Ensuring Reliable Networks TTTech

SMT-based task- and network-level static schedule generation for time-triggered networked systems

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TTTech Computertechnik AG
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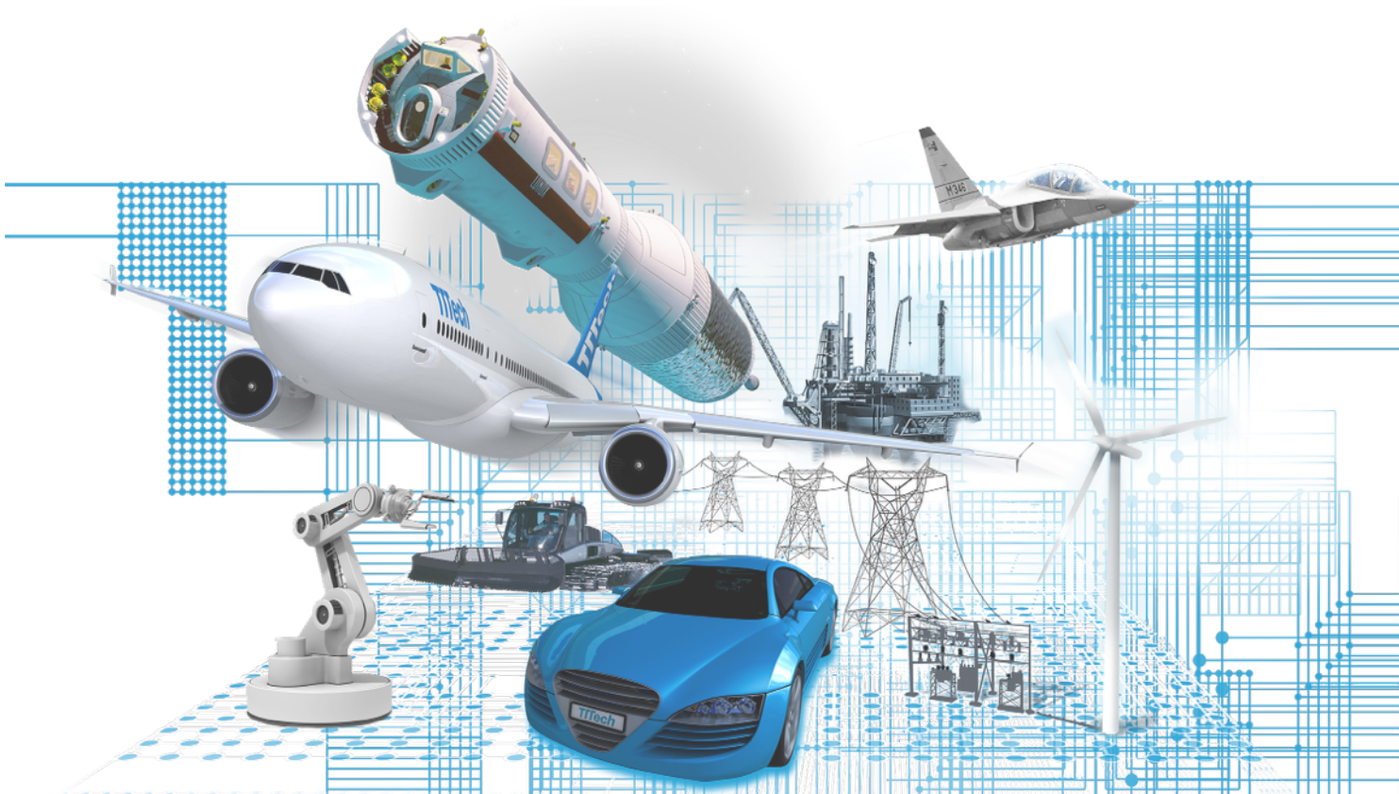

DREAMS

Time Triggered Networks

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Time triggered communication

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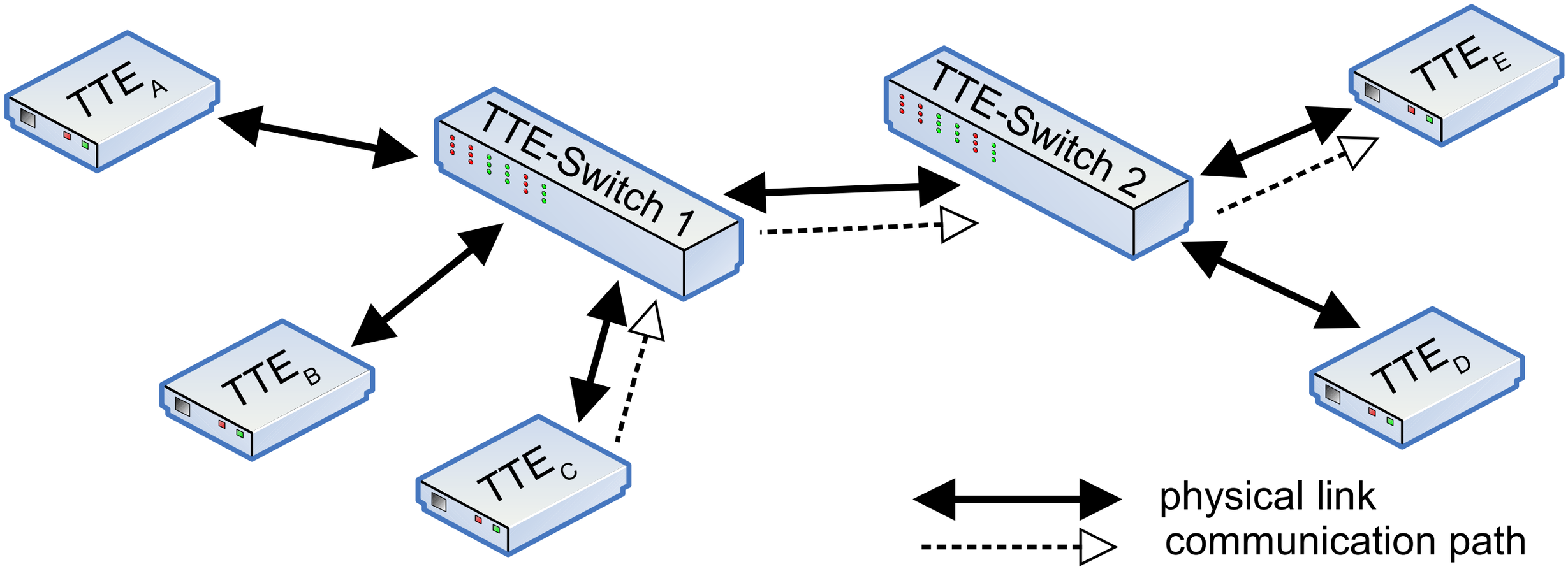

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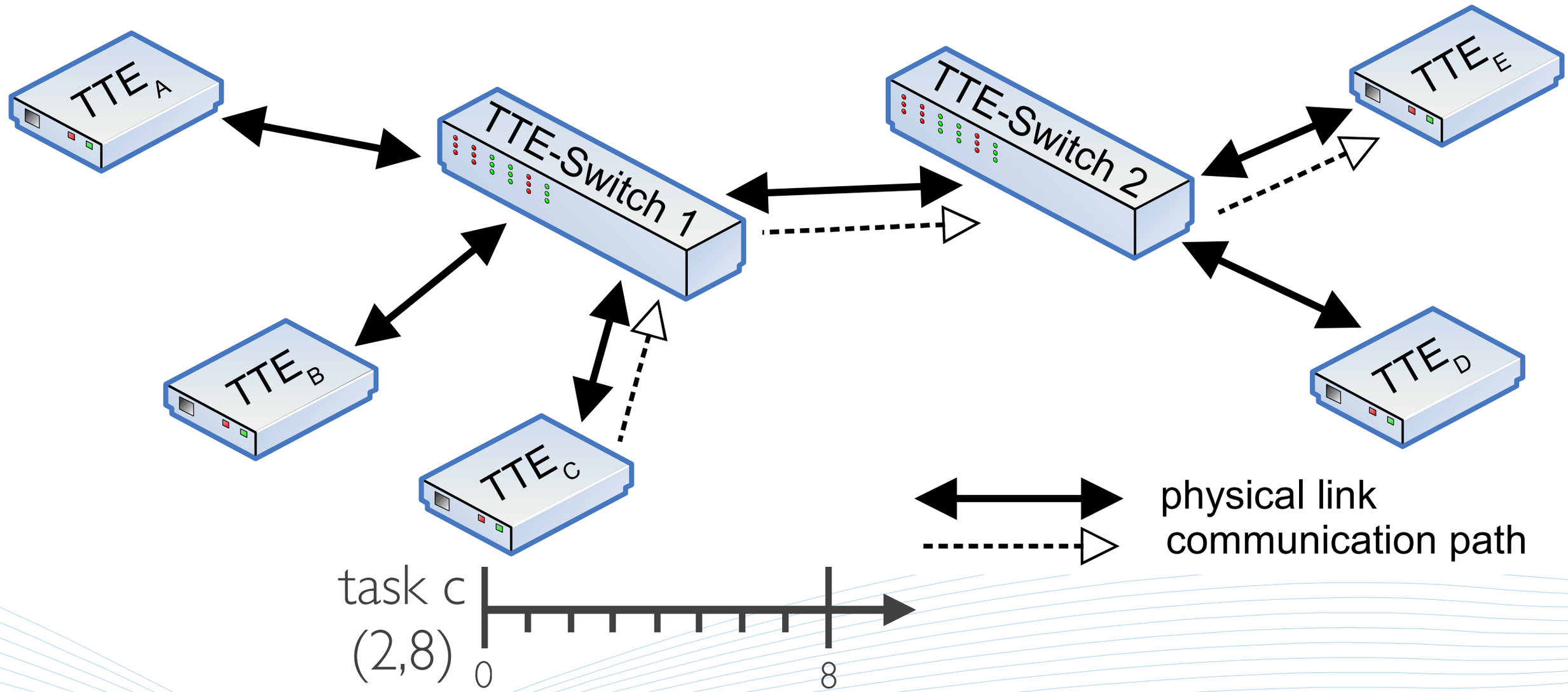

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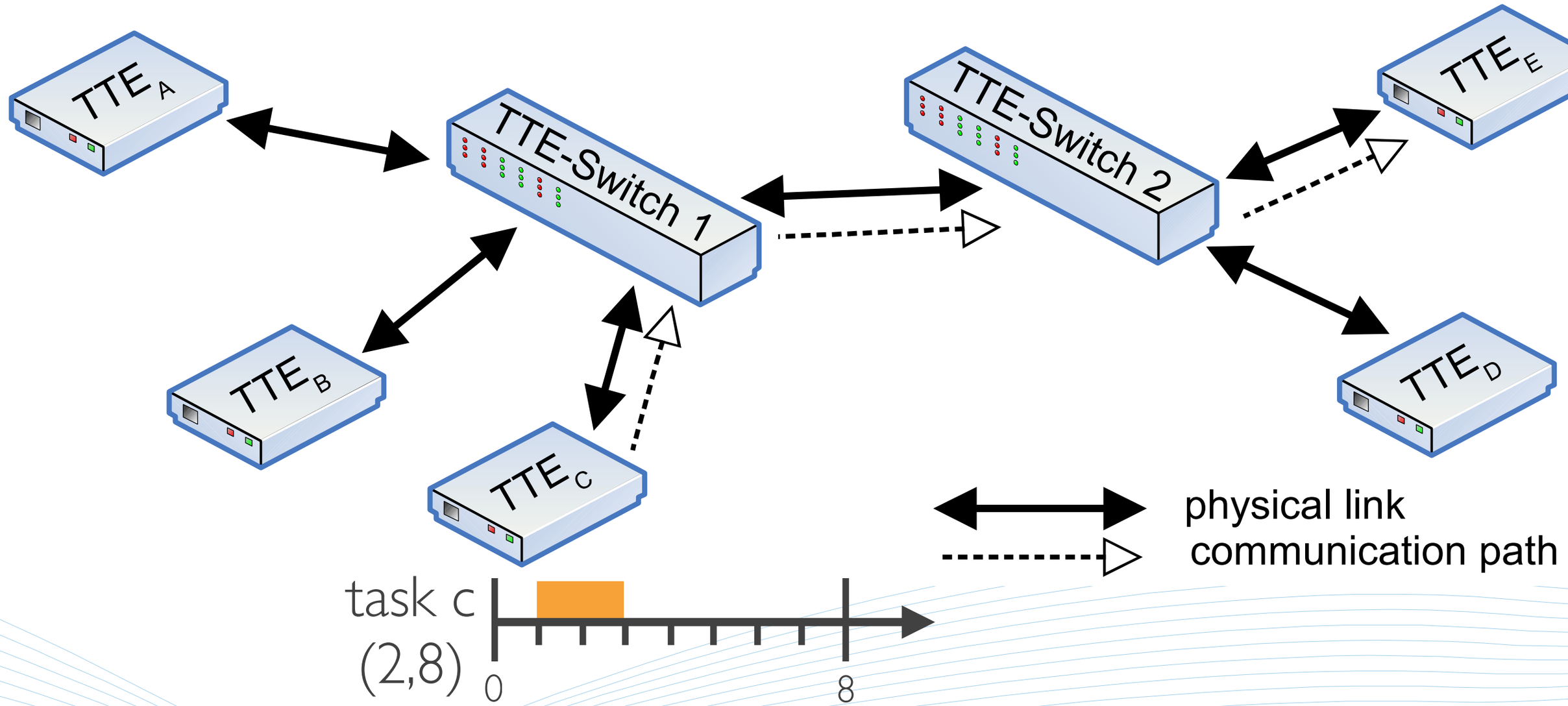

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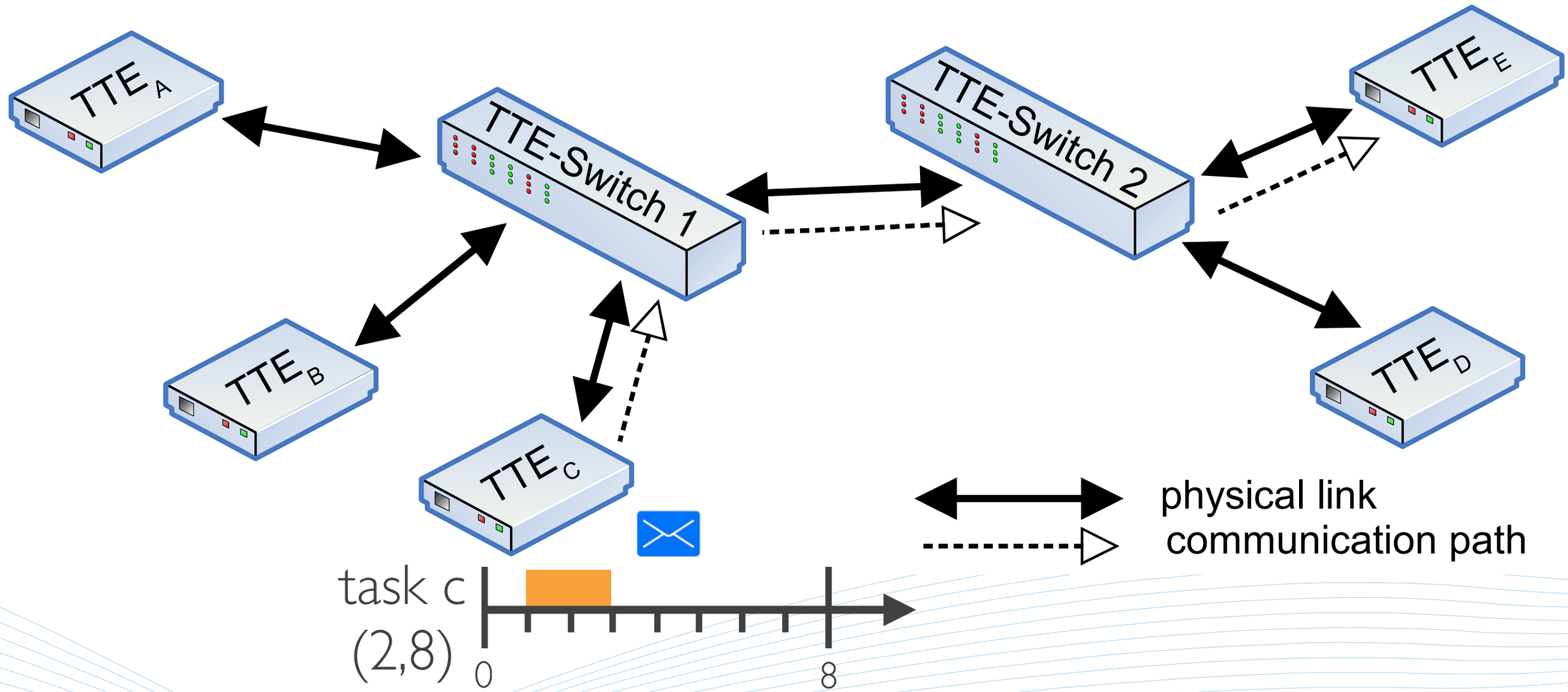

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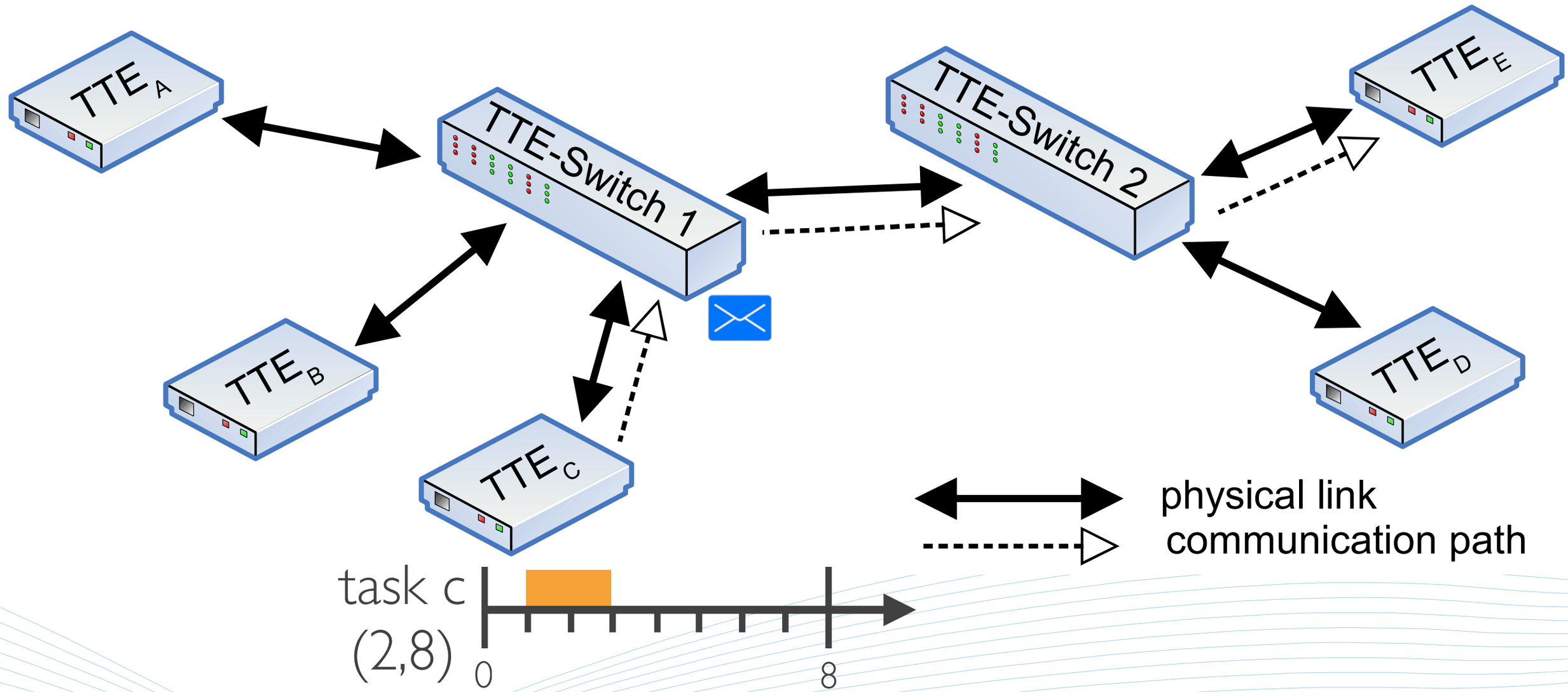

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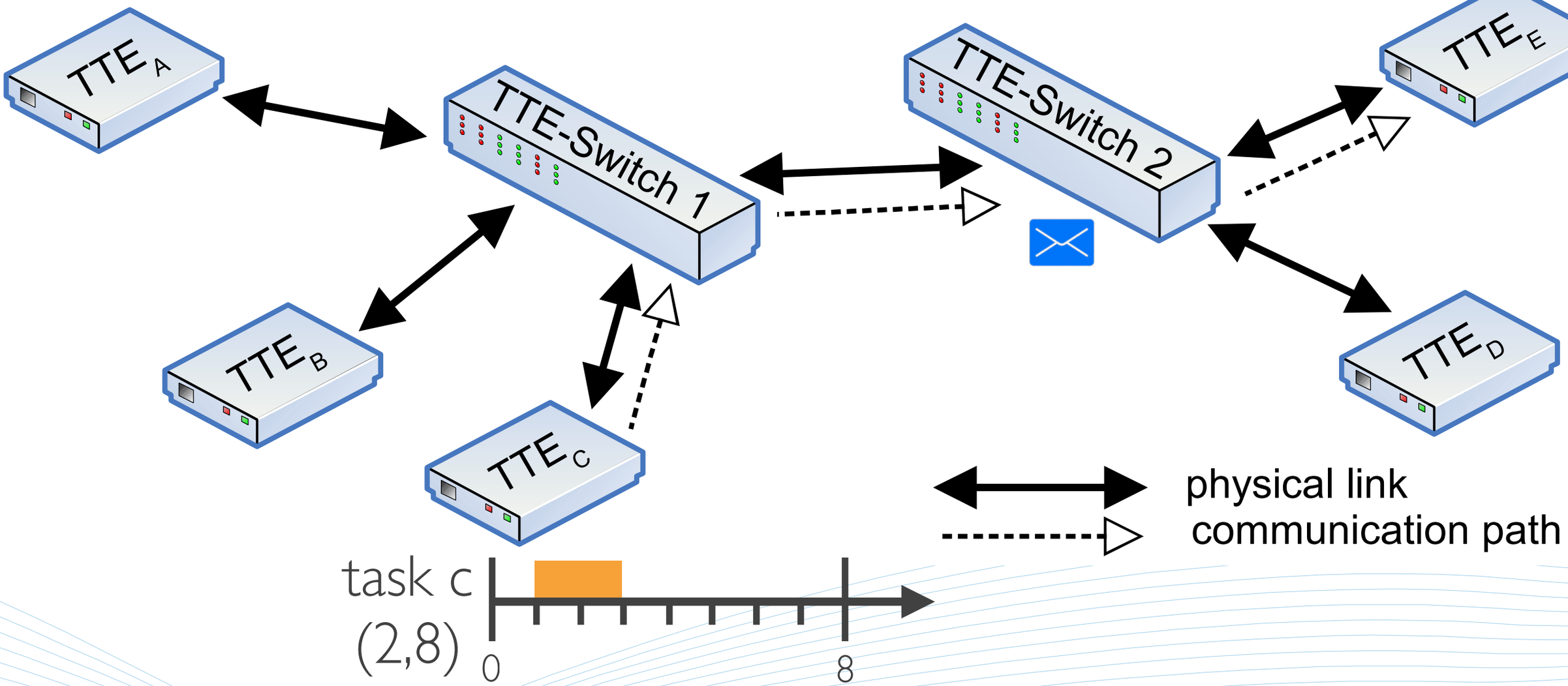

