow) isolation

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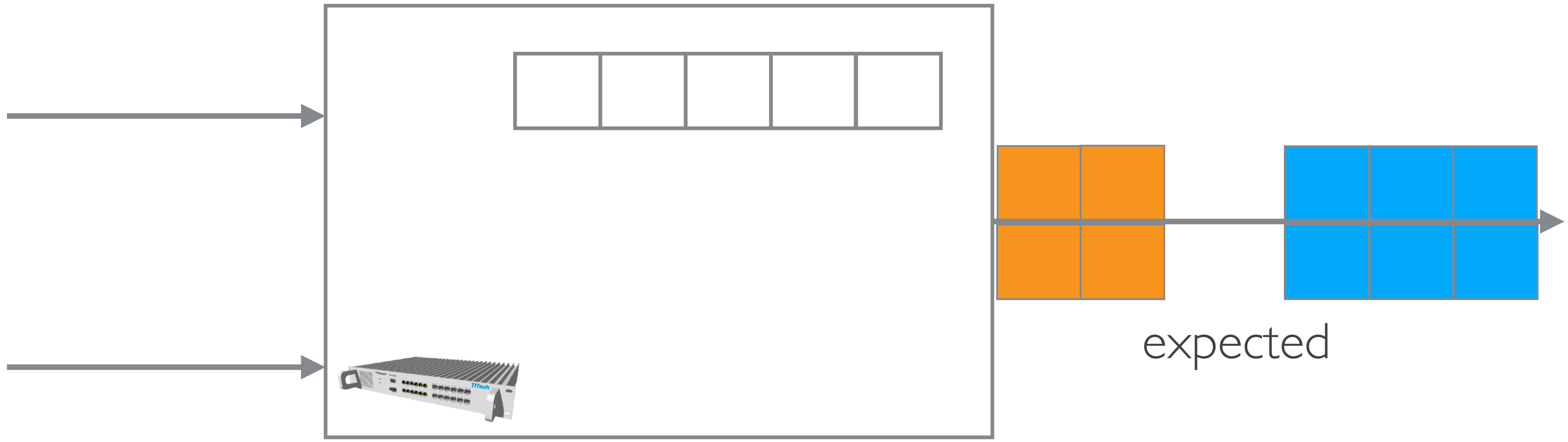

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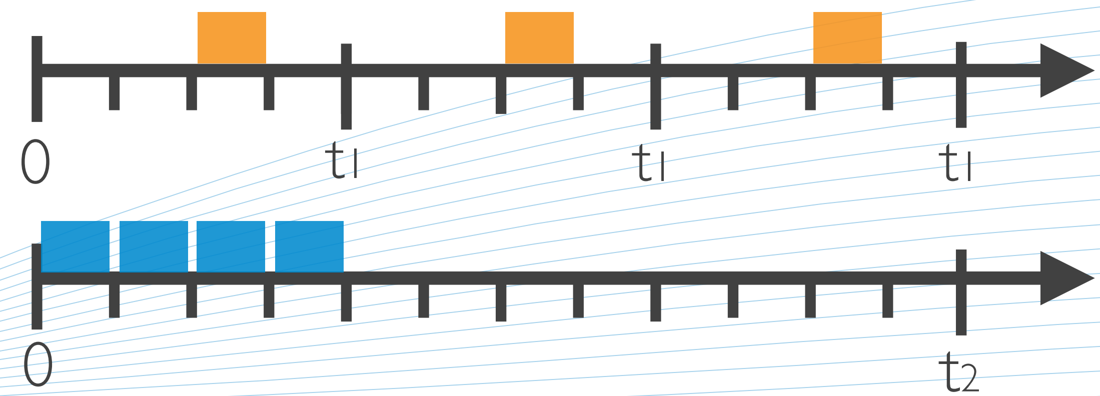

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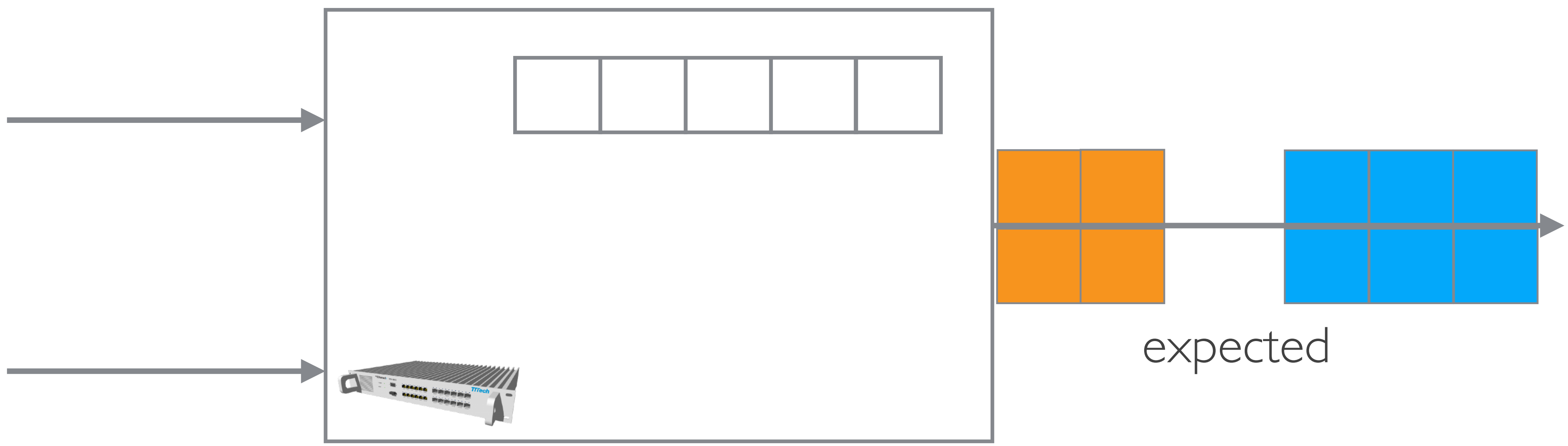

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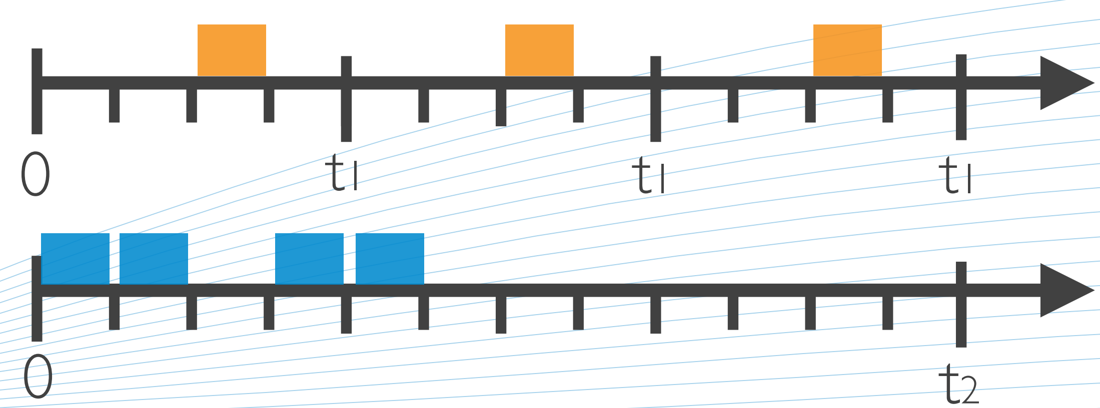