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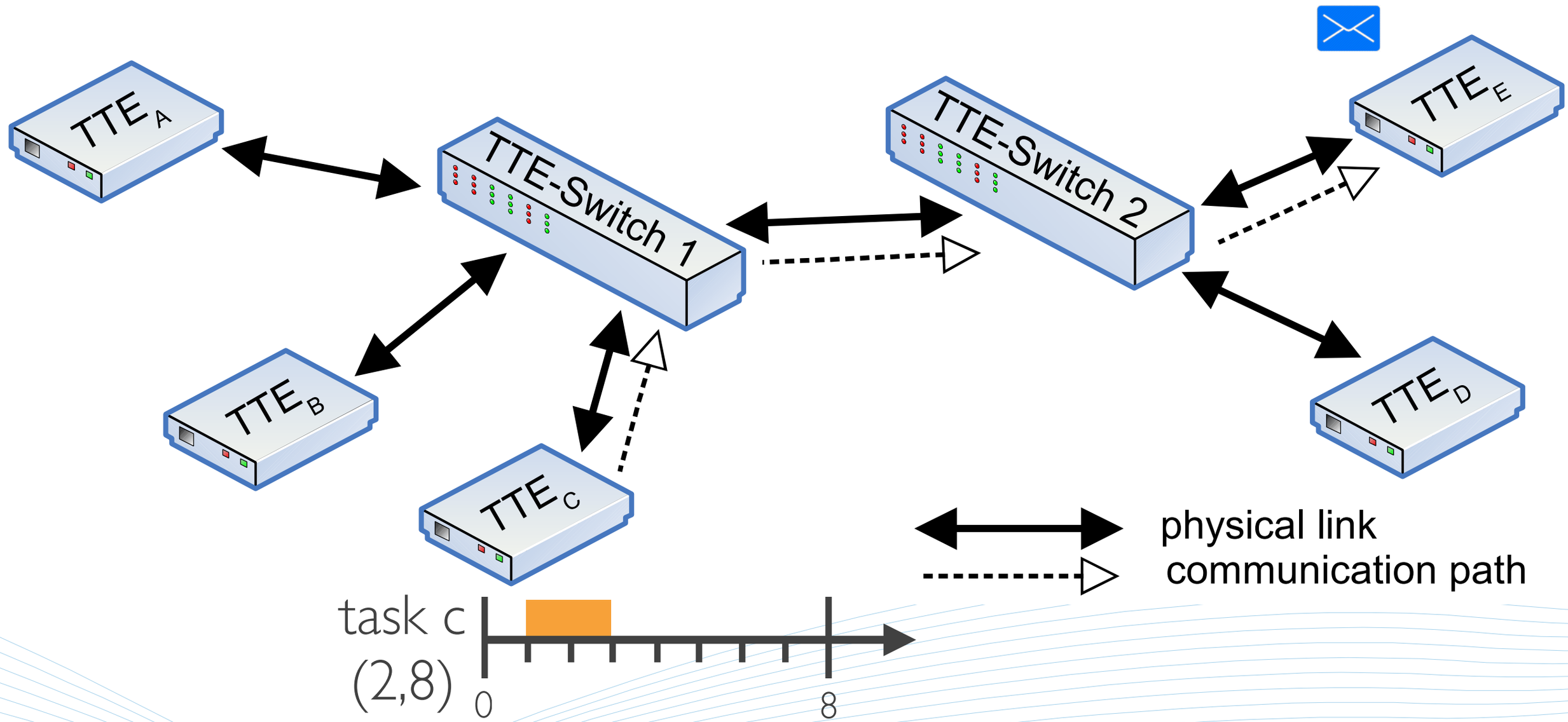

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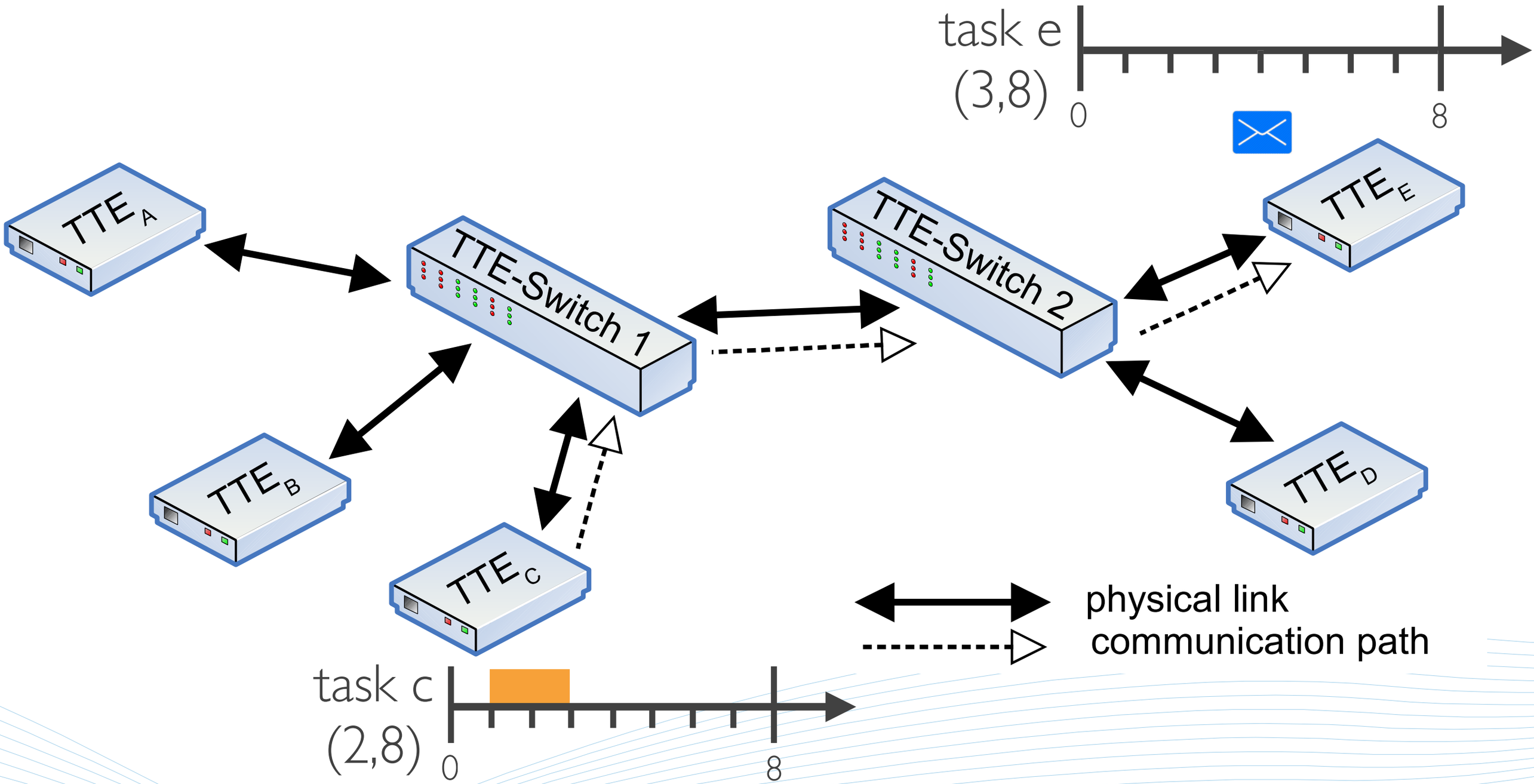

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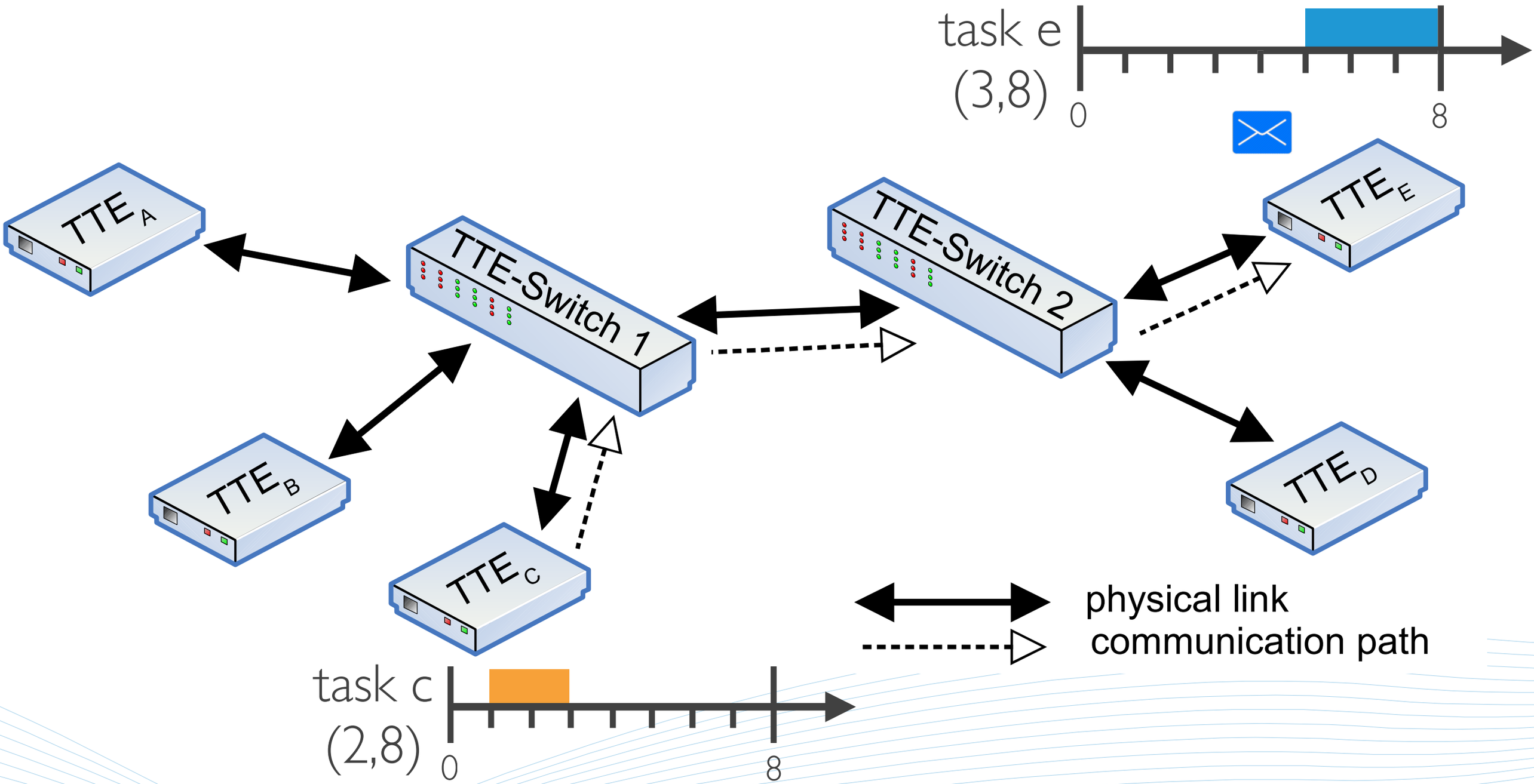

Scheduling

Scheduling

Sequential scheduling

- Network [Steiner@RTSS10] ▷ Tasks [Craciunas@ETFA14]
- Tasks ▷ Network [Hanzalek@ECRTS09]

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Network model

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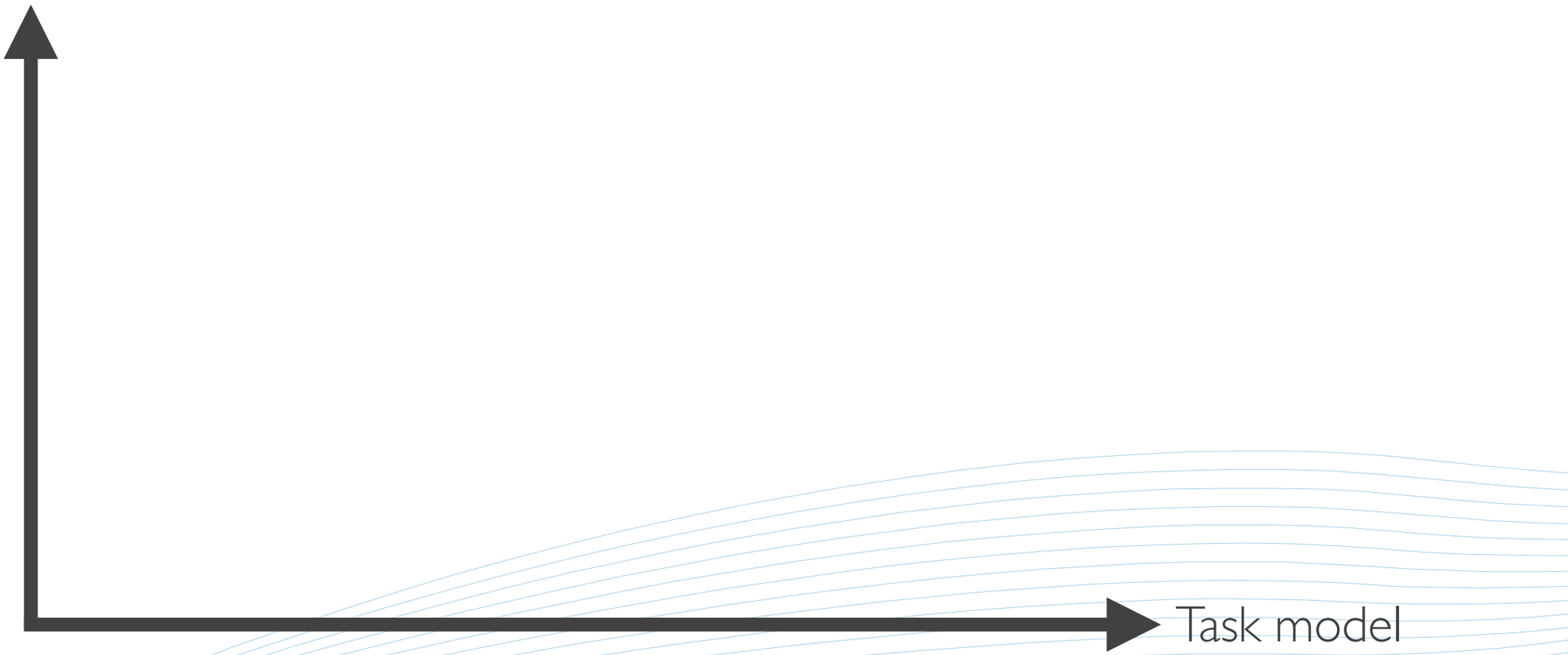

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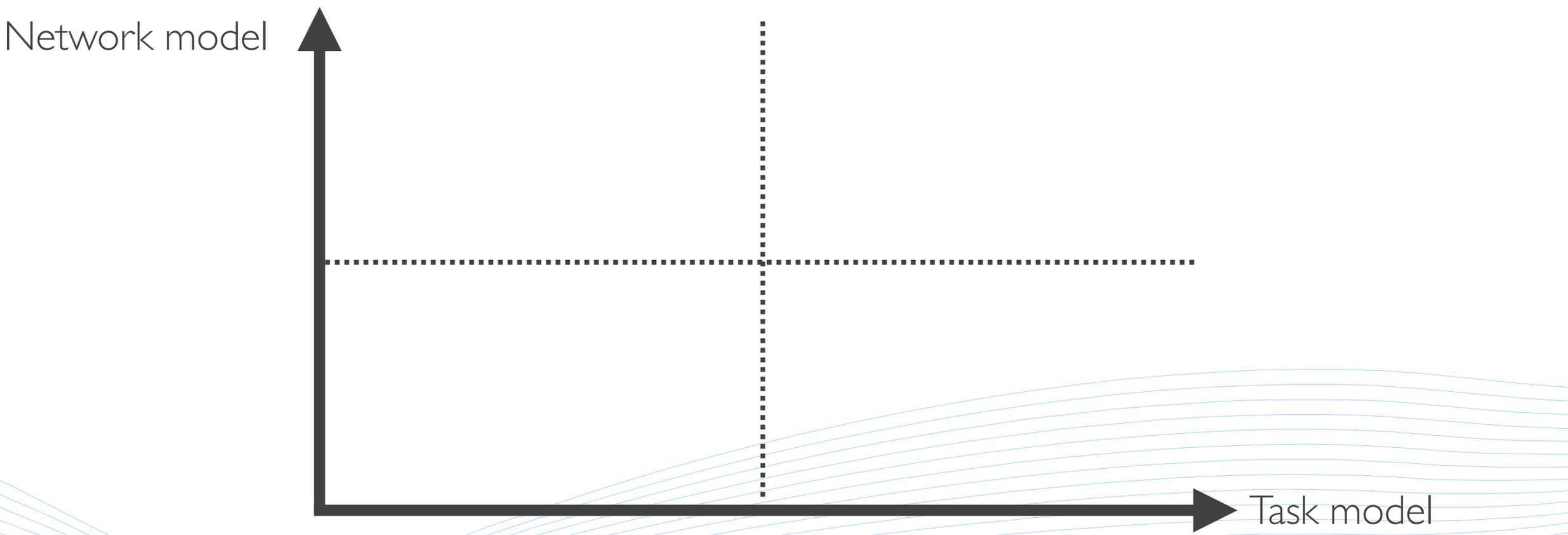

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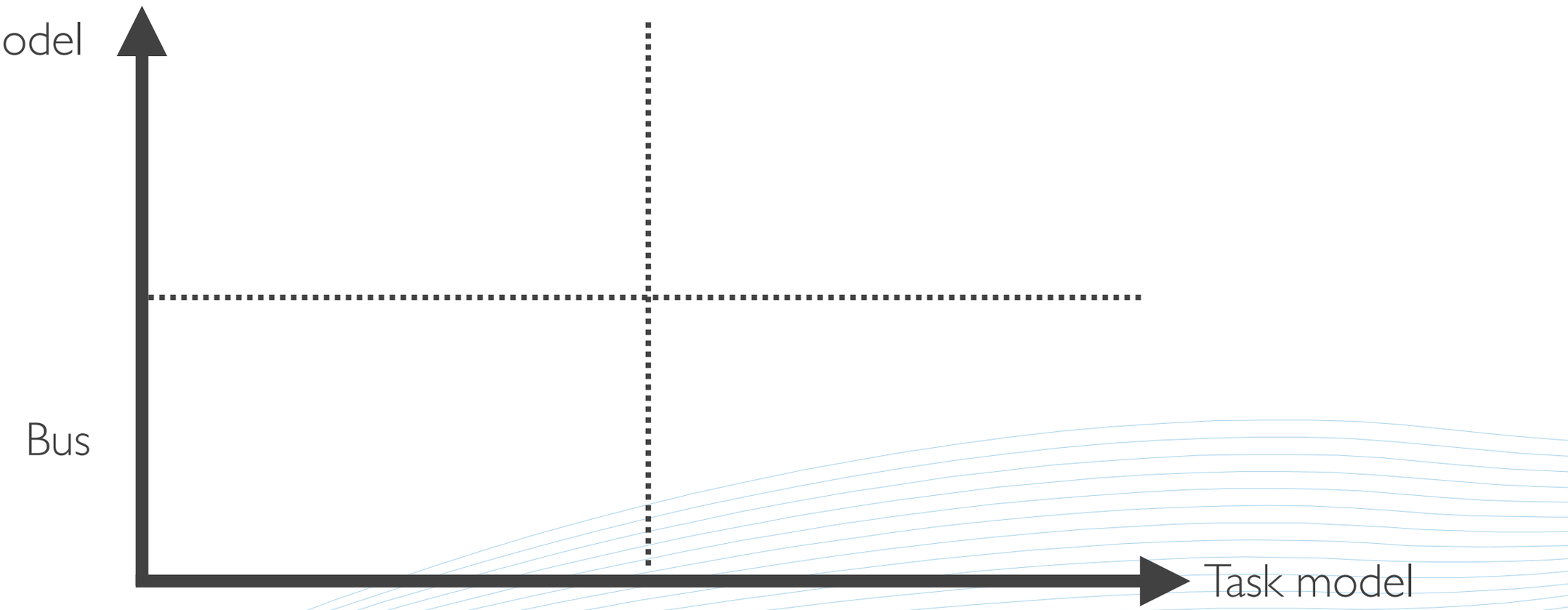

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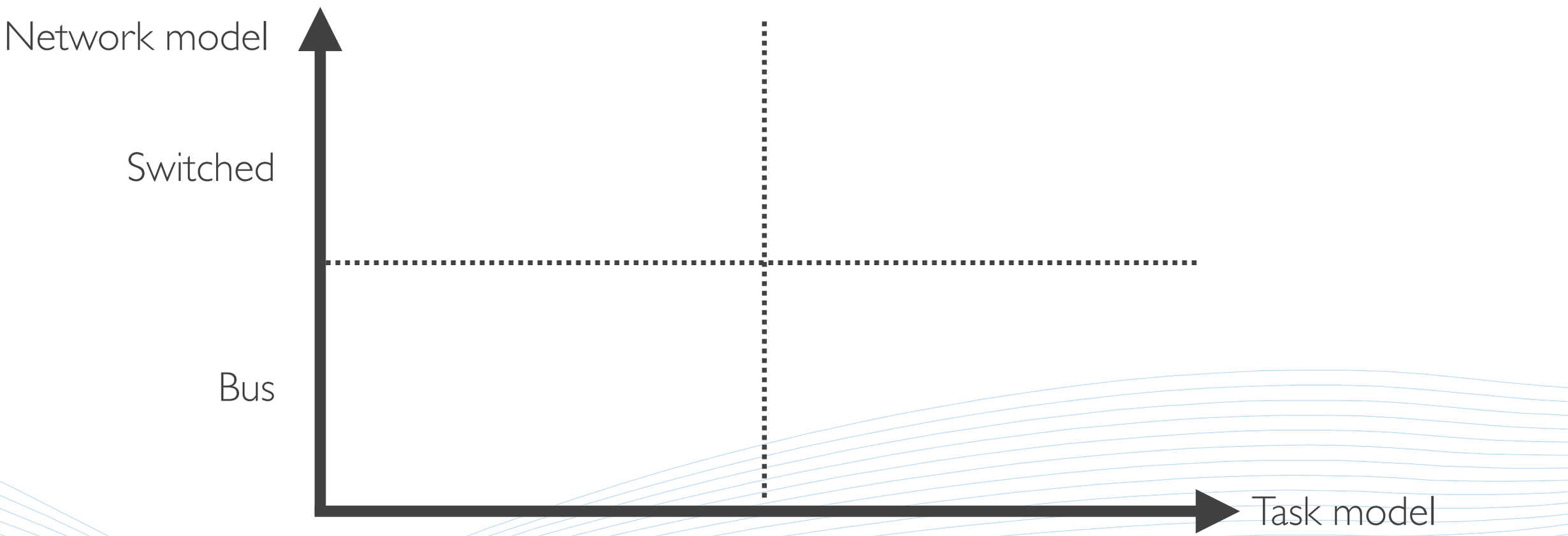