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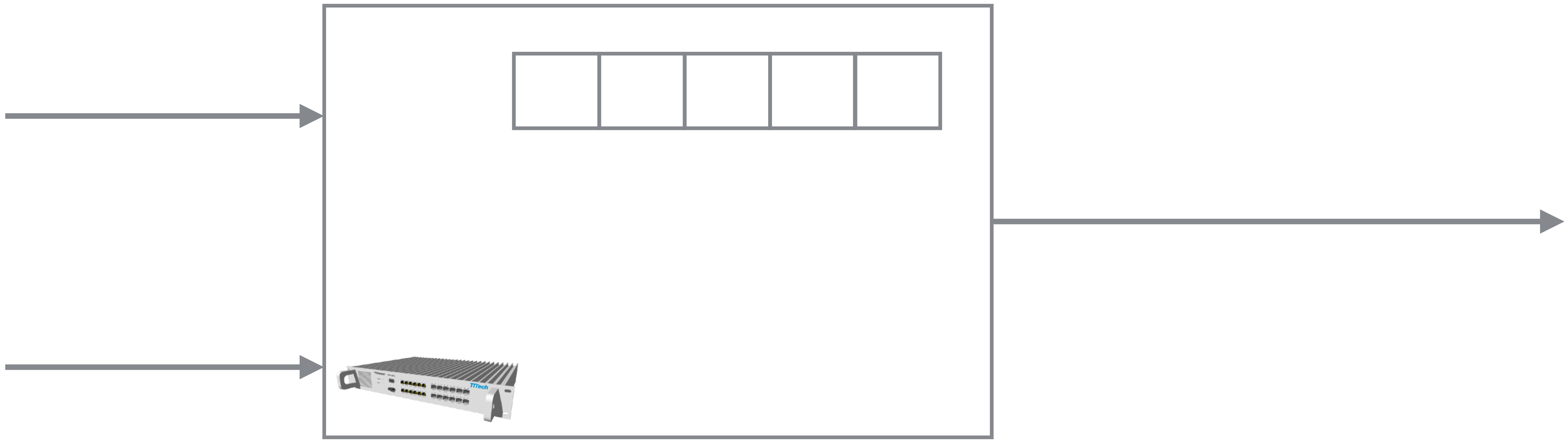

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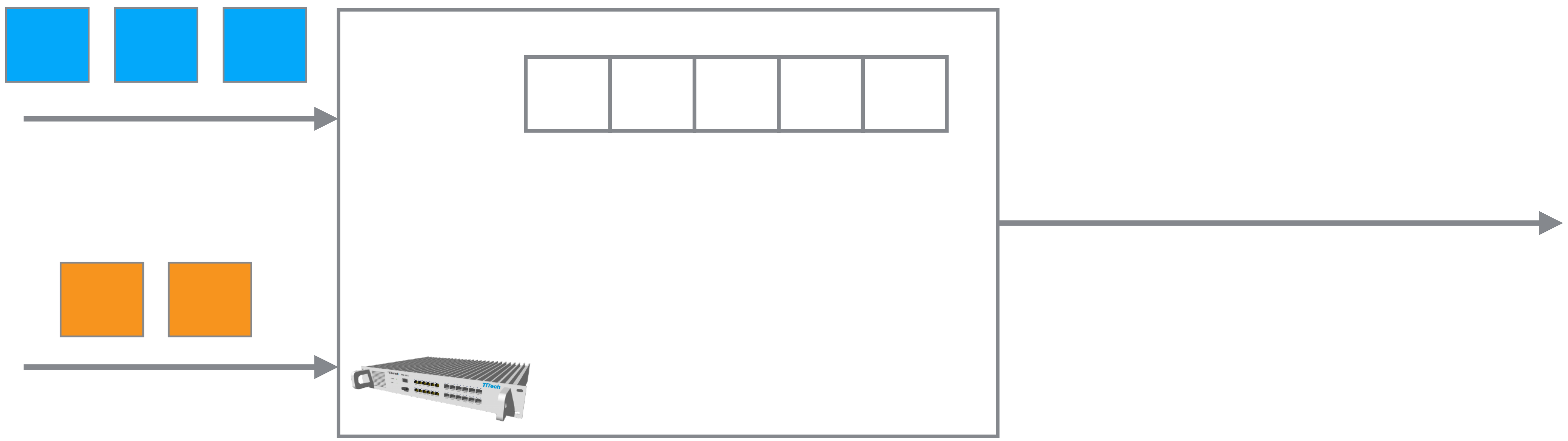

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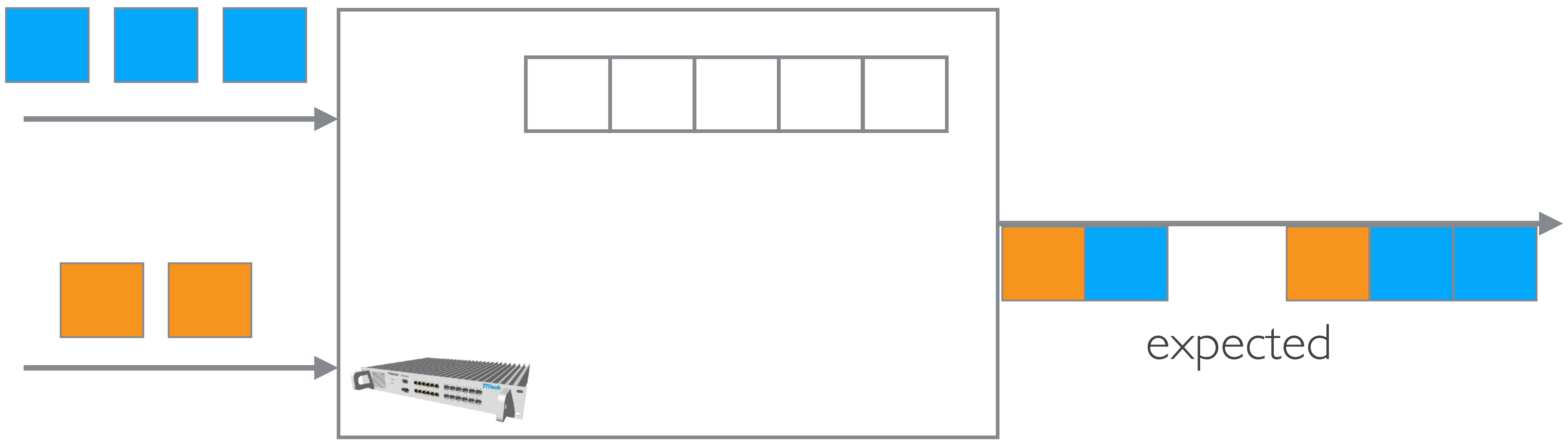