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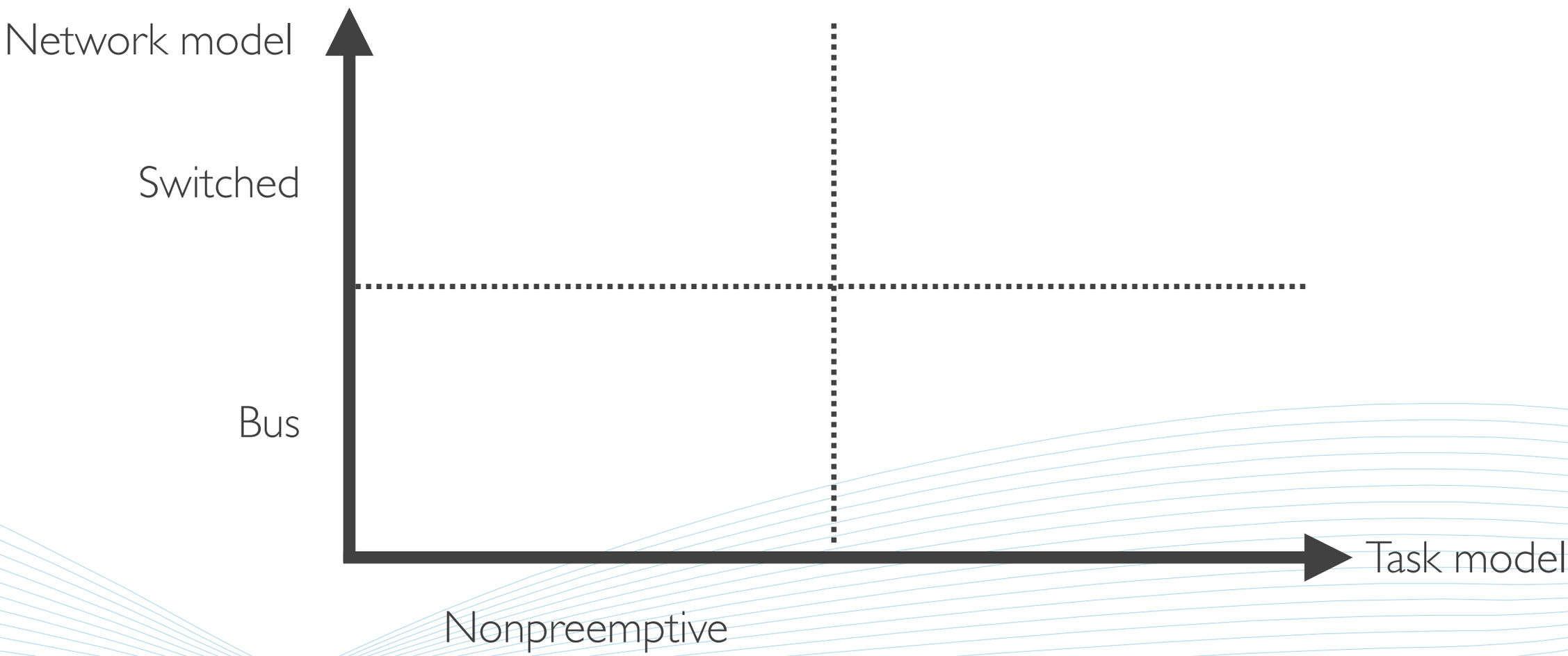

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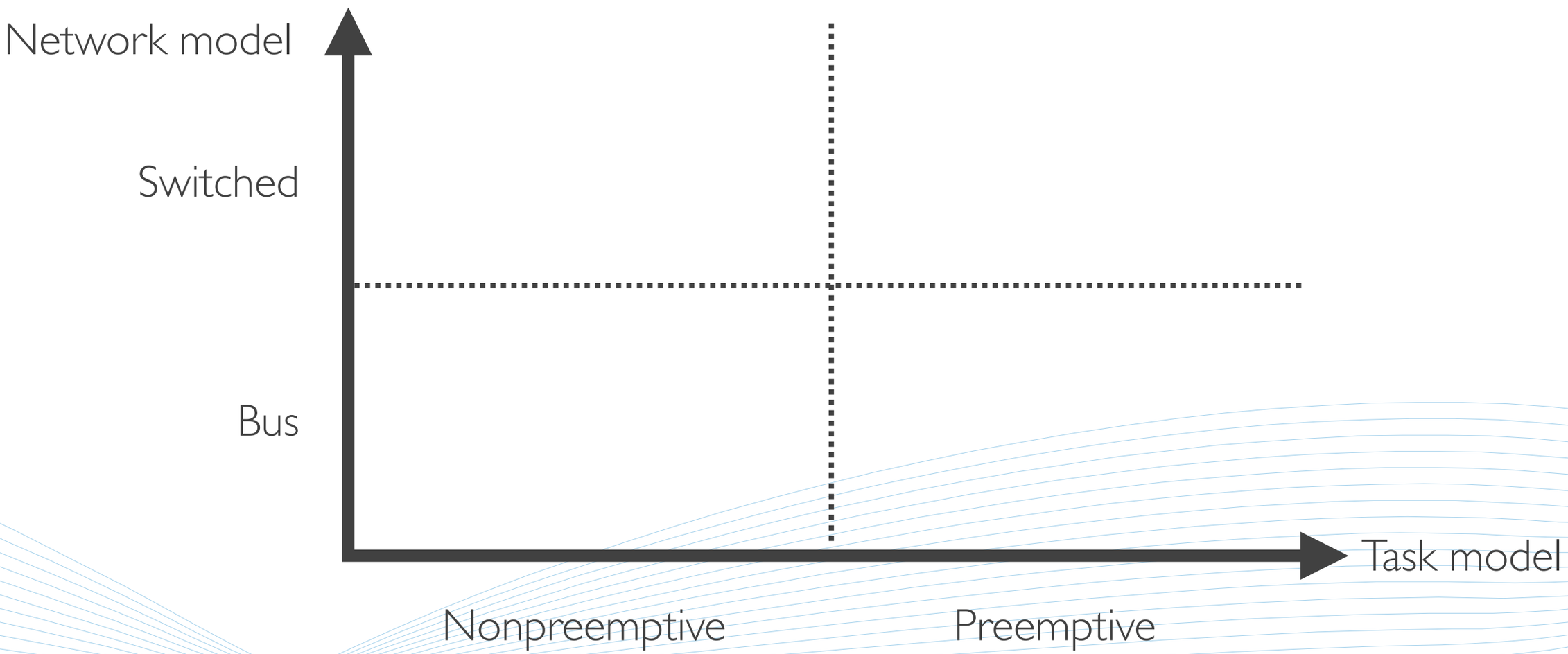

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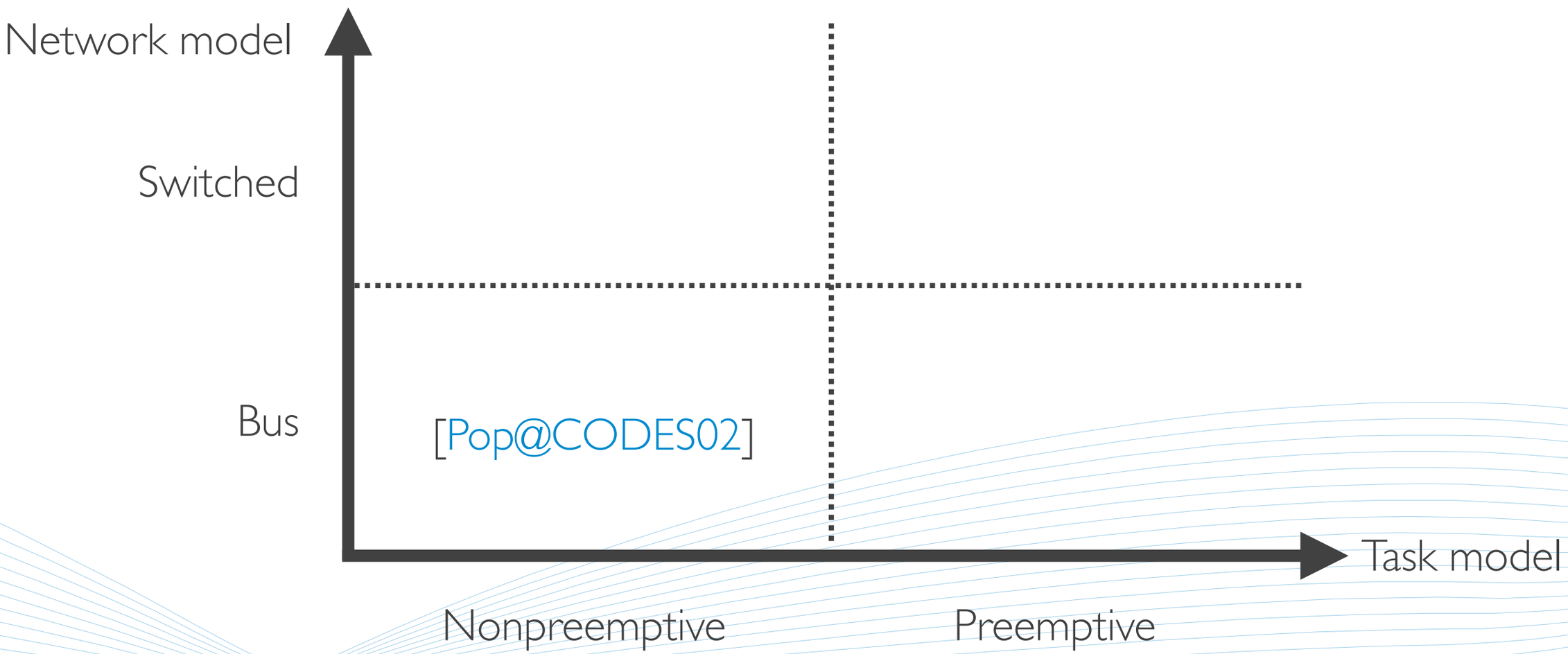

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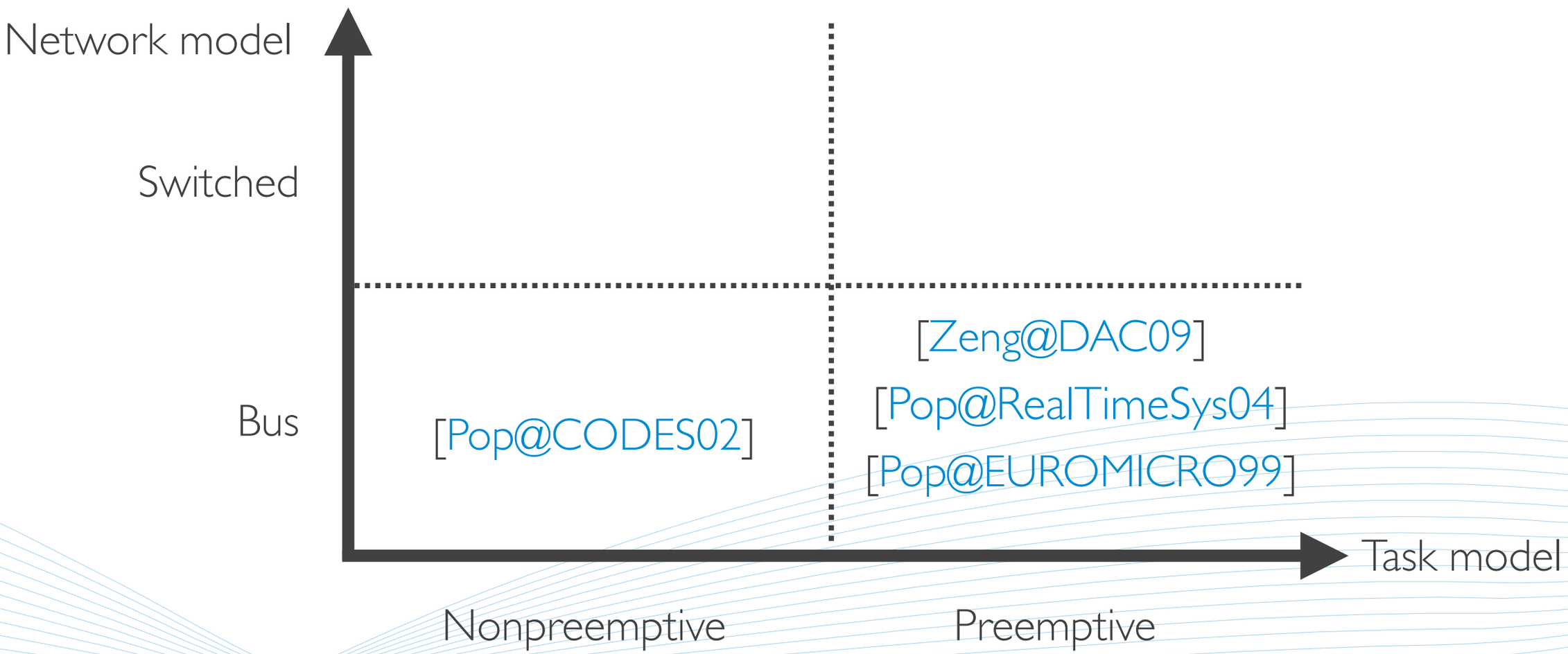

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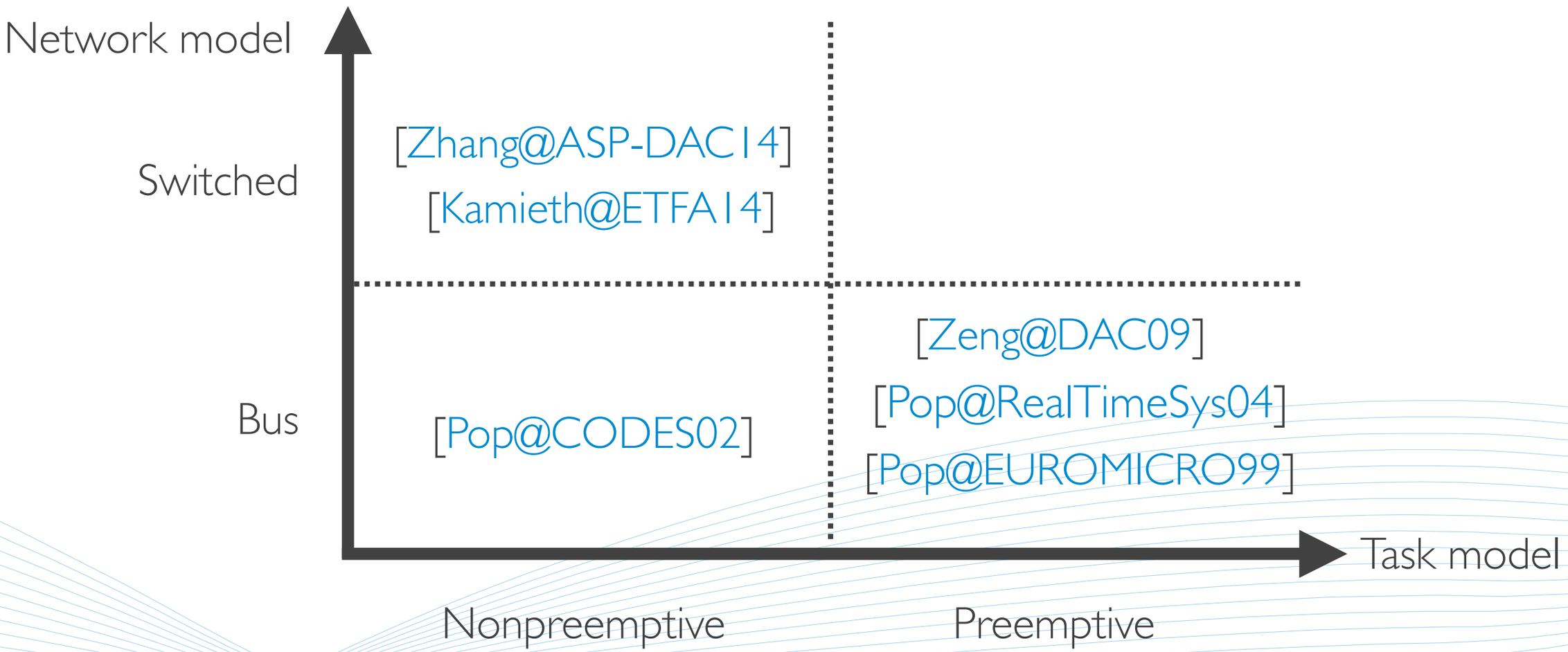

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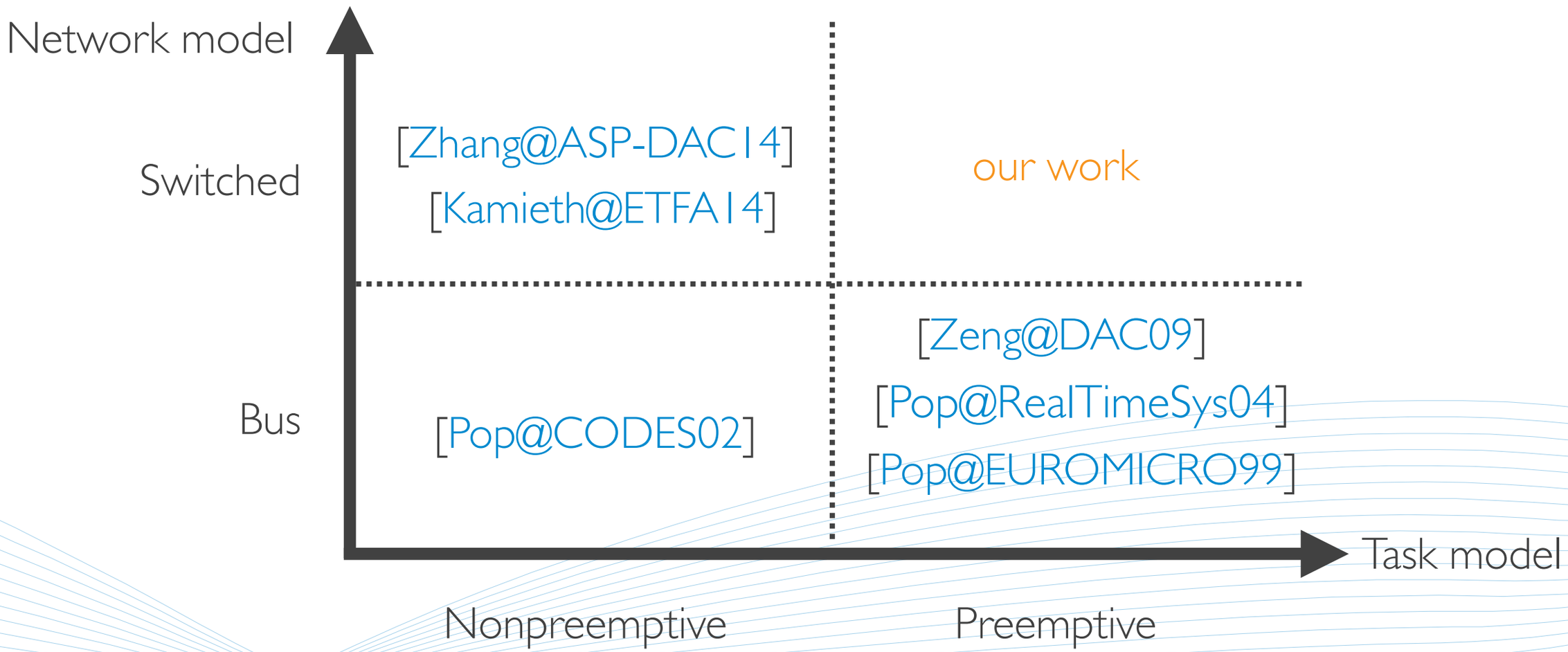
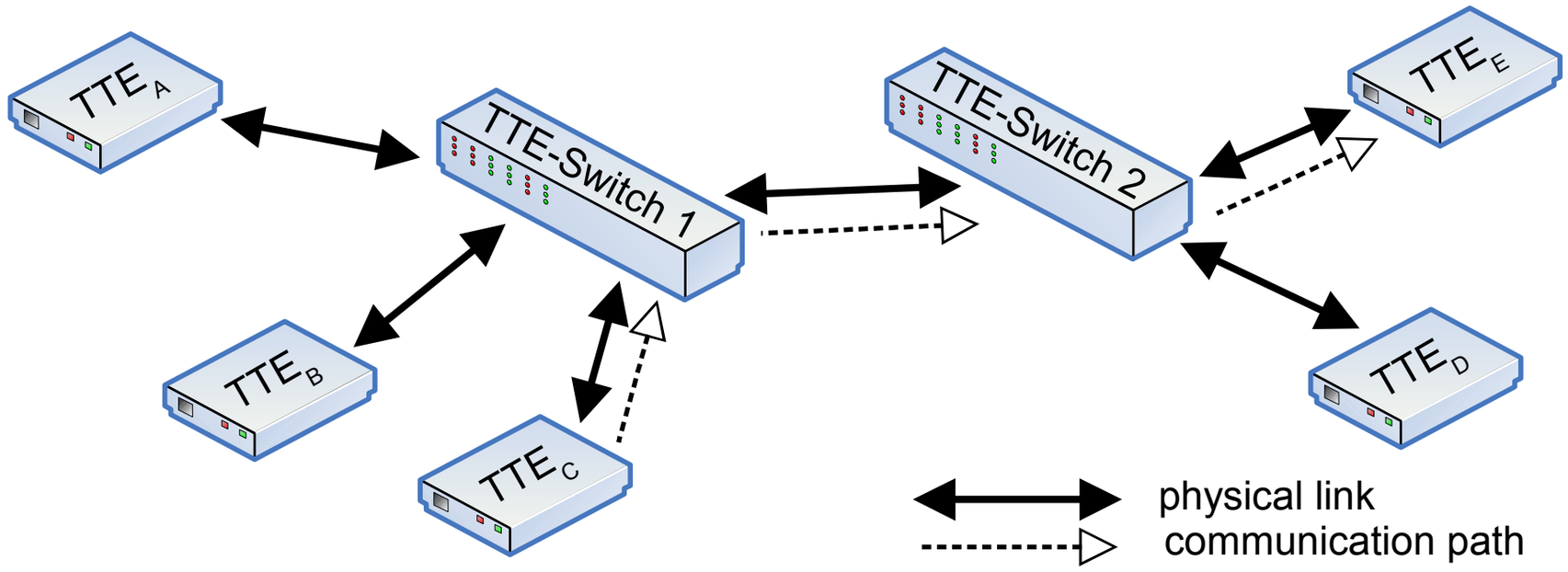


Network model



- multi-hop layer 2 switched network via full-duplex multi-speed links
- virtual links (ARINC 664 P-7)
- TT-traffic class (RC [Tamas-Selicean@CODES+ISSS12], BE)
- synchronised time (< 1 used precision)
- link delay for each link
- memory buffers on switches

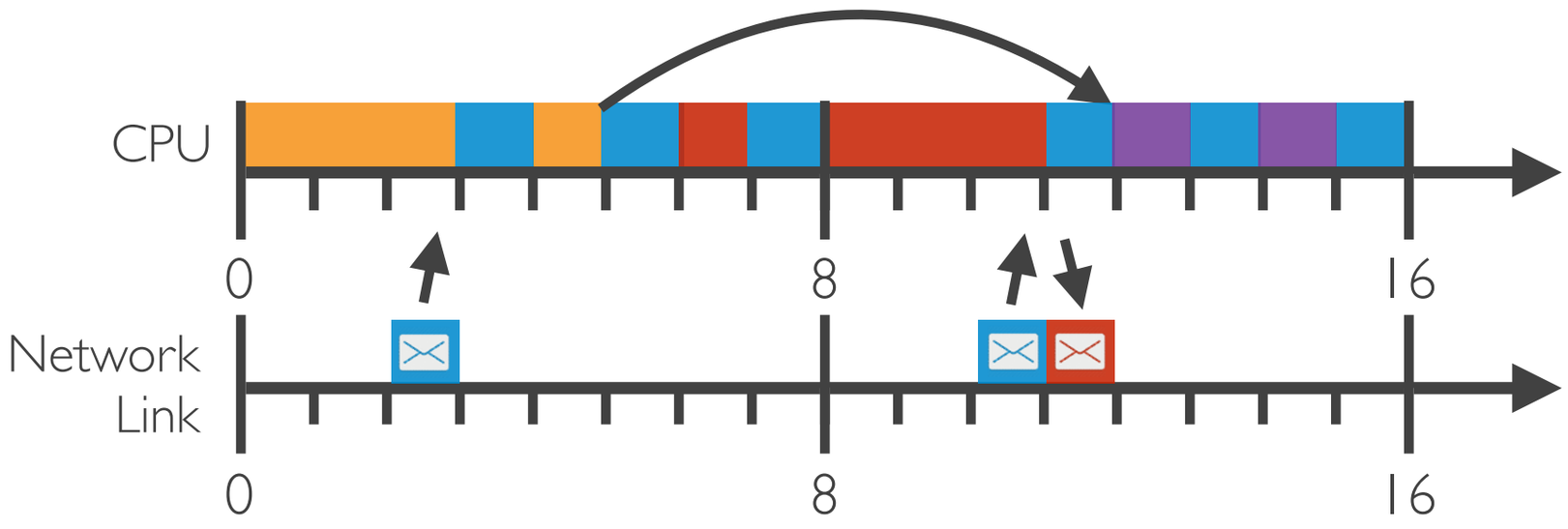
Task model

free (0, 4, 16, 16)

consumer (3, 3, 8, 6)

producer (5, 4, 16, 6)

free (12, 2, 16, 3)