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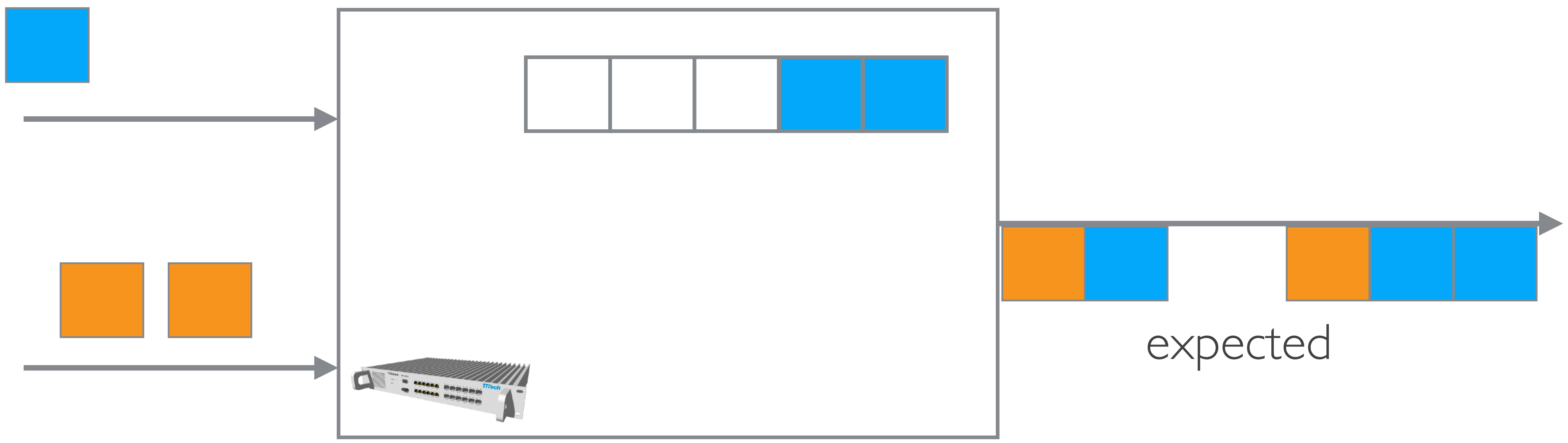

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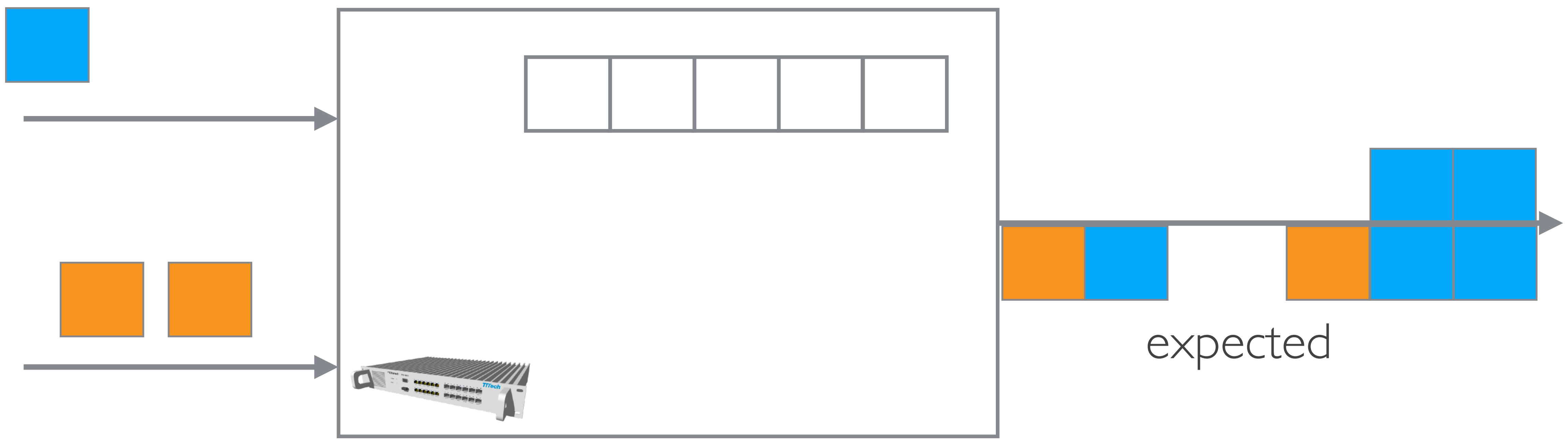

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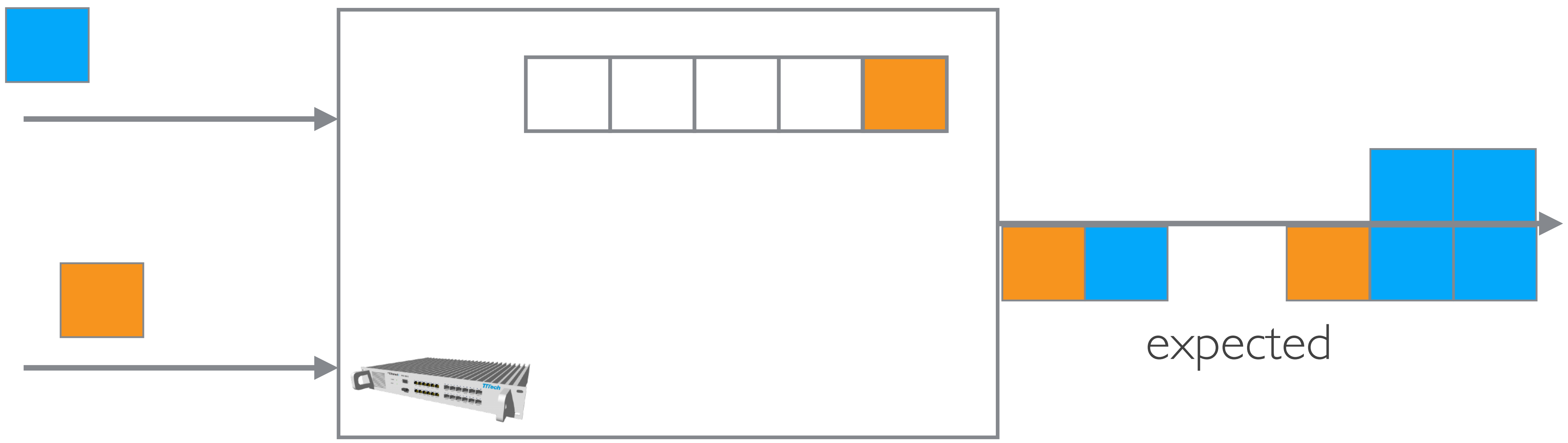