- periodic asynchronous TT-tasks (offset ϕ, wcet C, period T, deadline D)
- static time-driven schedule with preemption
- 3 types of tasks (producer, consumer, free)
- macrotick on ES (usec - ms)
- communication at beginning/end of consumer/producer ([Derler@CIT10])
- end-to-end latency, dependencies between tasks

Networked system model

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Network $G(\mathcal{V}, \mathcal{L}) \quad \mathcal{L} \subseteq \mathcal{V} \times \mathcal{V}$

$$\forall [v_a, v_b] \in \mathcal{L} \Rightarrow [v_b, v_a] \in \mathcal{L}$$

Network links $[v_a, v_b]$

CPU self-links $[v_a, v_a]$

(speed, link delay, macrotick, memory buffer)

Virtual link - dataflow from one producer to one receiver

$$vl_i = [[v_a, v_a], [v_a, v_1], [v_1, v_2], \ldots, [v_{n-1}, v_n], [v_n, v_b], [v_b, v_b]].$$

Frames

Frames

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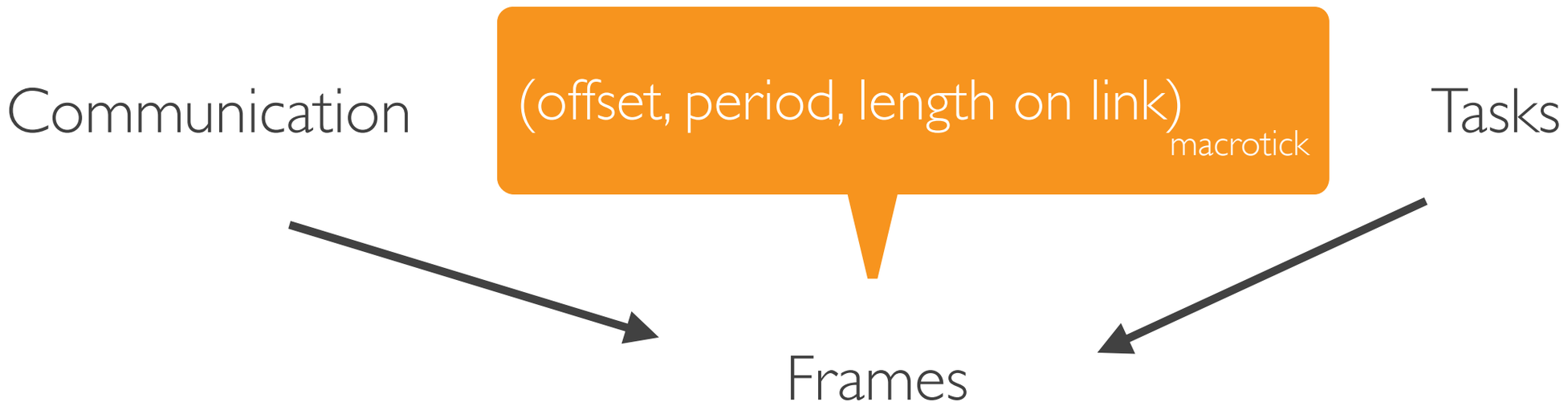
Communication

Tasks

Frames



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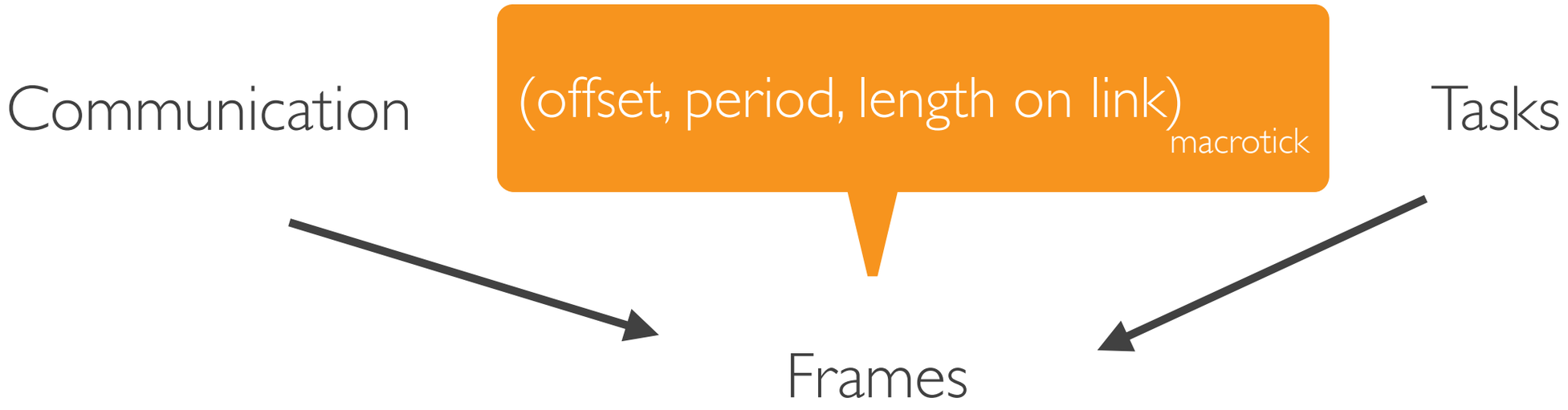

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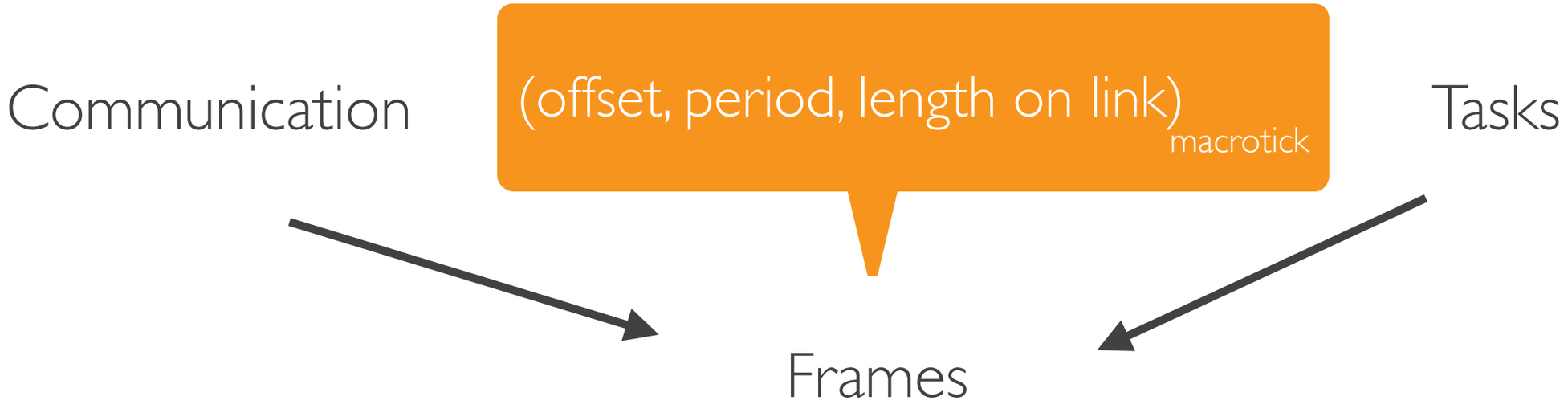

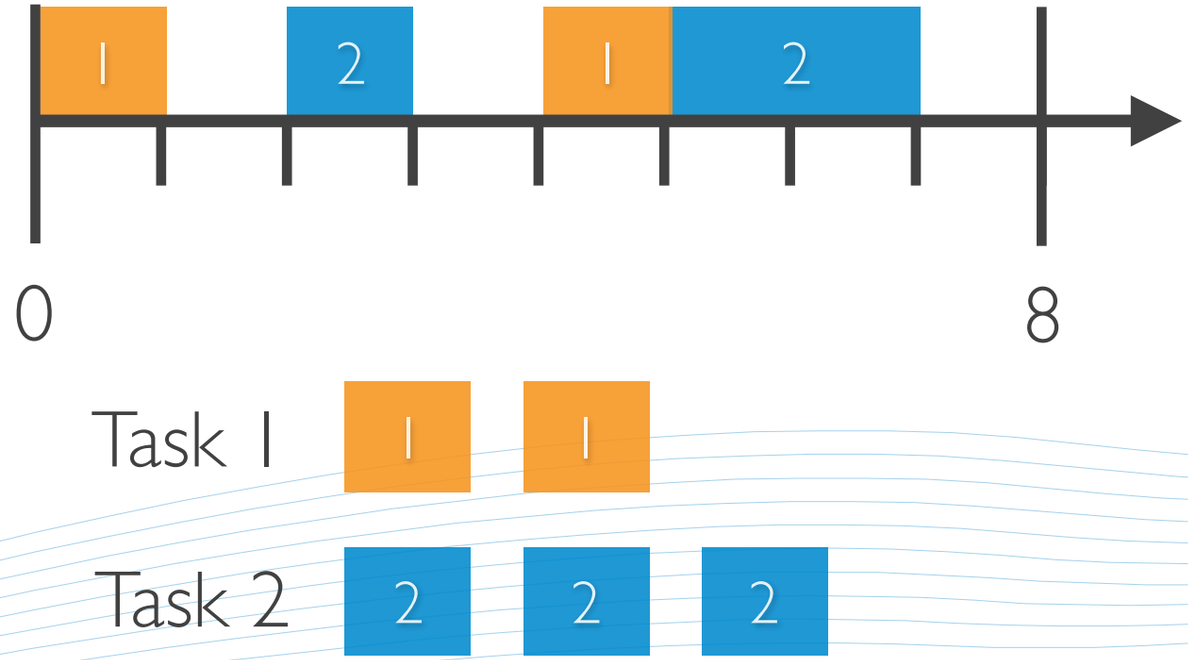

Scheduling problem

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find offsets for the frames (on links and virtual task frames)

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reduces to finding a solution for a set of constraints

- frame constraints
- link constraints
- virtual link constraints
- memory constraints
- end-to-end latency constraints
- precedence constraints

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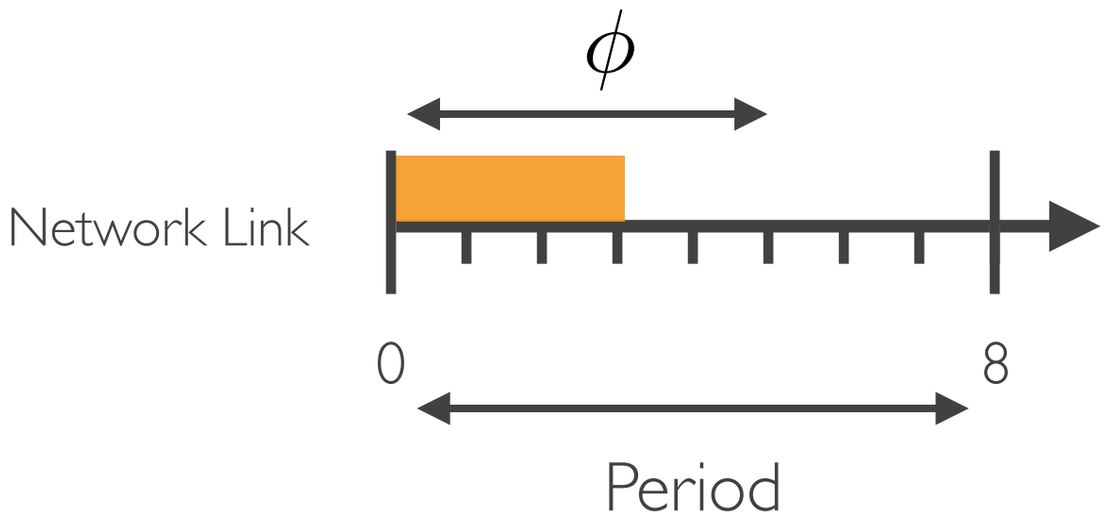
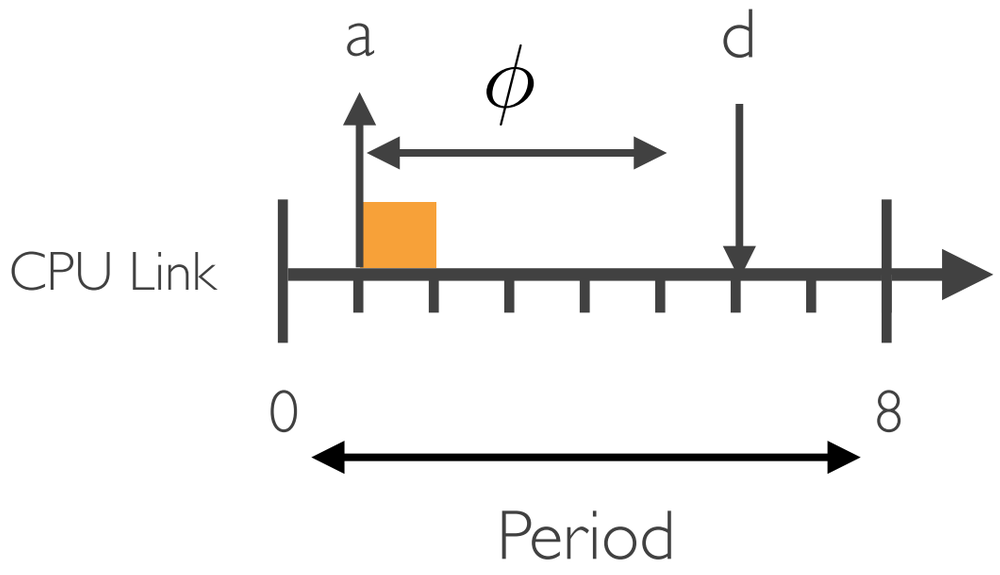
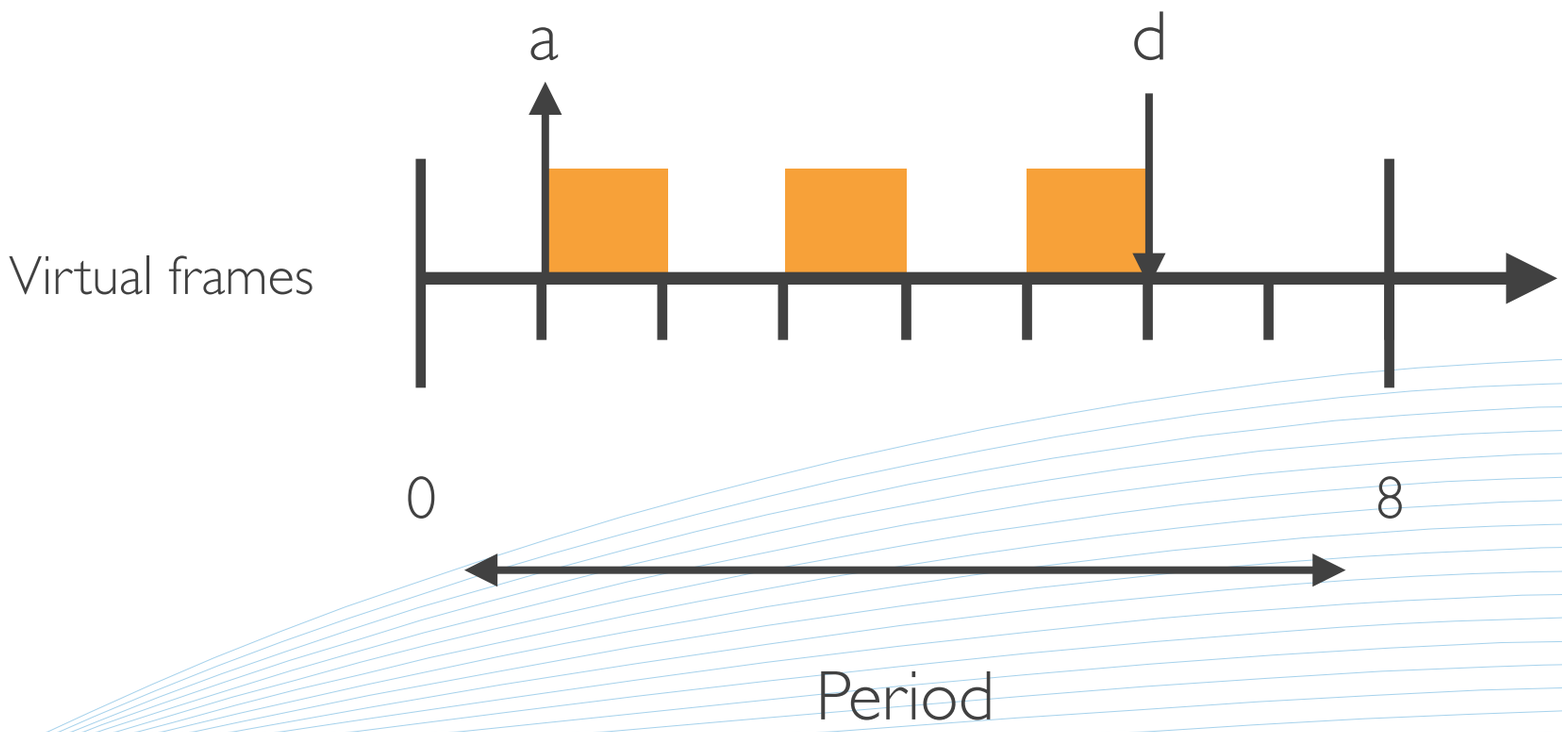
NP-complete

Frame constraints







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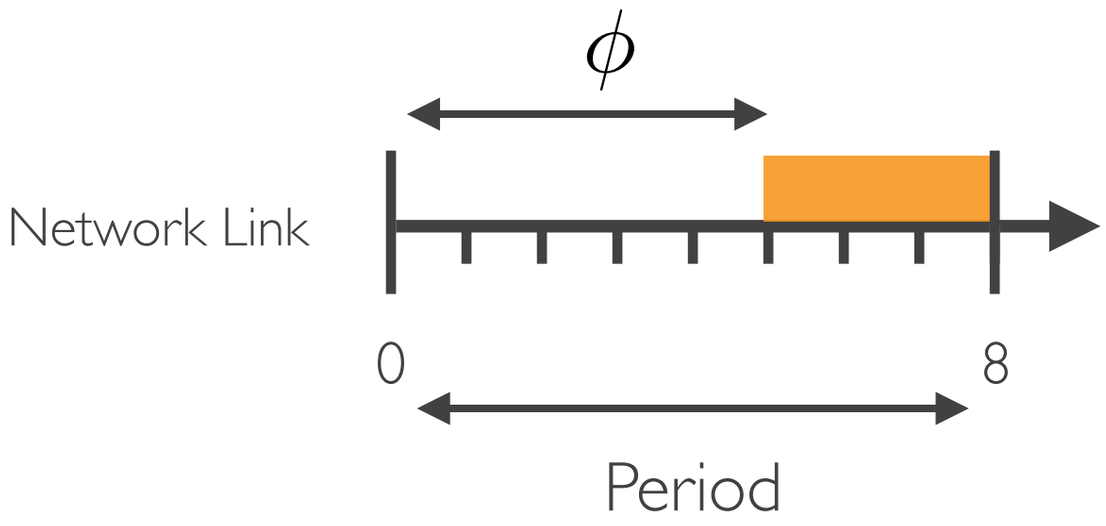

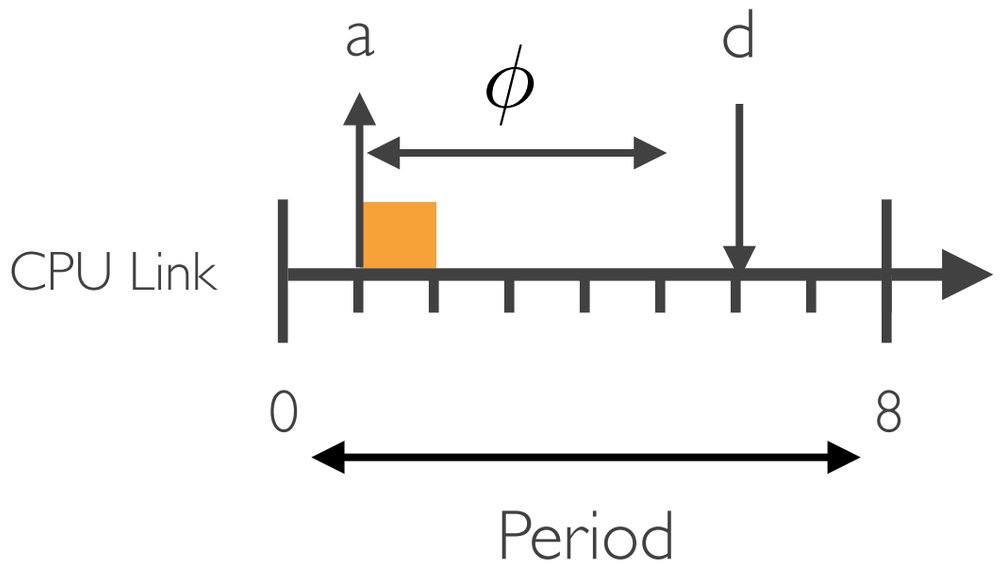

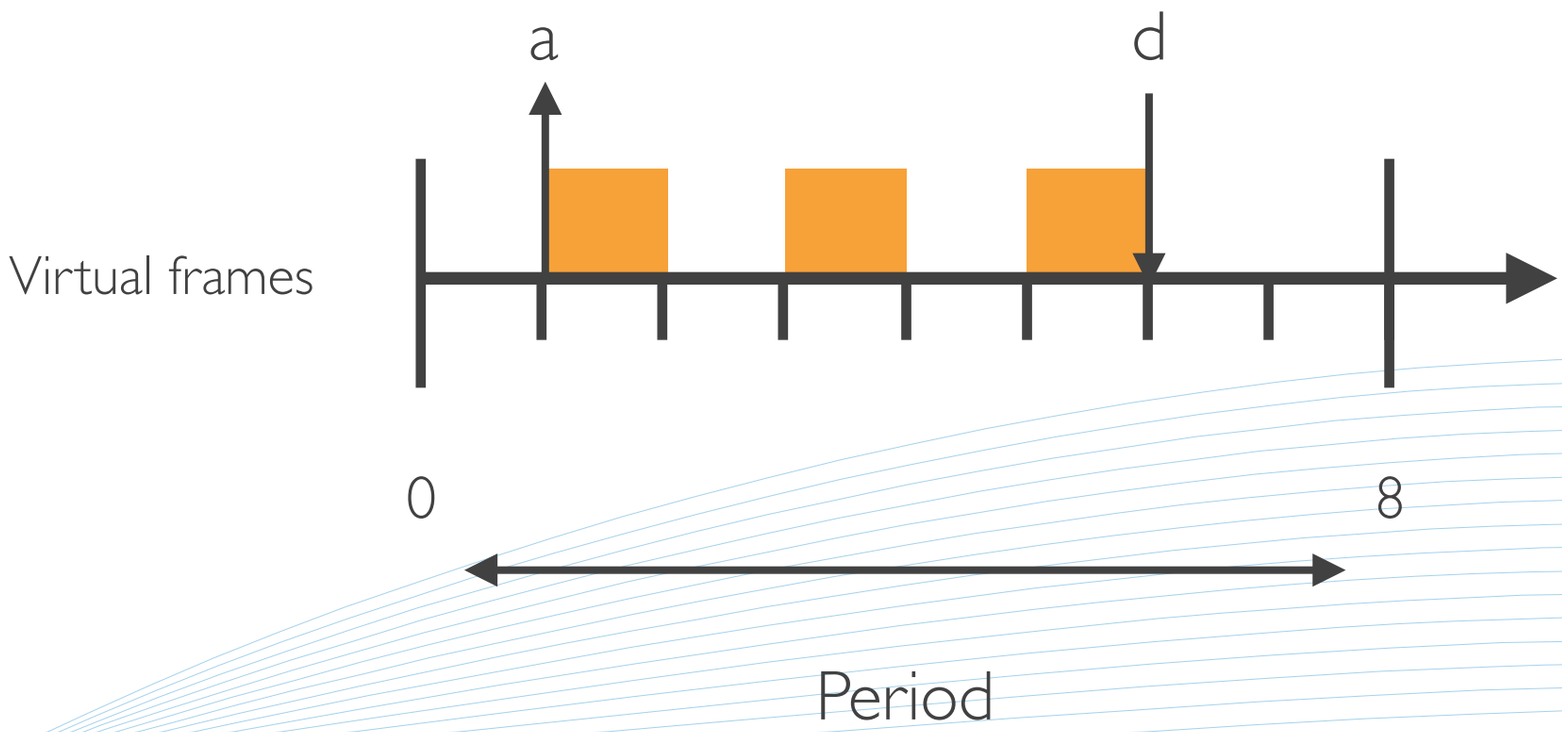

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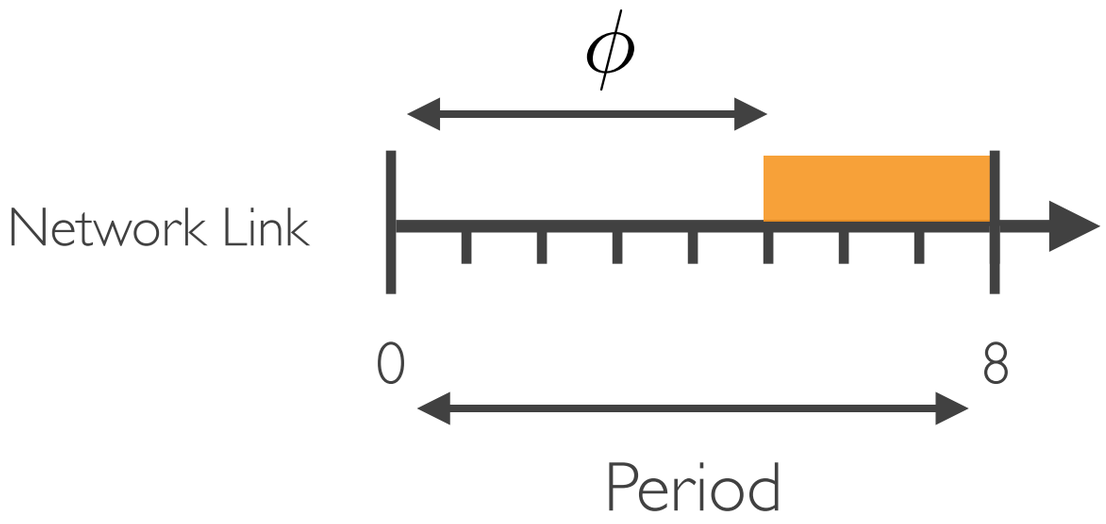

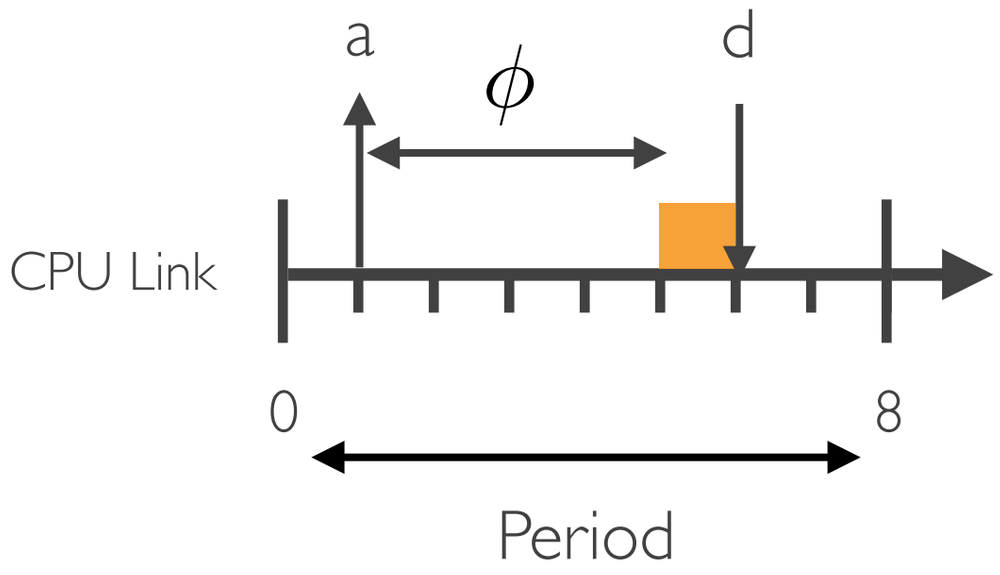

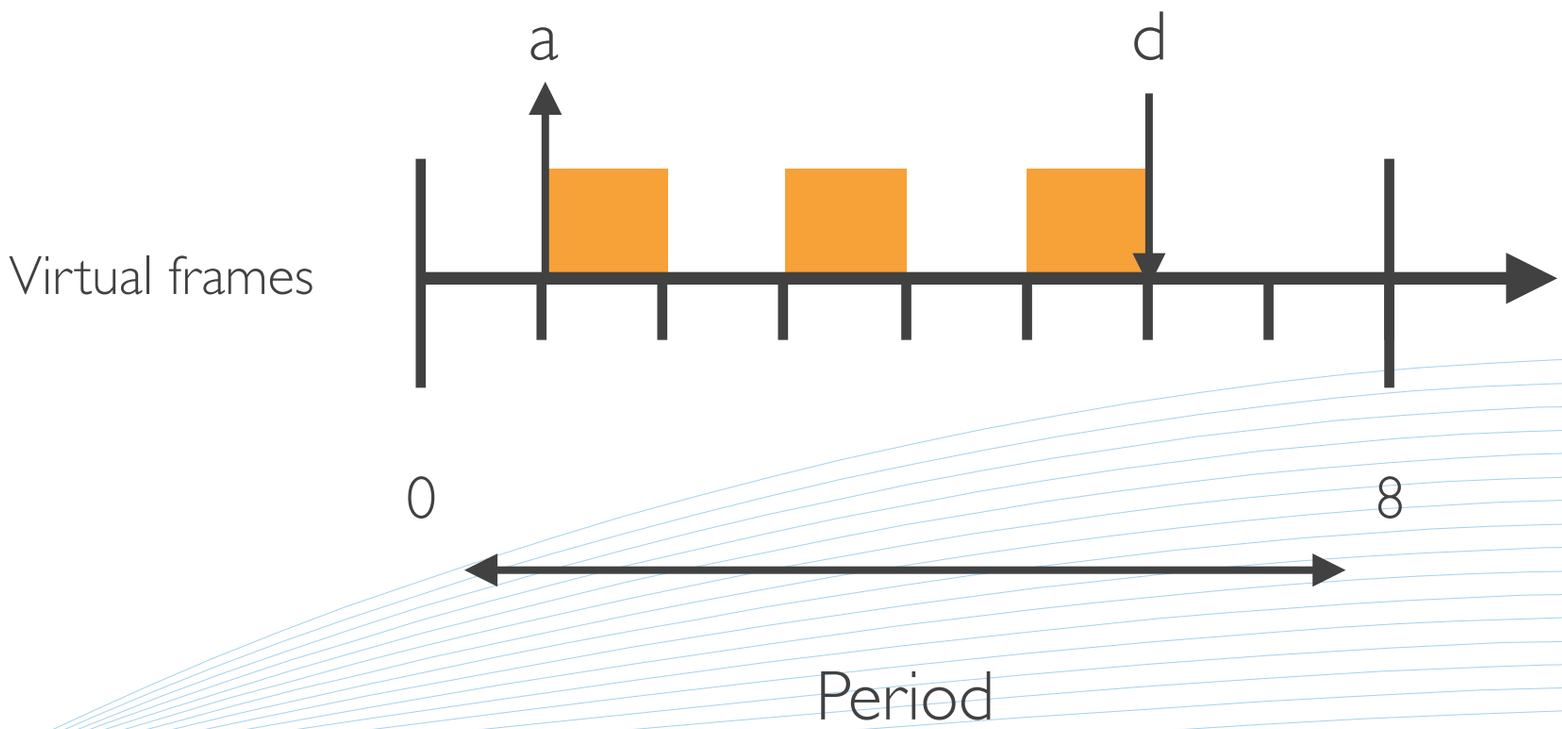

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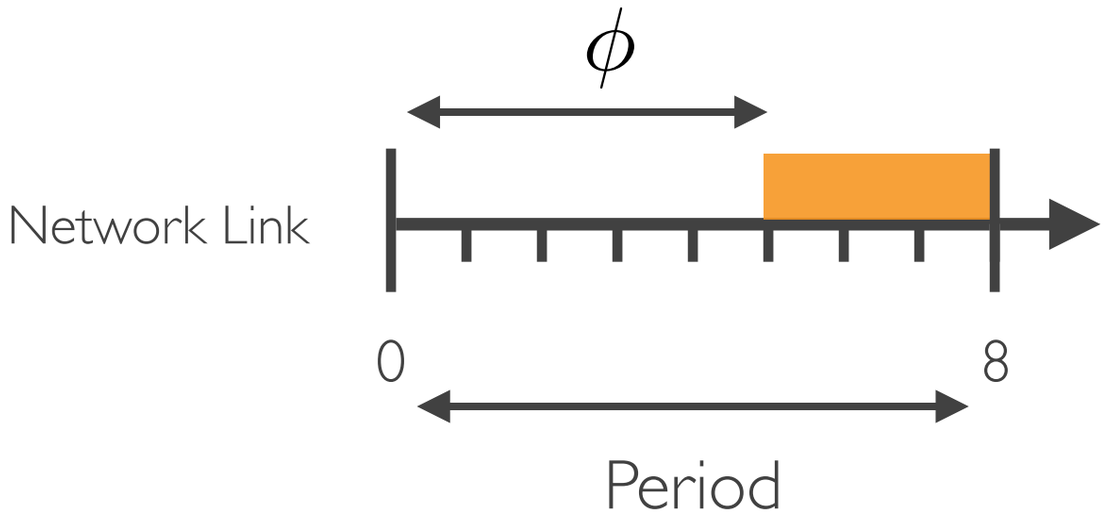
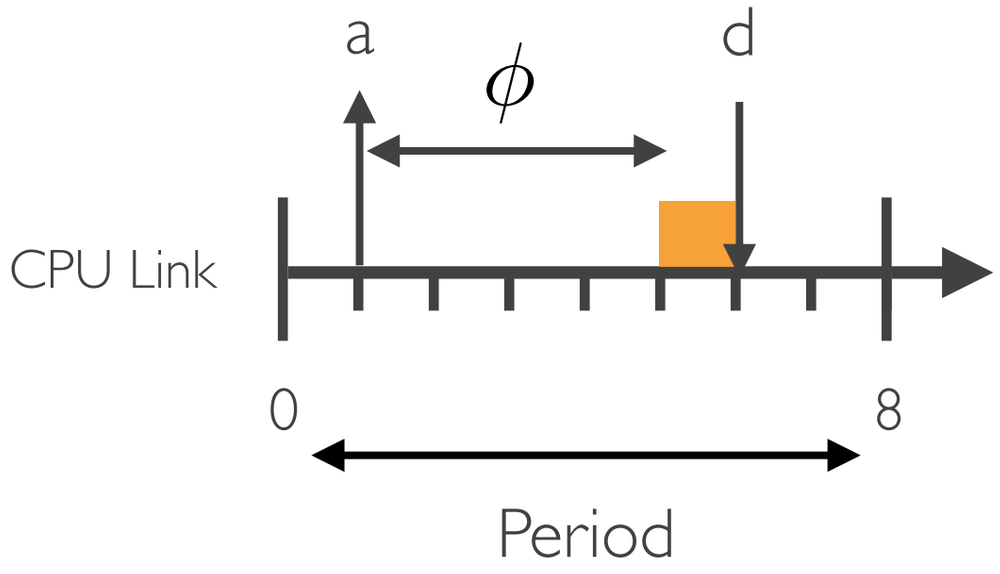
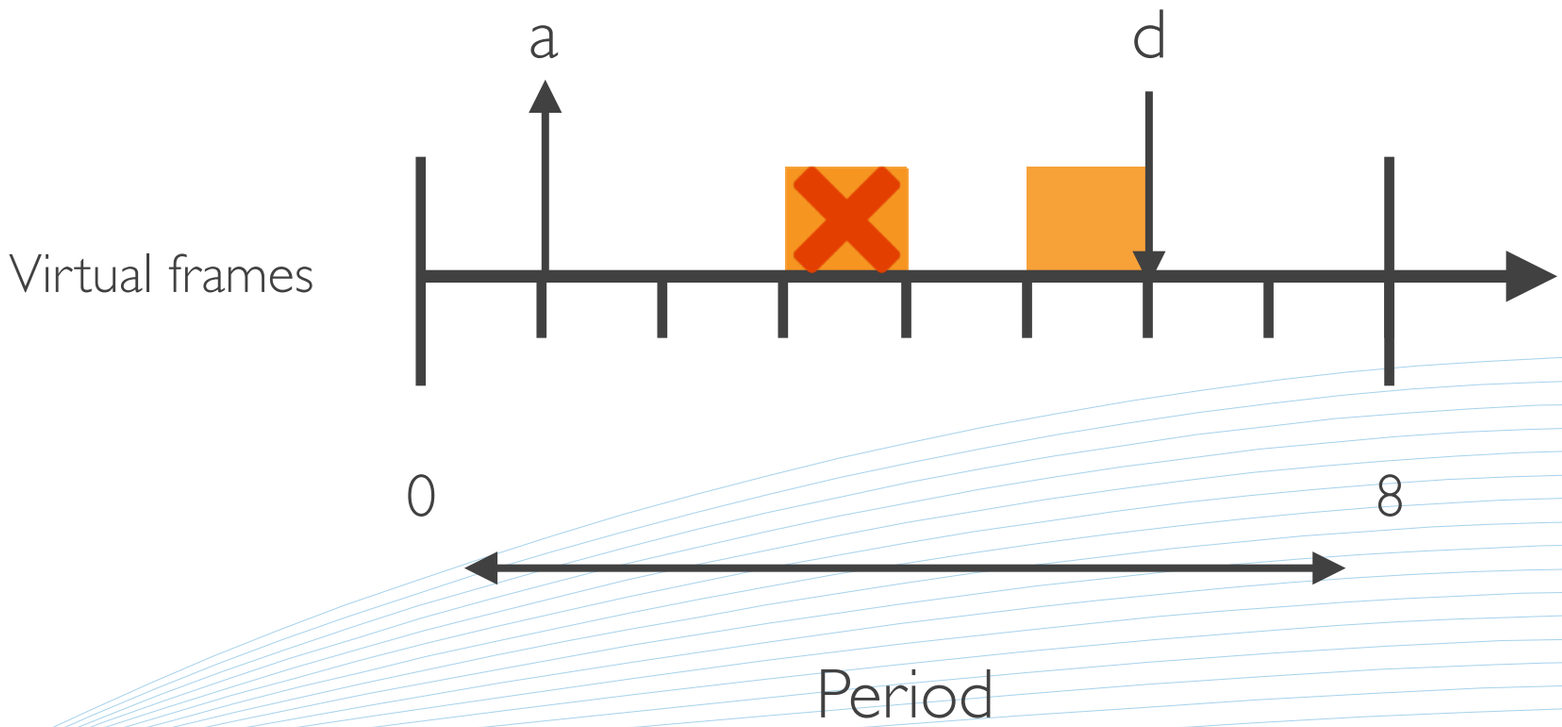
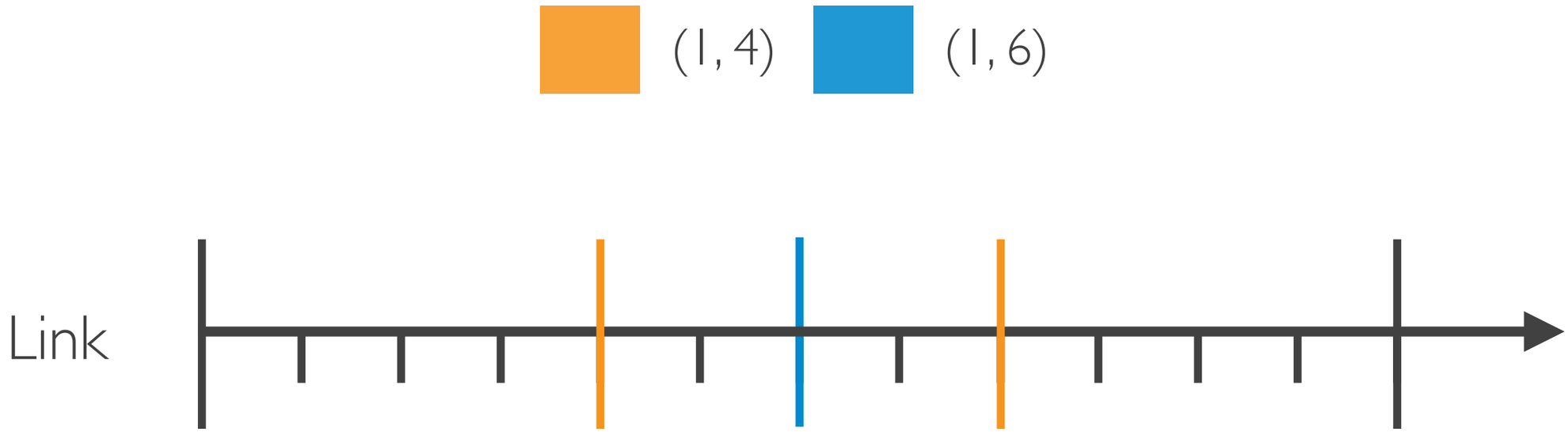






Link constraints



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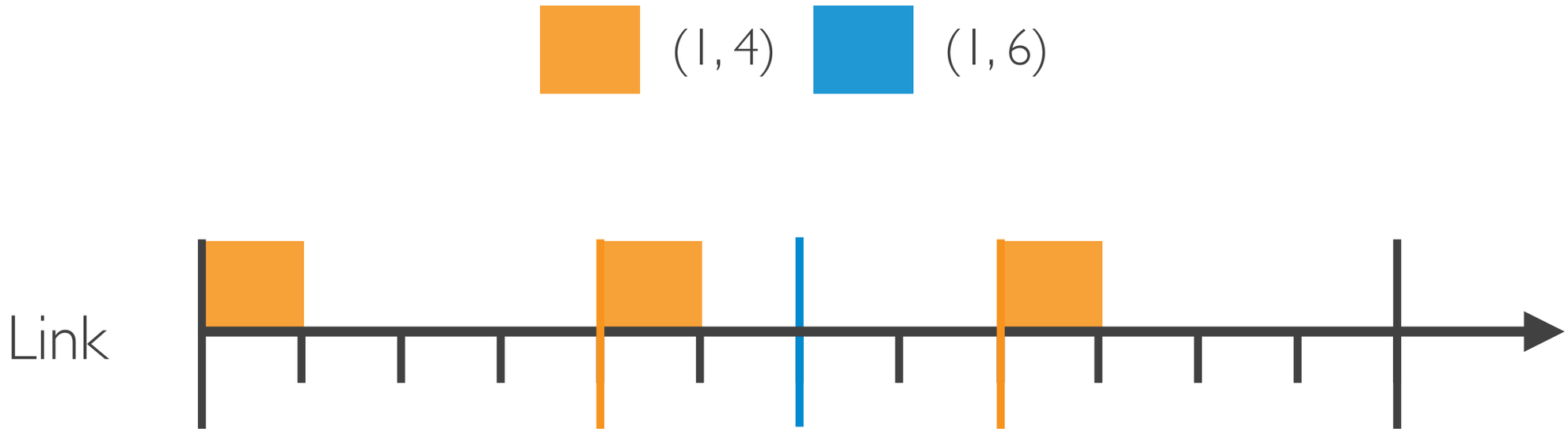

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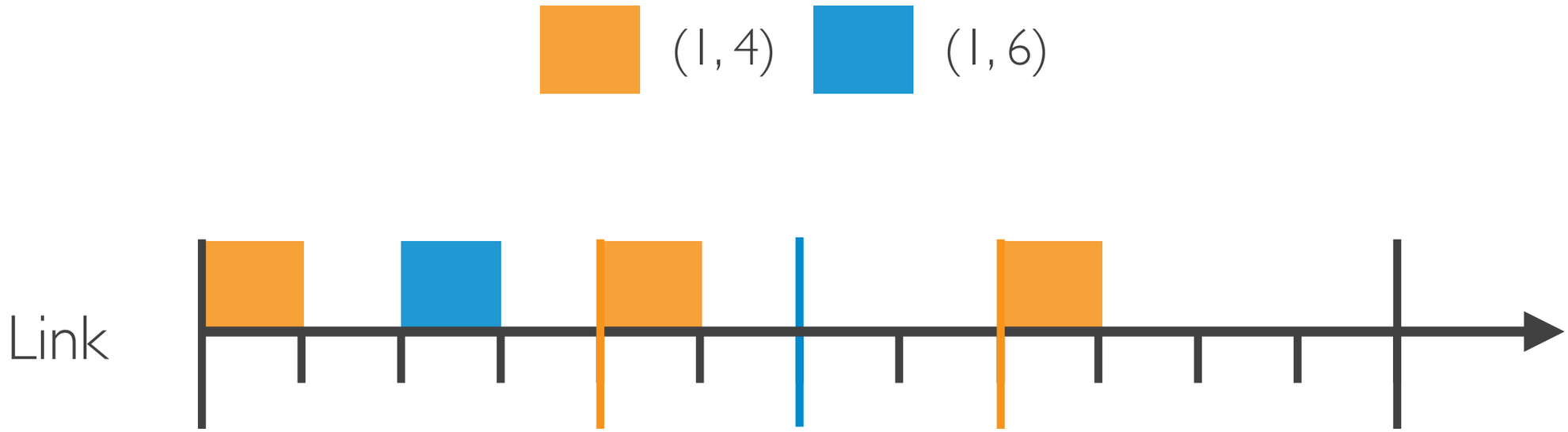