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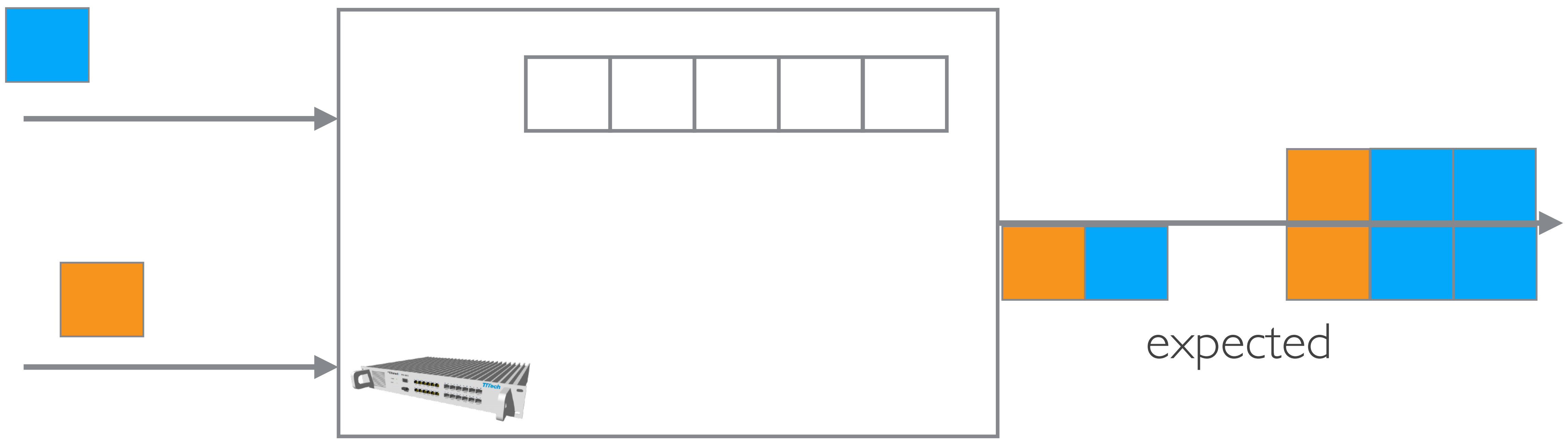
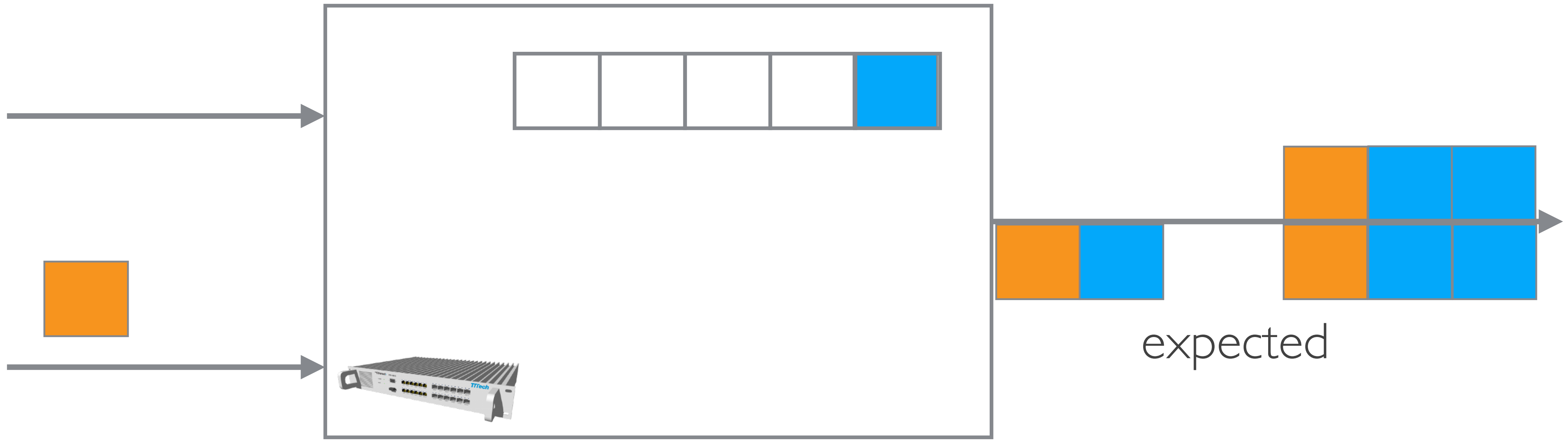


Frame isolation

Ensuring Reliable Networks TTTech



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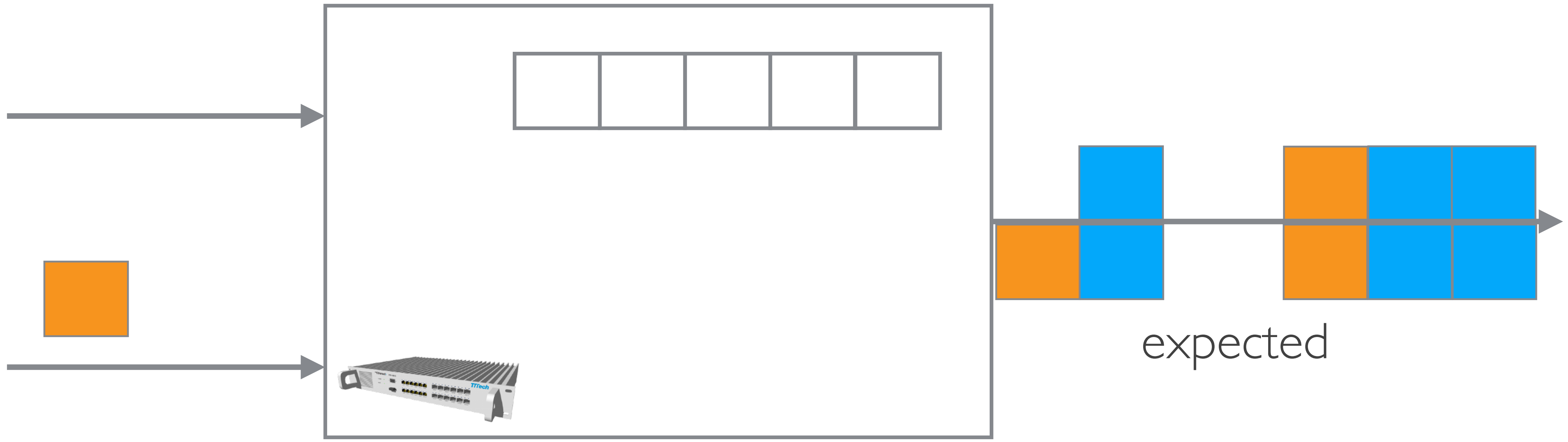