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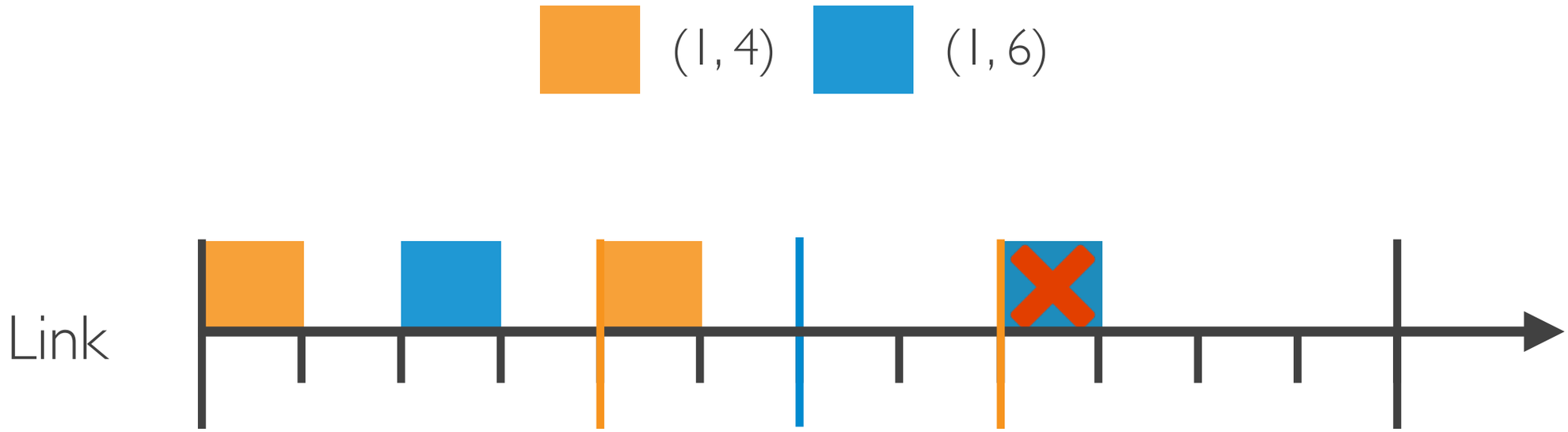

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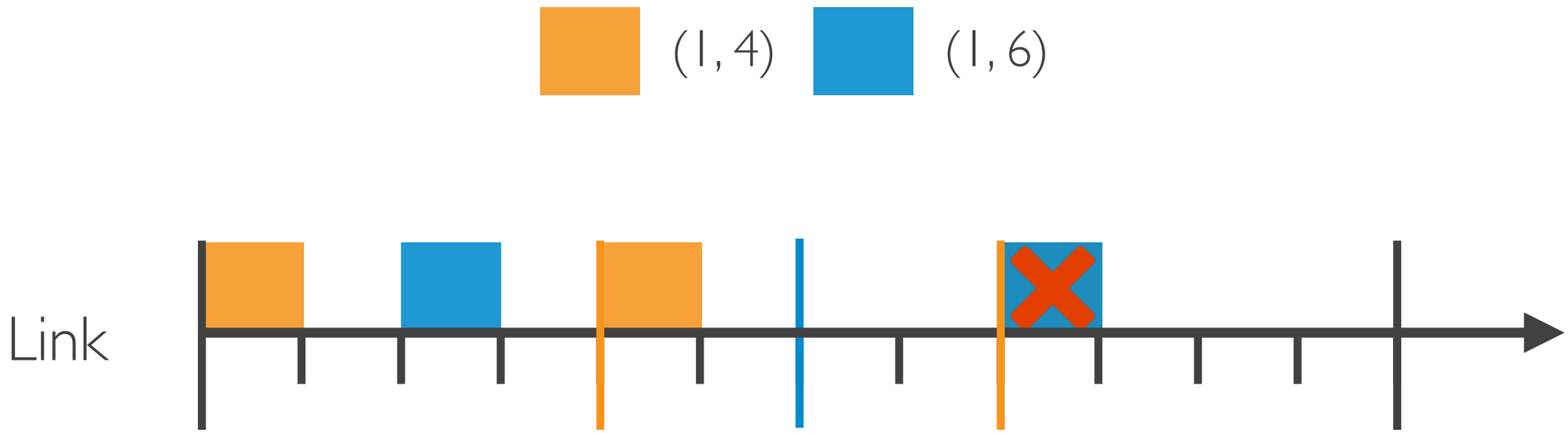

no two frames scheduled on the same link may overlap

Virtual link constraints

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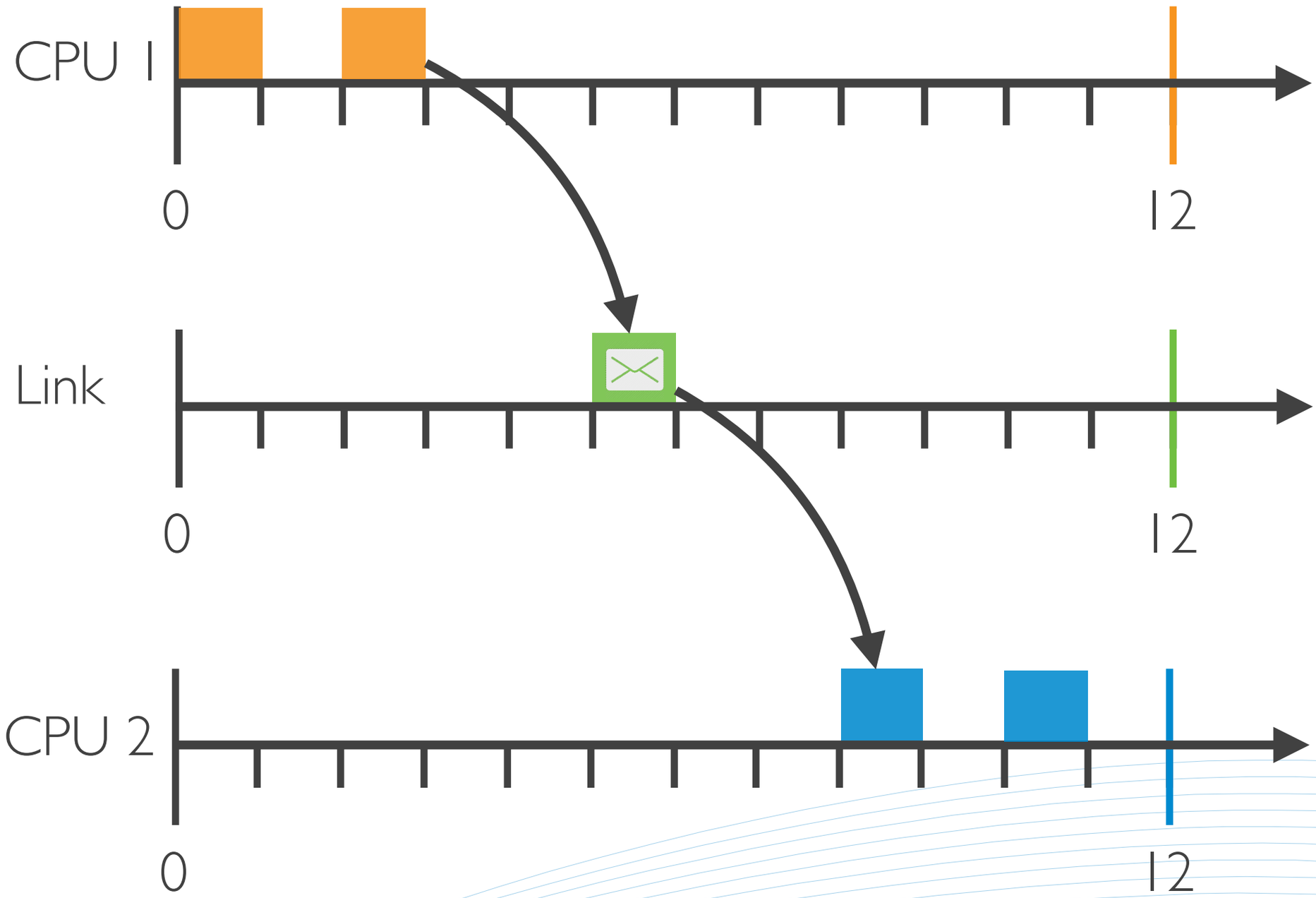

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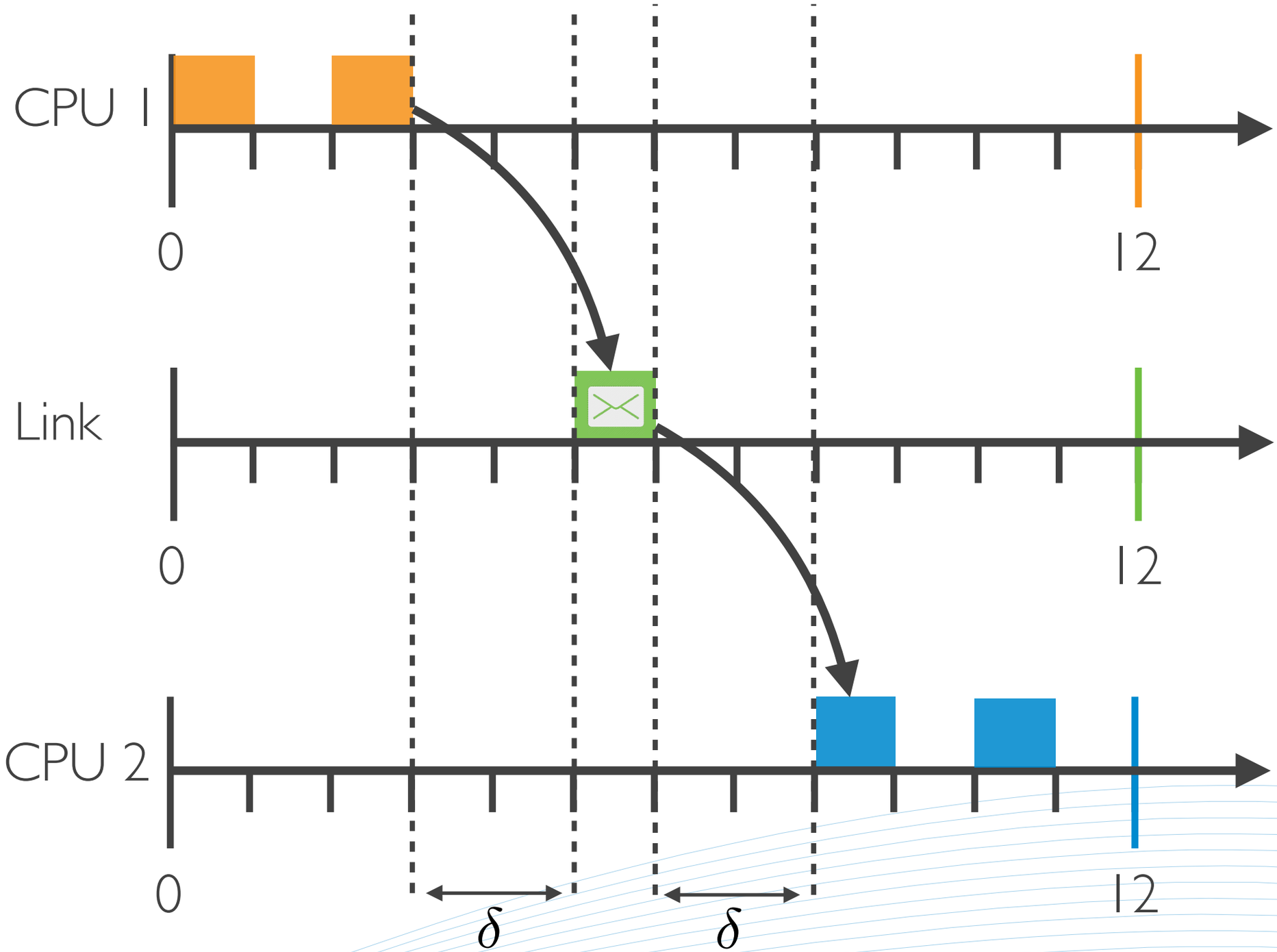
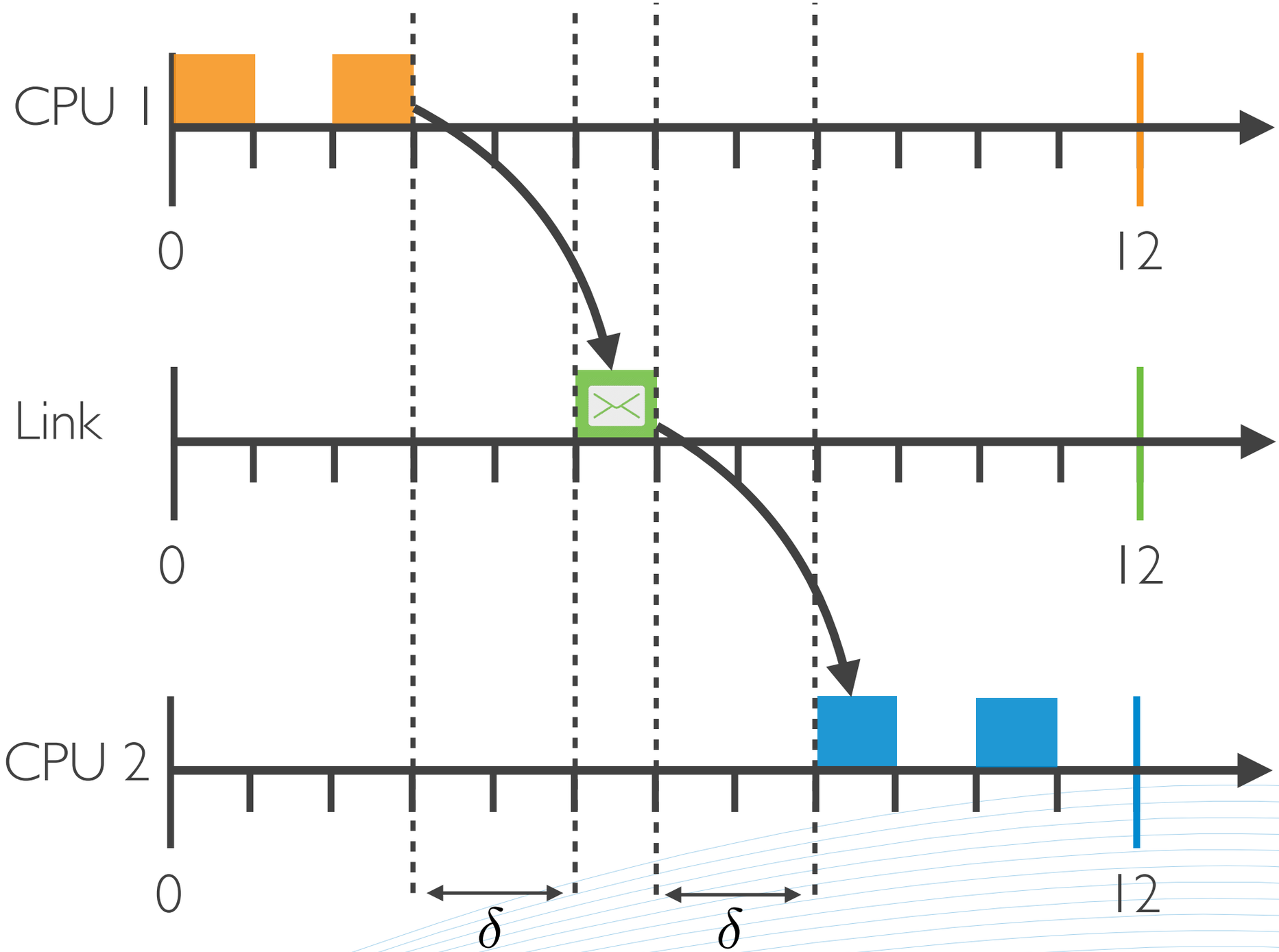


E2E latency constraints



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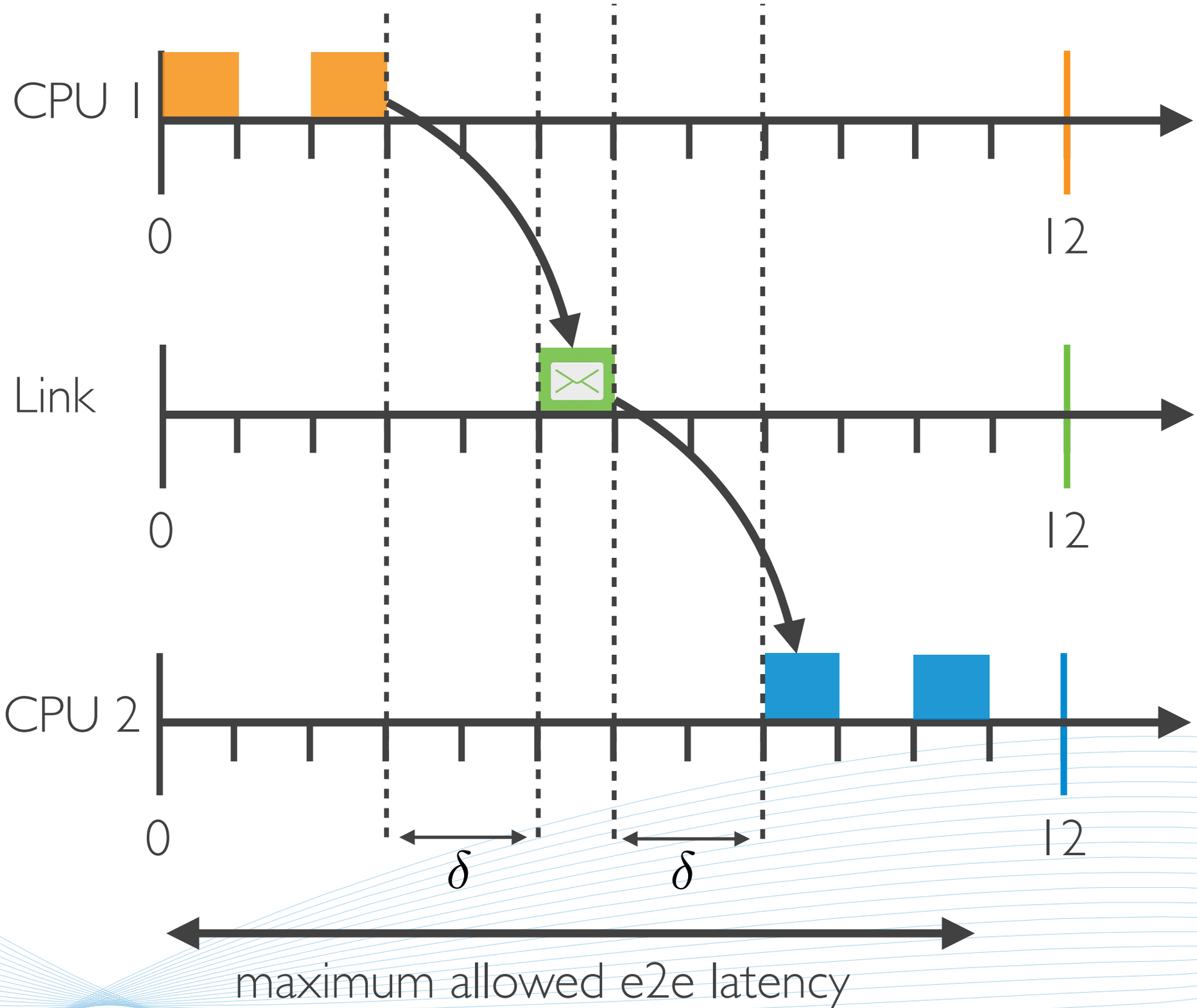
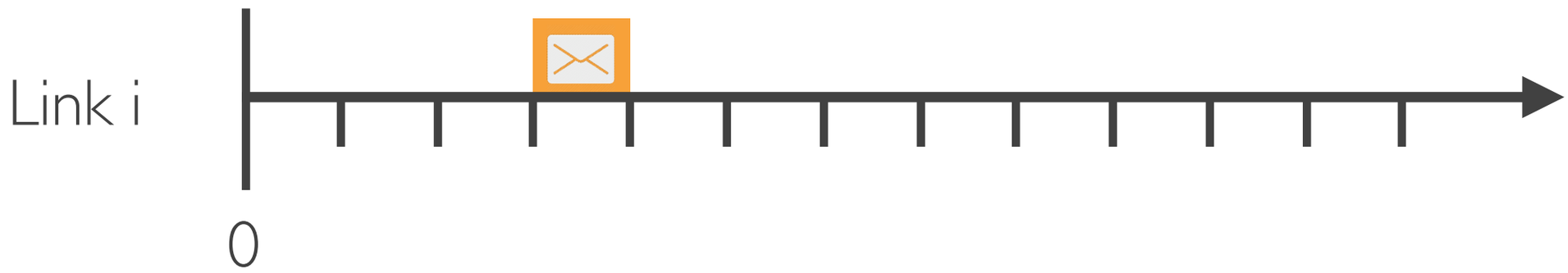
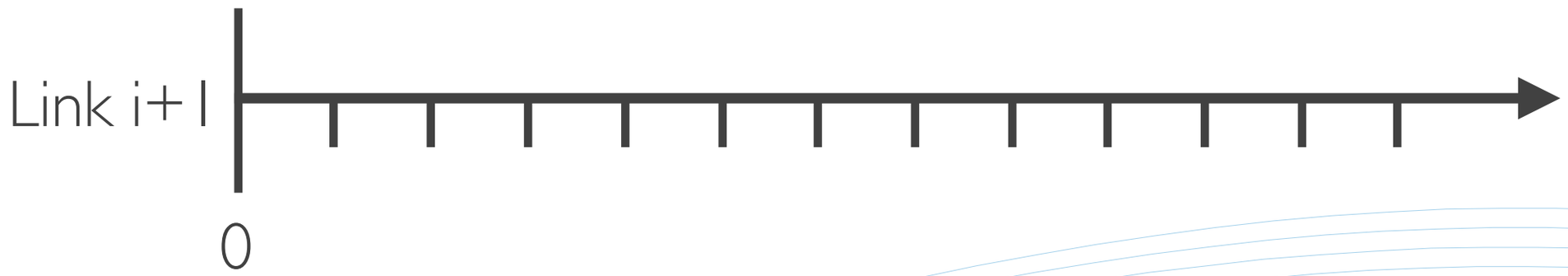


Memory constraints





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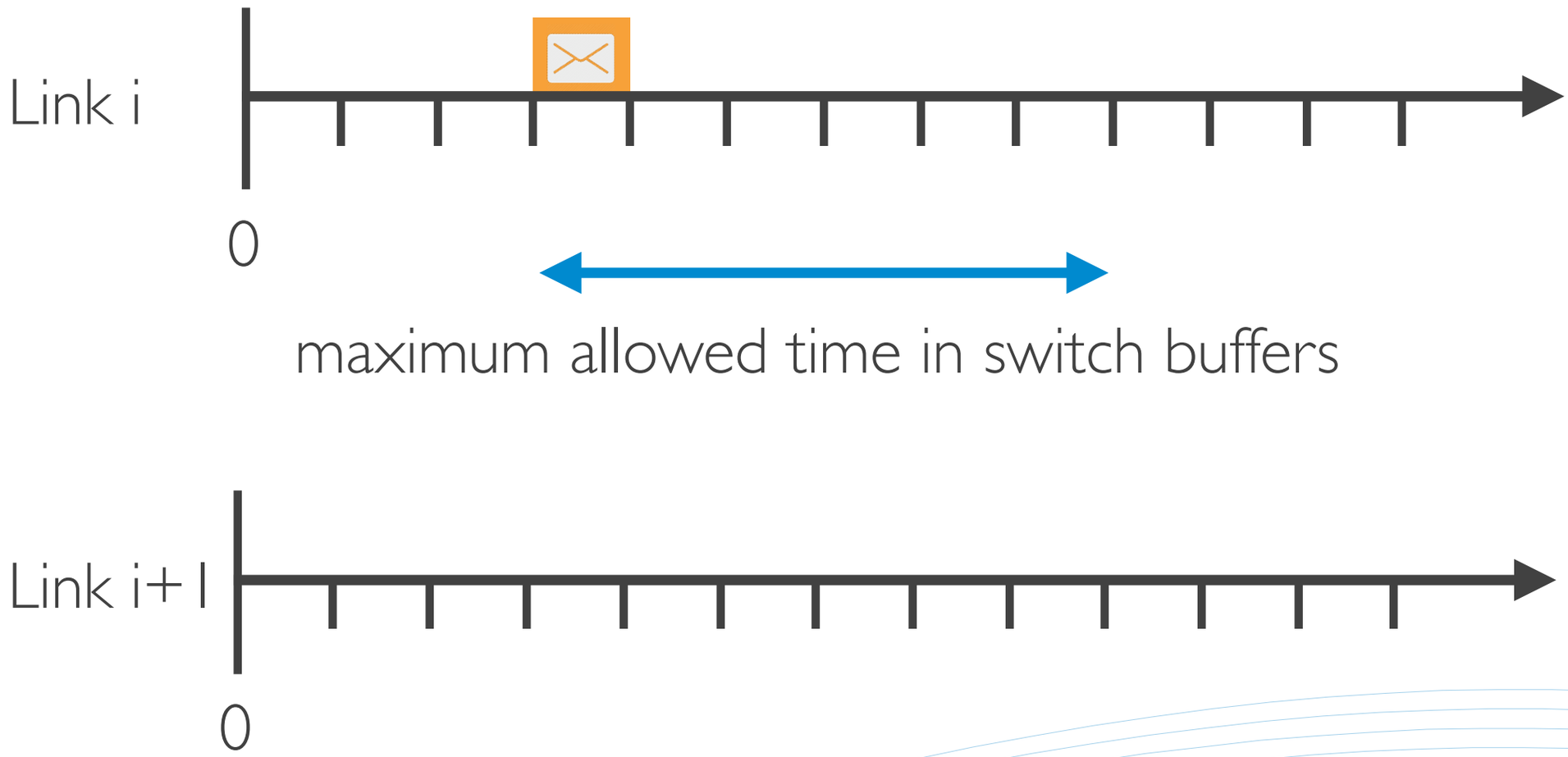

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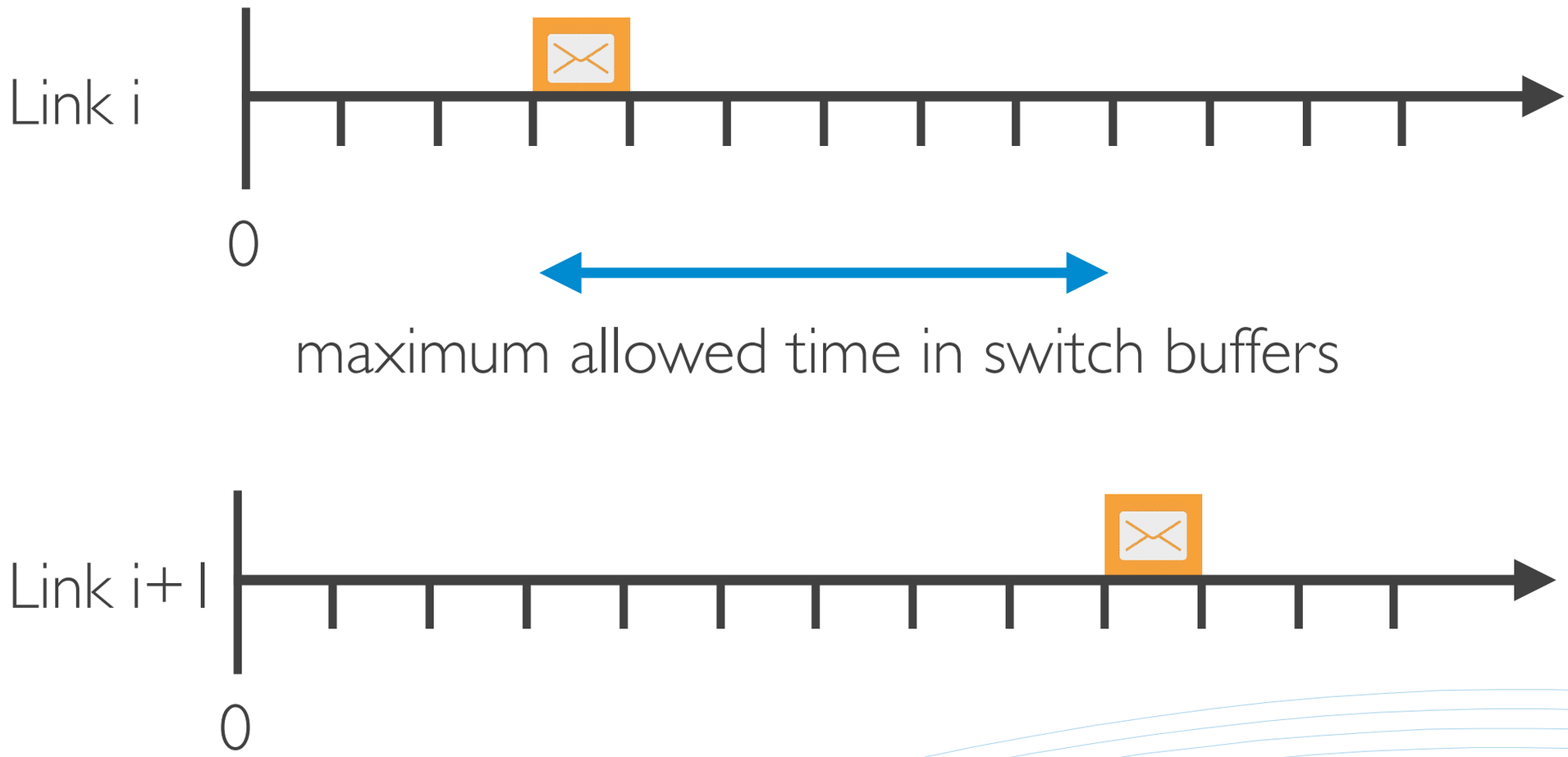

Satisfiability Modulo Theories

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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 $\exists, \forall$

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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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Satisfiability Modulo Theories

Ensuring Reliable Networks TTTech

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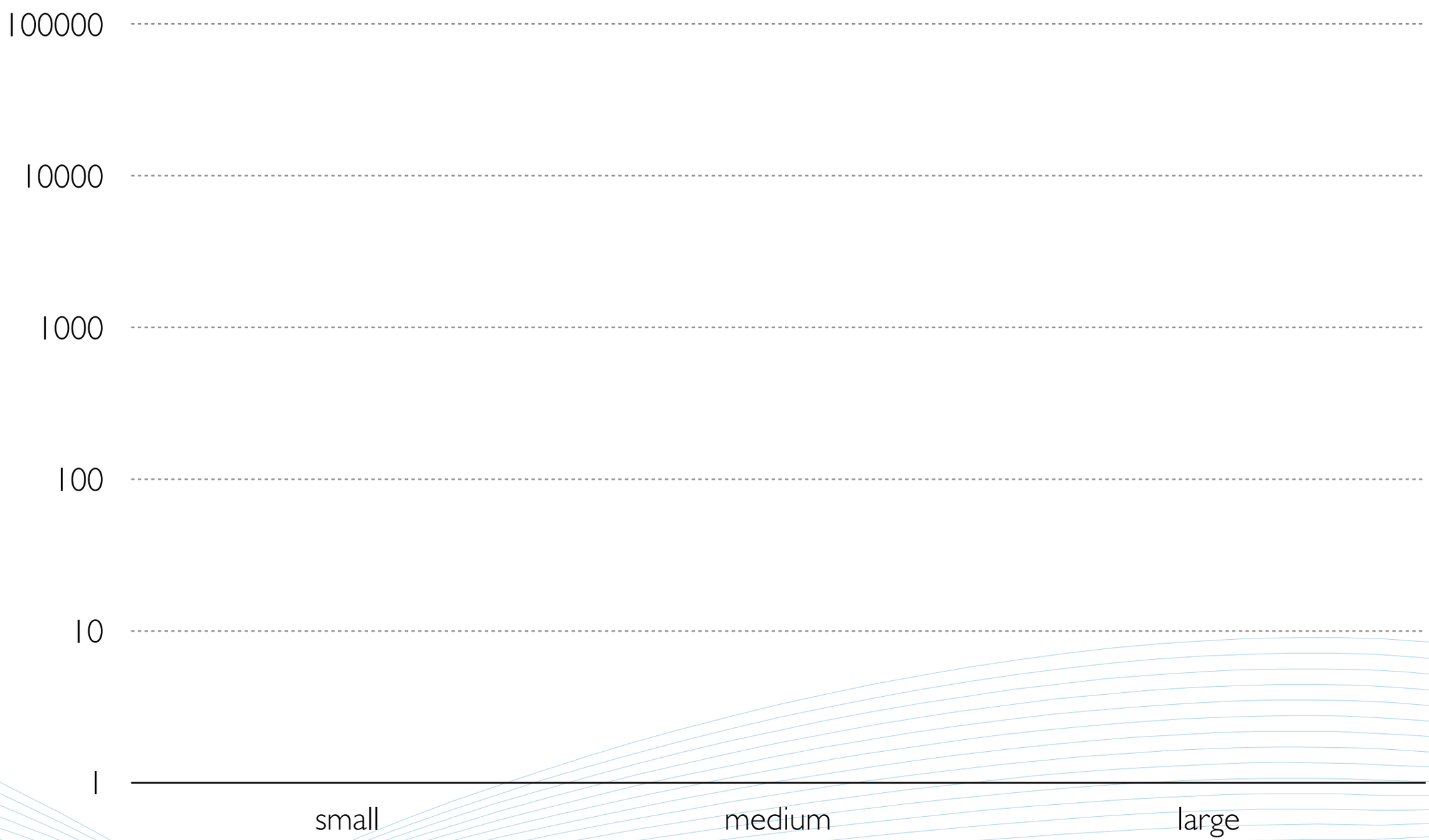
One-shot

Ensuring Reliable Networks TTTech

One-shot



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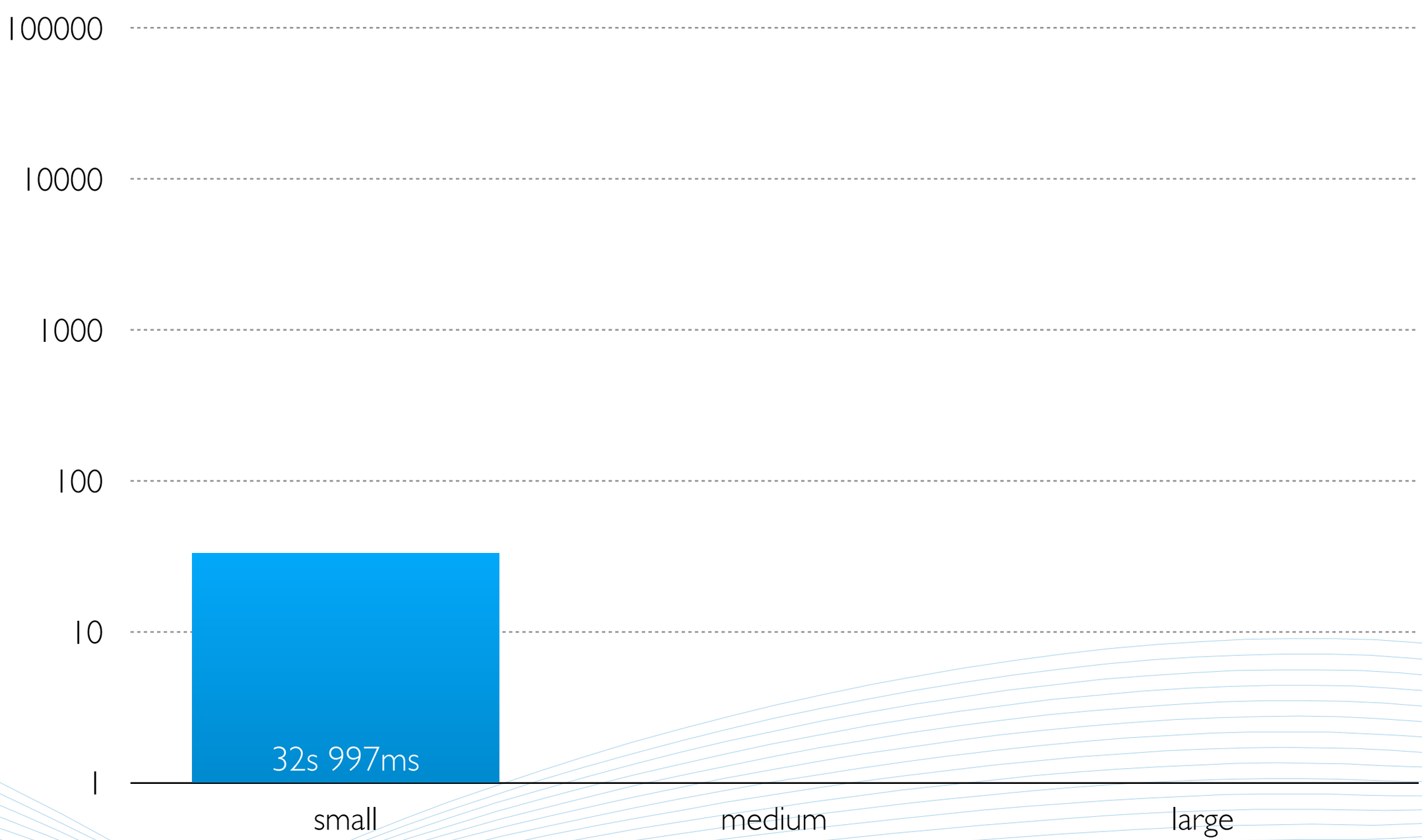
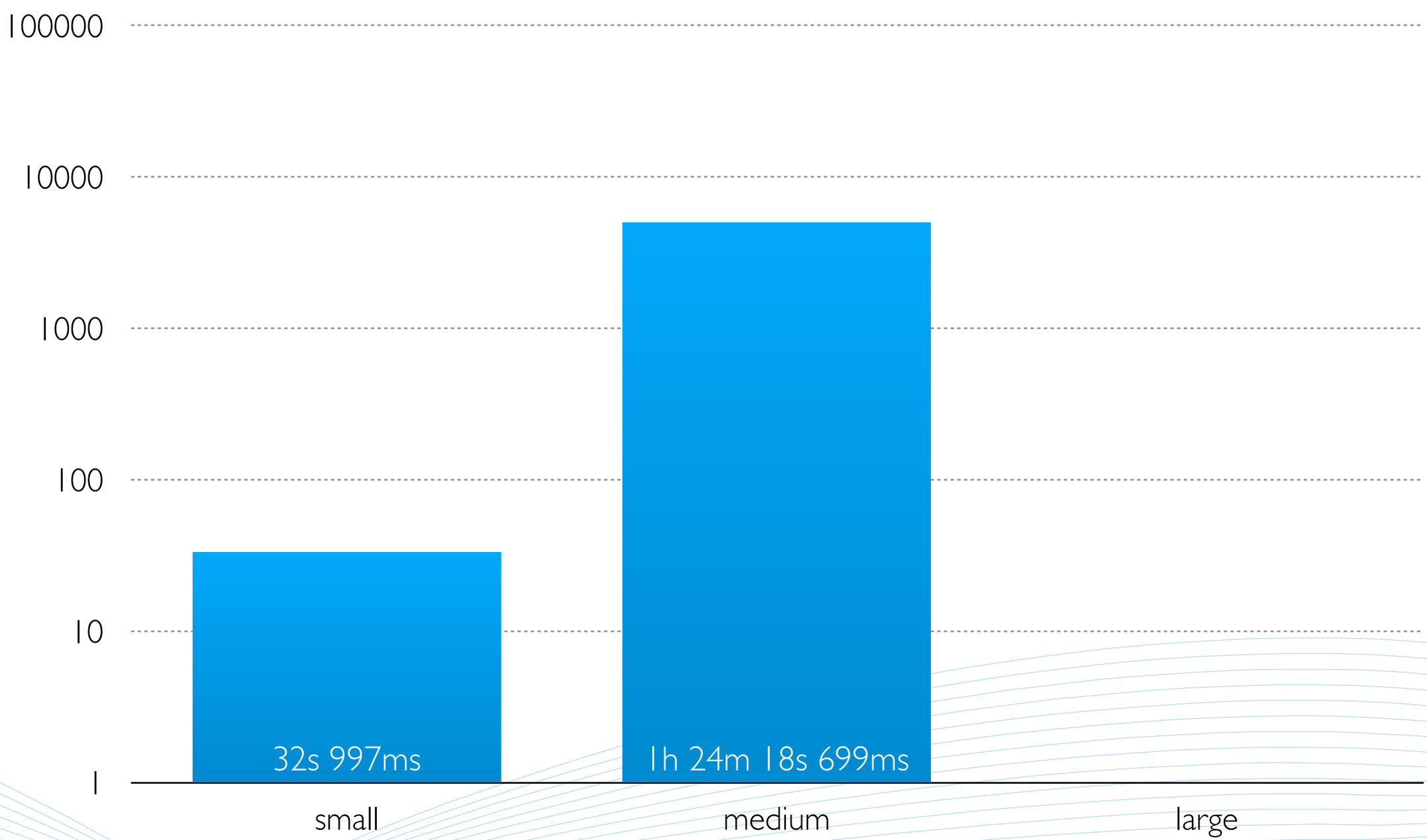


One-shot

Ensuring Reliable Networks TTTech



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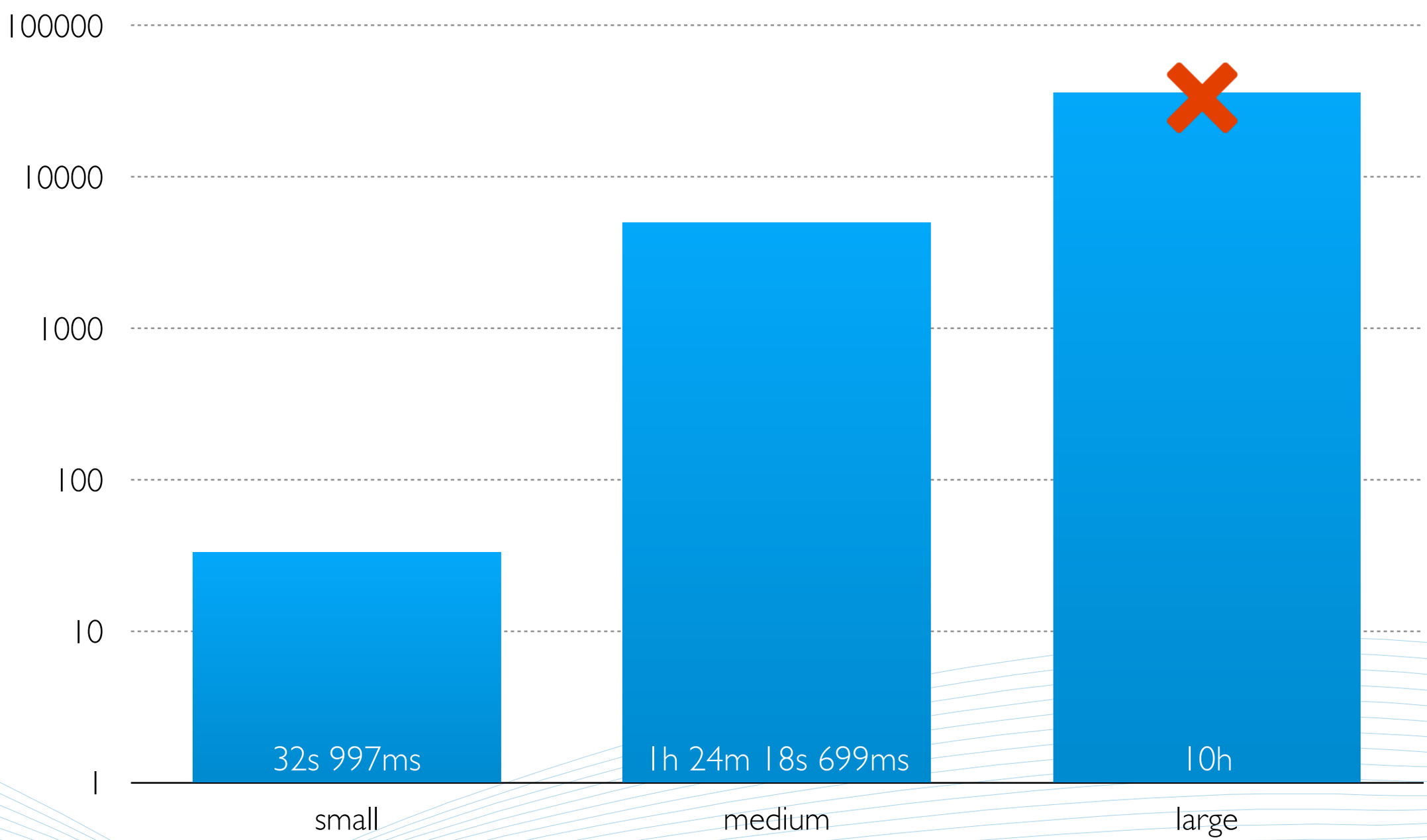

One-shot

Ensuring Reliable Networks TTTech

One-shot

Ensuring Reliable Networks TTTech

where does the complexity come from?

One-shot

where does the complexity come from?

where do the frames come from?