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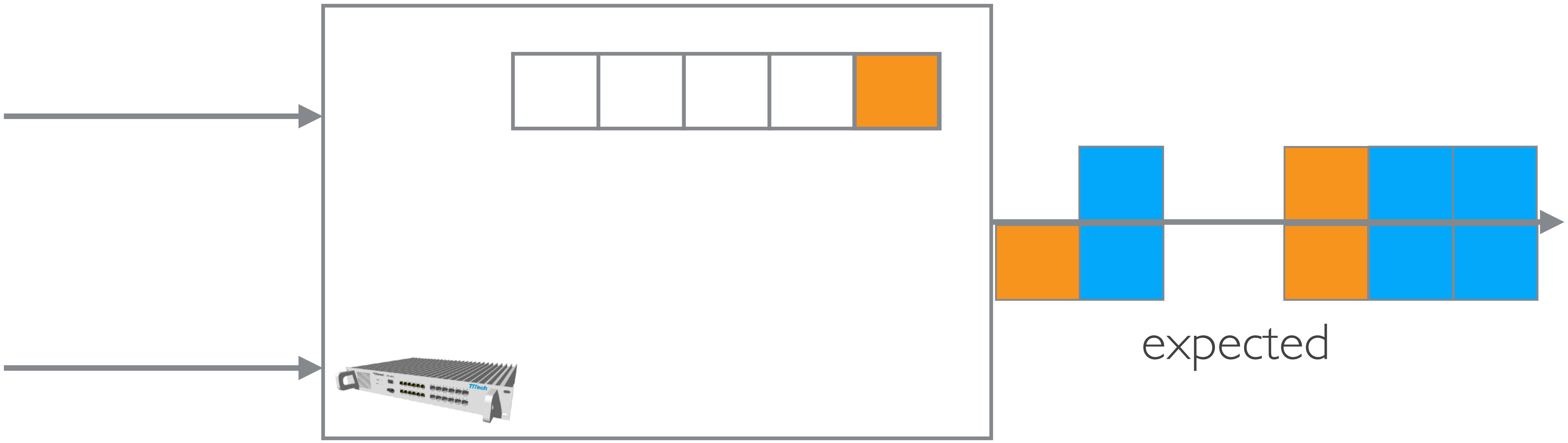

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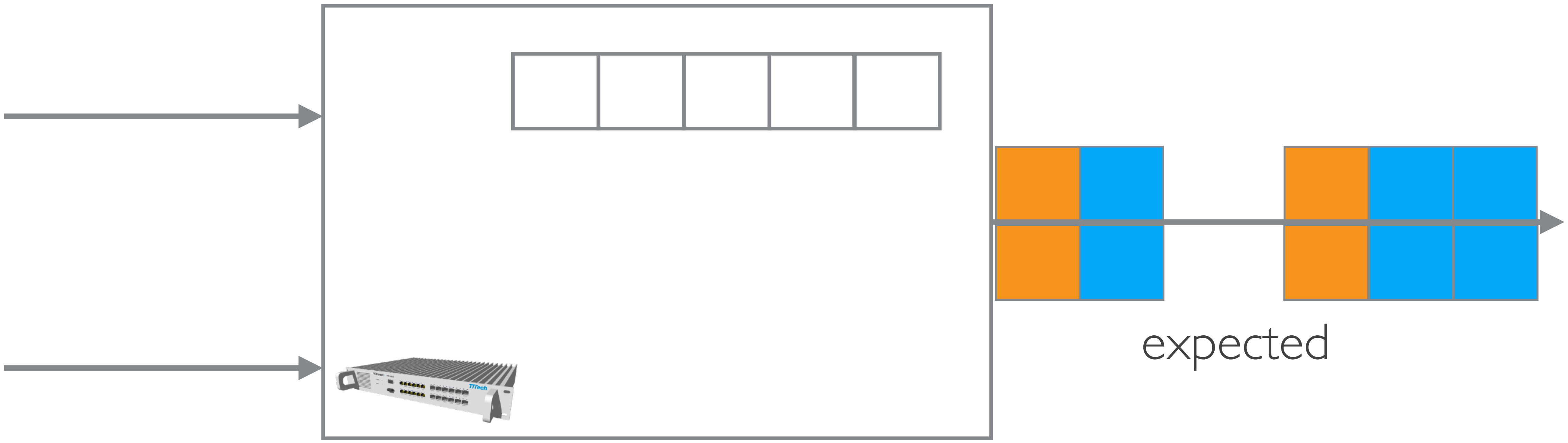

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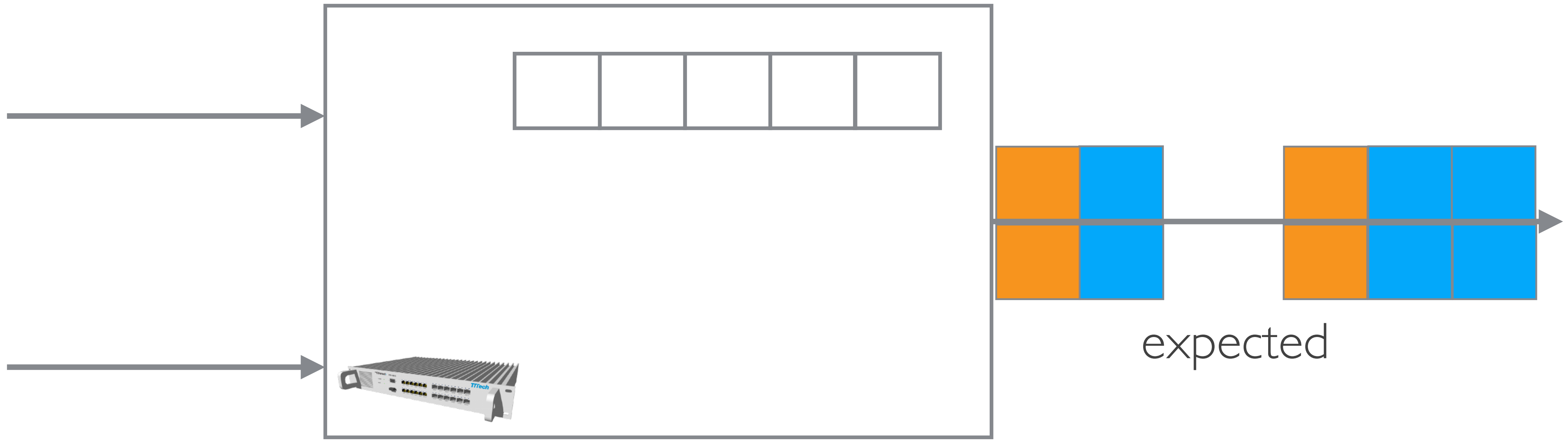

- Ensure that there are only frames of one flow in the queue at a time
- Frames from another flow may only enter the queue if the already queued frames of the initial flow have been serviced
- Less performant than stream isolation since the solver has to consider at all frame interleavings

802.1Qbv scheduling constraint

Ensuring Reliable Networks

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**

802.1Qbv configurations

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

Scheduling problem

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

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- link constraints
- stream constraints
- end-to-end latency constraints
- **stream or frame isolation constraints** ⇨ 802.1Qbv

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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]

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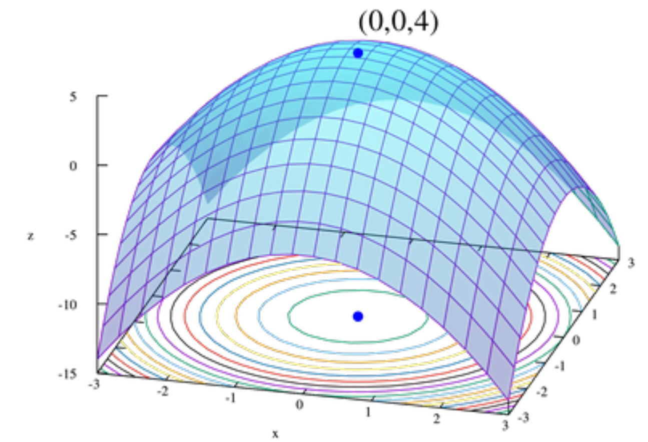
Optimization

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

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- **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

Scalability Experiments

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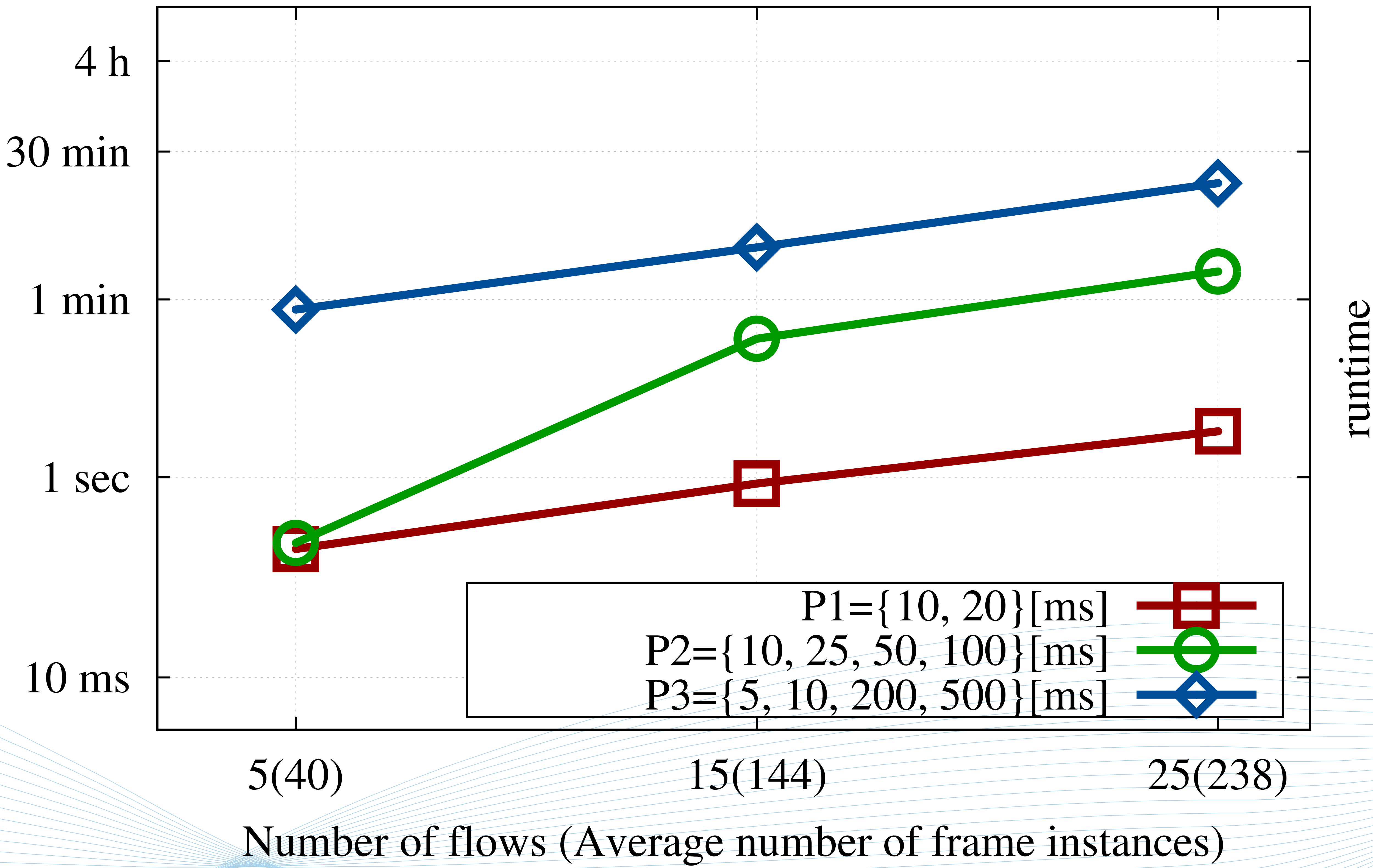
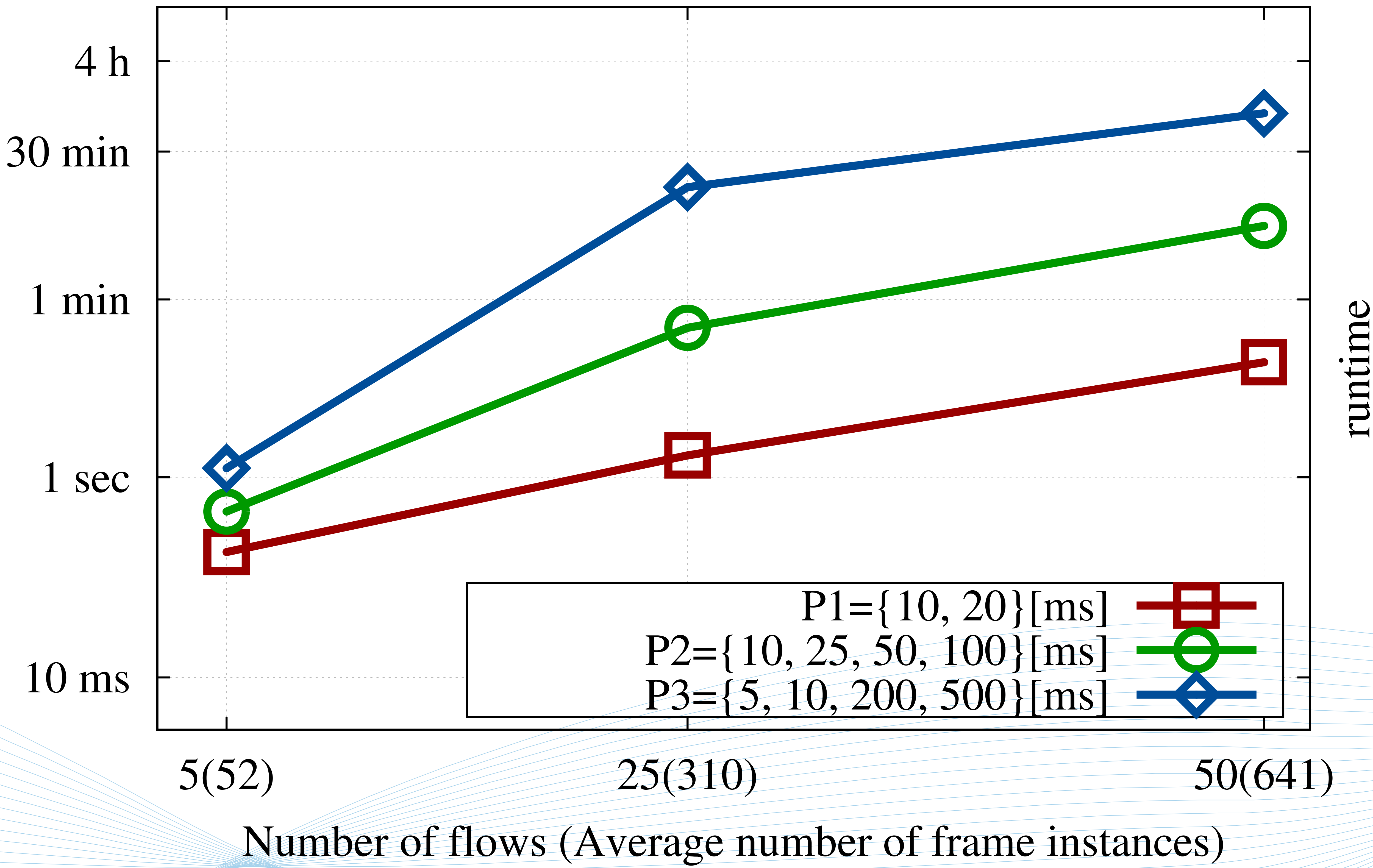
- **Frame isolation** method (using an incremental backtracking algorithm with step size of 1)
- Vary the problem set in **3 dimensions**:
  1. topology size,
  2. number of flows,
  3. flow periods (chosen randomly from 3 sets of predefined periods)
- Data size uniformly between **2** and **8 MTU**-sized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

Scalability Experiments



Scalability Experiments

Ensuring Reliable Networks TTTech



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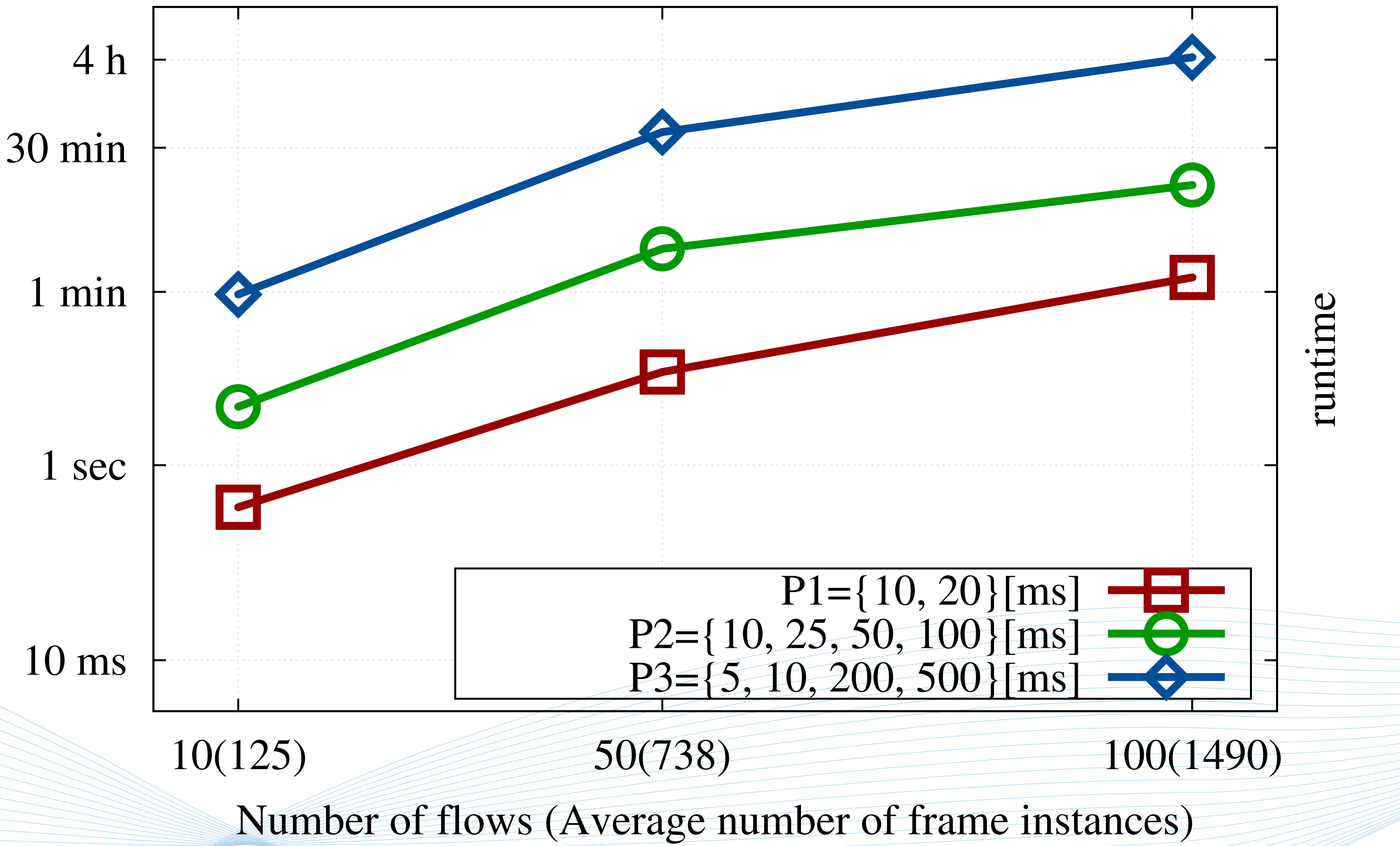
Ensuring Reliable Networks TTTech



Frame vs. Stream Isolation

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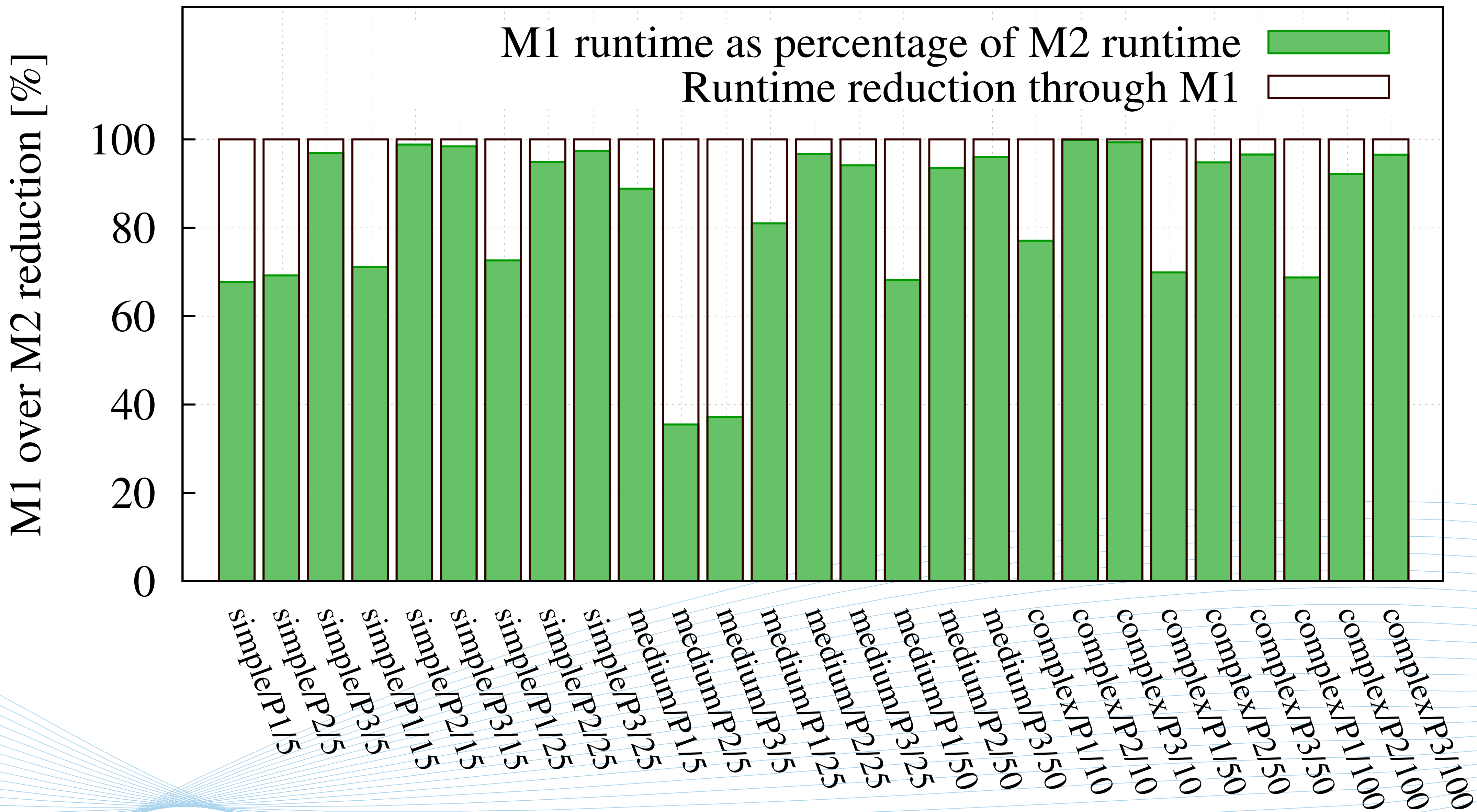
- **381** randomly generated test cases with up to **1000 streams**
- **17** reached the **time-out**
- Stream isolation was on average **13%** faster with a median of **8.03%**
- **36.7h** for stream isolation and **59h** for frame isolation - **30.73%** improvement



Schedulability Experiments

- 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

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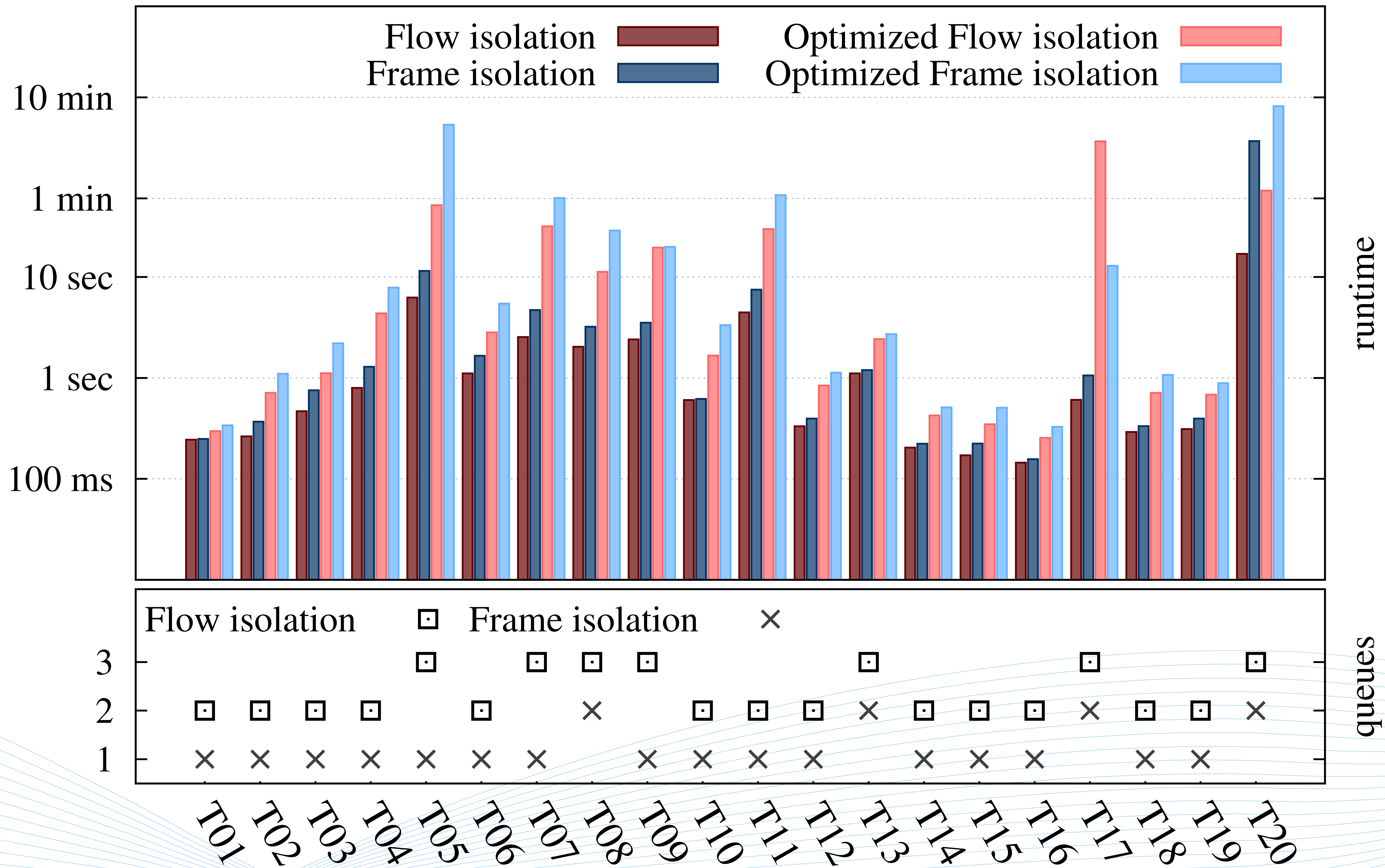

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Thank you!

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