One-shot

where does the complexity come from?

where do the frames come from?

consumer tasks
producer tasks
communication

One-shot

where does the complexity come from?

where do the frames come from?

consumer tasks
producer tasks
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free tasks

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Ensuring Reliable Networks TTTech

where does the complexity come from?

where do the frames come from?

consumer tasks
producer tasks
communication

free tasks

let's treat them differently

Demand-based

Ensuring Reliable Networks TTTech

Demand-based

Ensuring Reliable Networks TTTech

consumer tasks
producer tasks
communication

free tasks

Demand-based

consumer tasks
producer tasks
communication

free tasks

SMT

Demand-based

free tasks

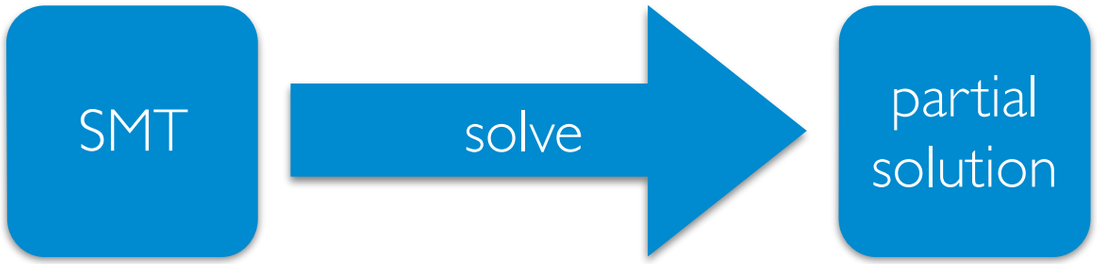
SMT

Demand-based

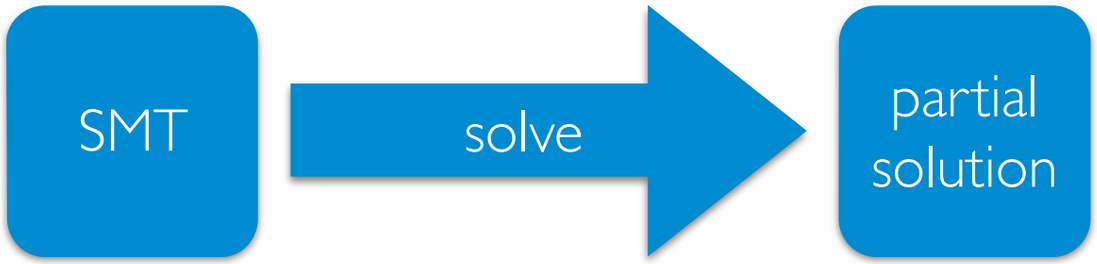
free tasks

Demand-based

free tasks



Demand-based



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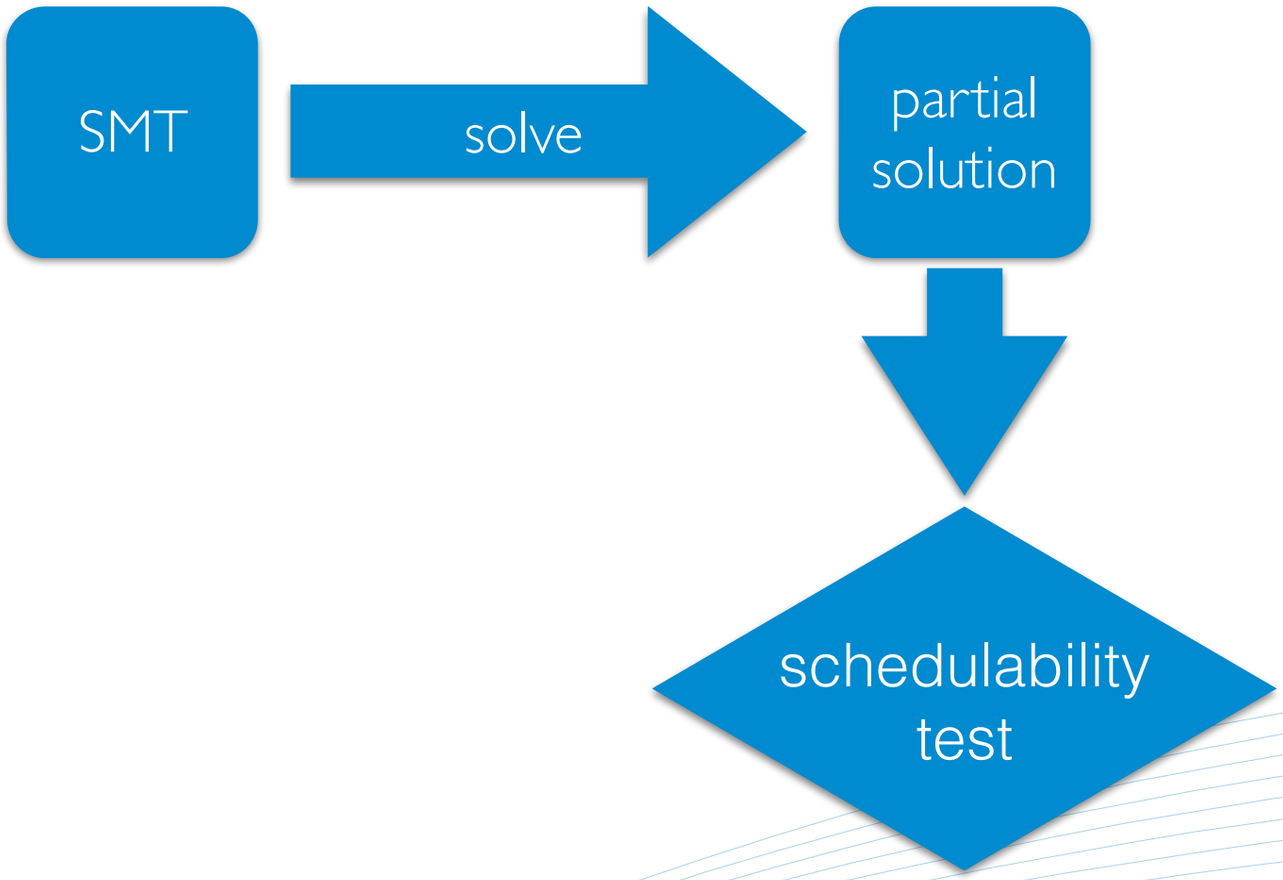

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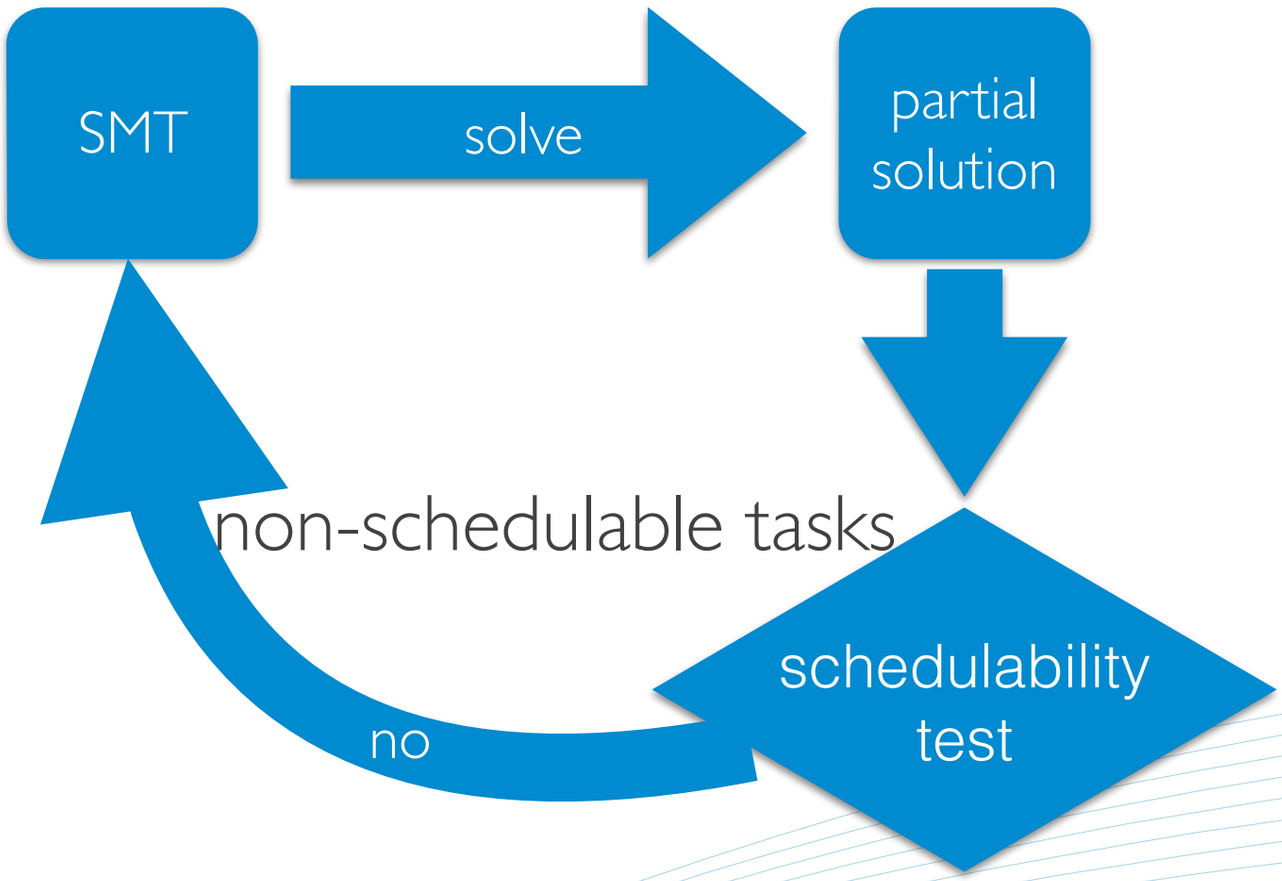

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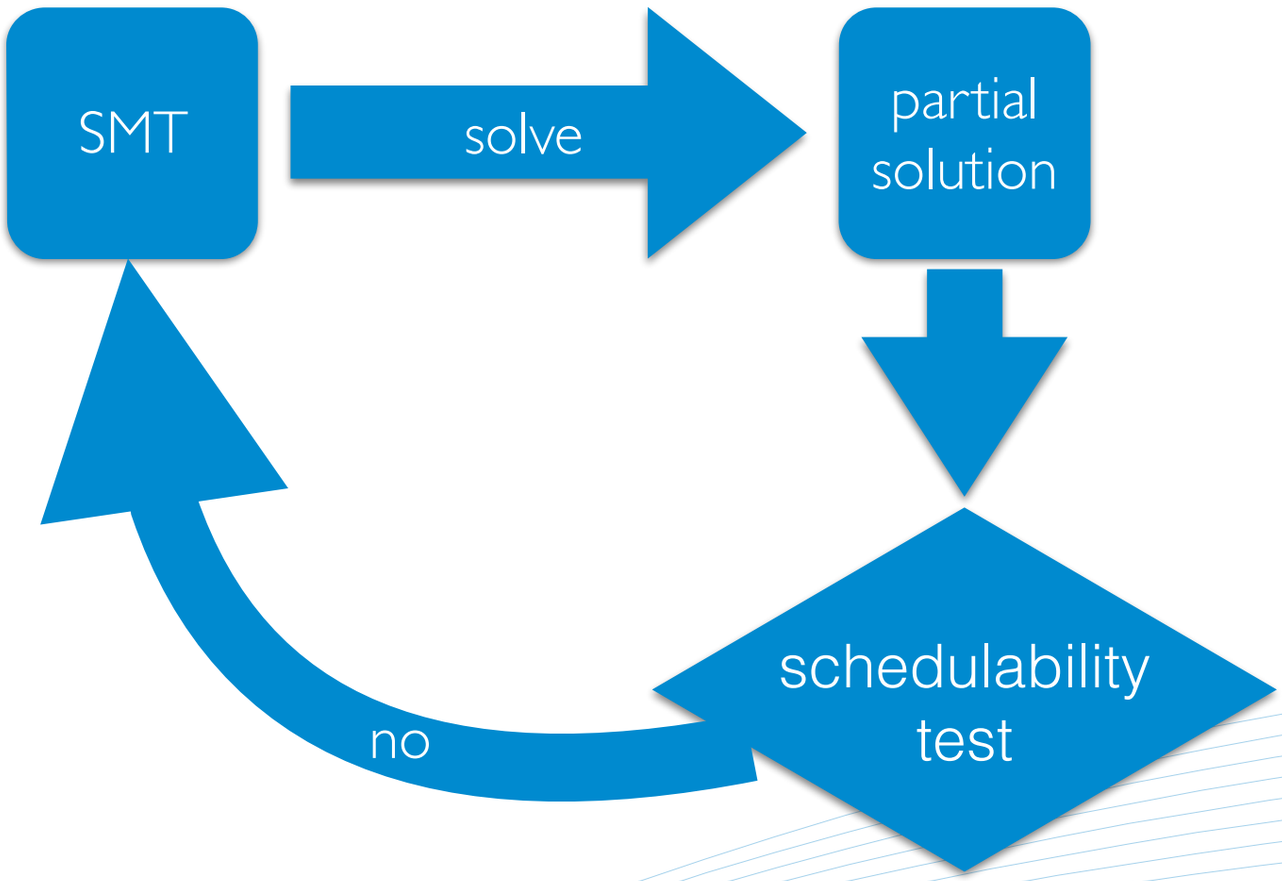

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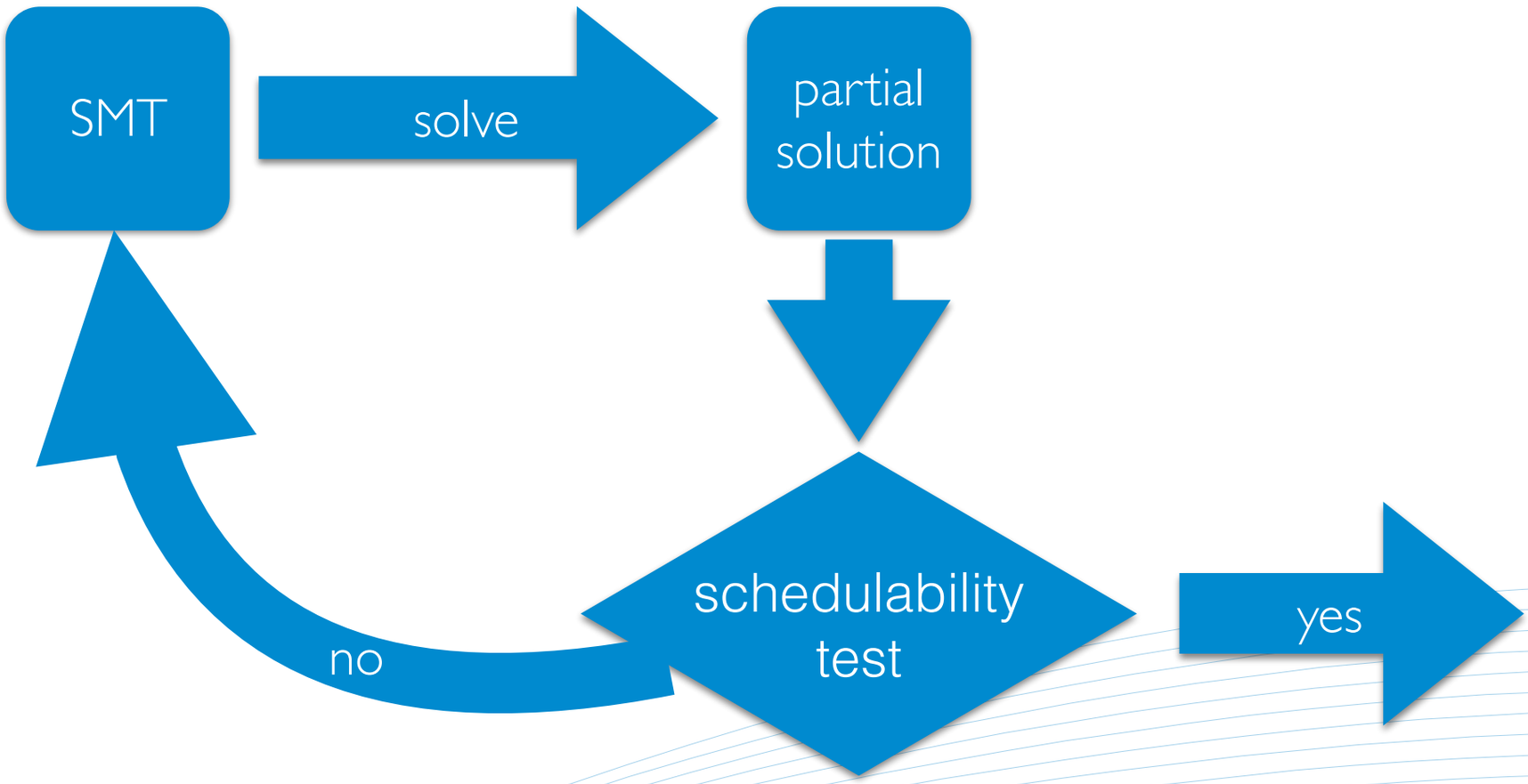

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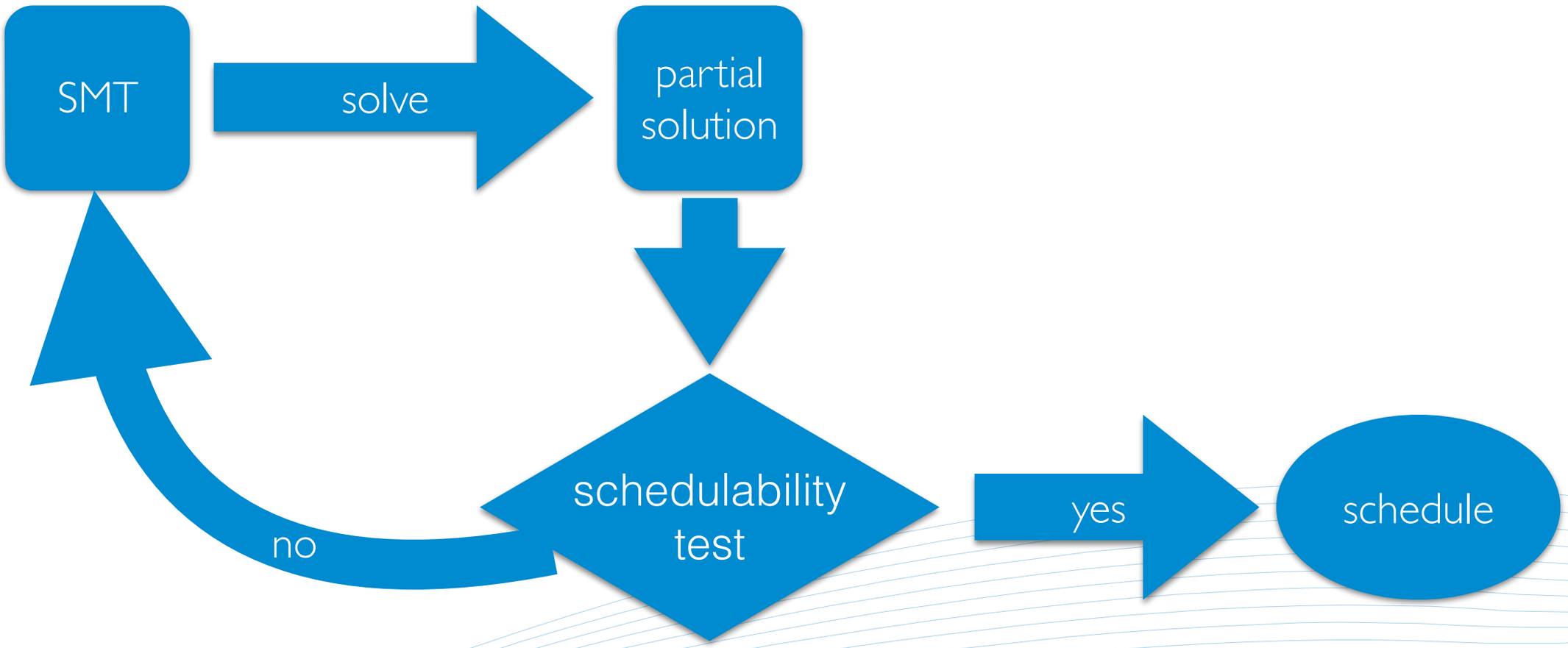

Demand-based

Ensuring Reliable Networks TTTech

Demand-based

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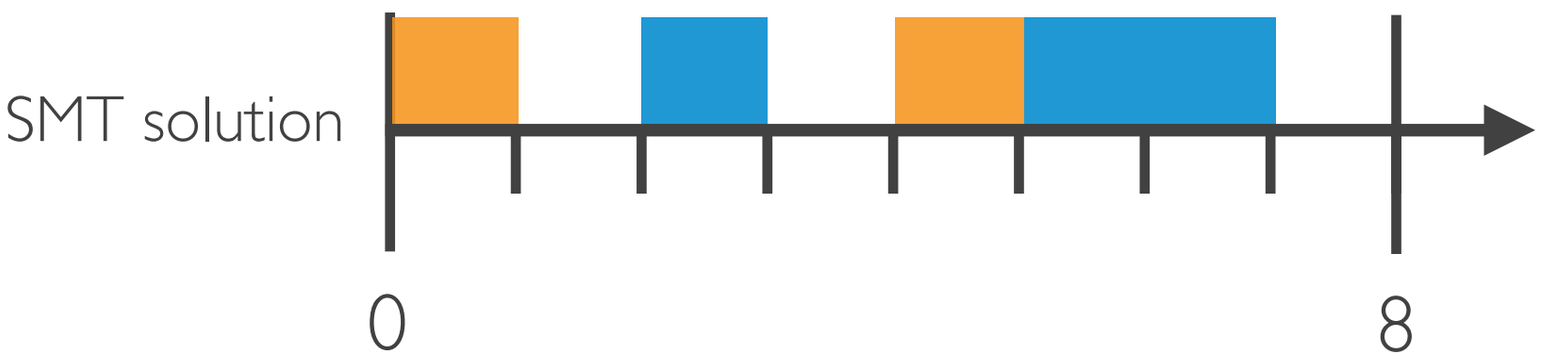

EDF tasks

(0, 1, 8, 1)

(2, 1, 8, 1)

(4, 1, 8, 1)

(5, 2, 8, 2)

Demand-based

EDF tasks

(0, 1, 8, 1)

(2, 1, 8, 1)

(4, 1, 8, 1)

(5, 2, 8, 2)

⊕

free tasks

(0, 2, 8, 8)

(0, 1, 8, 8)

Demand-based

SMT solution

EDF ta

$$\forall v_a \in \mathcal{V}, \forall t_1 \in \Phi^{v_a}, \forall t_2 \in \Delta^{v_a}, t_1 < t_2 :$$

$$\sum_{\widetilde{\tau}_i{}^{v_a} \in \widetilde{\Gamma}^{v_a}} \widetilde{\tau}_i{}^{v_a}.C \times \left(\left\lfloor \frac{t_2 - \widetilde{\tau}_i{}^{v_a}.\phi - \widetilde{\tau}_i{}^{v_a}.D}{\widetilde{\tau}_i{}^{v_a}.T} \right\rfloor - \left\lceil \frac{t_1 - \widetilde{\tau}_i{}^{v_a}.\phi}{\widetilde{\tau}_i{}^{v_a}.T} \right\rceil + 1 \right)_0 \leq t_2 - t_1,$$

where

$$\Phi^{v_a} \stackrel{def}{=} \{a_{i,j}^{v_a} = \widetilde{\tau}_i{}^{v_a}.\phi + j \times \widetilde{\tau}_i{}^{v_a}.T | \widetilde{\tau}_i{}^{v_a} \in \widetilde{\Gamma}^{v_a}, j \geq 0, a_{i,j}^{v_a} \leq \lambda^{v_a}\},$$

$$\Delta^{v_a} \stackrel{def}{=} \{d_{i,j}^{v_a} = a_{i,j}^{v_a} + \widetilde{\tau}_i{}^{v_a}.D | \widetilde{\tau}_i{}^{v_a} \in \widetilde{\Gamma}^{v_a}, j \geq 0, d_{i,j}^{v_a} \leq \lambda^{v_a}\},$$

$$\lambda^{v_a} = max(\{\widetilde{\tau}_i{}^{v_a}.\phi | \widetilde{\tau}_i{}^{v_a} \in \widetilde{\Gamma}^{v_a}\}) + 2 \times lcm(\{\widetilde{\tau}_i{}^{v_a}.T | \widetilde{\tau}_i{}^{v_a} \in \widetilde{\Gamma}^{v_a}\}).$$

Demand-based

EDF tasks

(0, 1, 8, 1)

(2, 1, 8, 1)

(4, 1, 8, 1)

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$\oplus$

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(0, 2, 8, 8)

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Demand-based

Ensuring Reliable Networks TTTech

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(2, 1, 8, 1)

(4, 1, 8, 1)

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⊕

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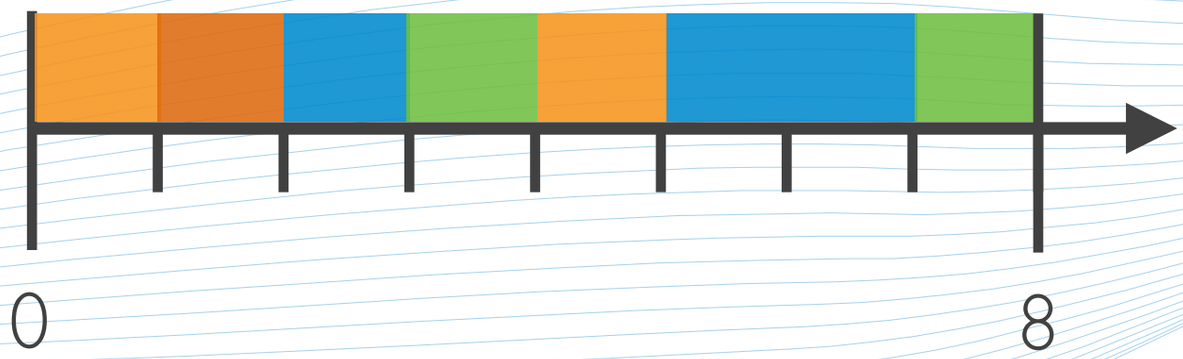

Demand-based

Ensuring Reliable Networks TTTech

Demand-based

- transform scheduled frames on CPUs into asynchronous periodic tasks

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- add free tasks and apply schedulability test [Pellizzoni@RealTimeSyst05]

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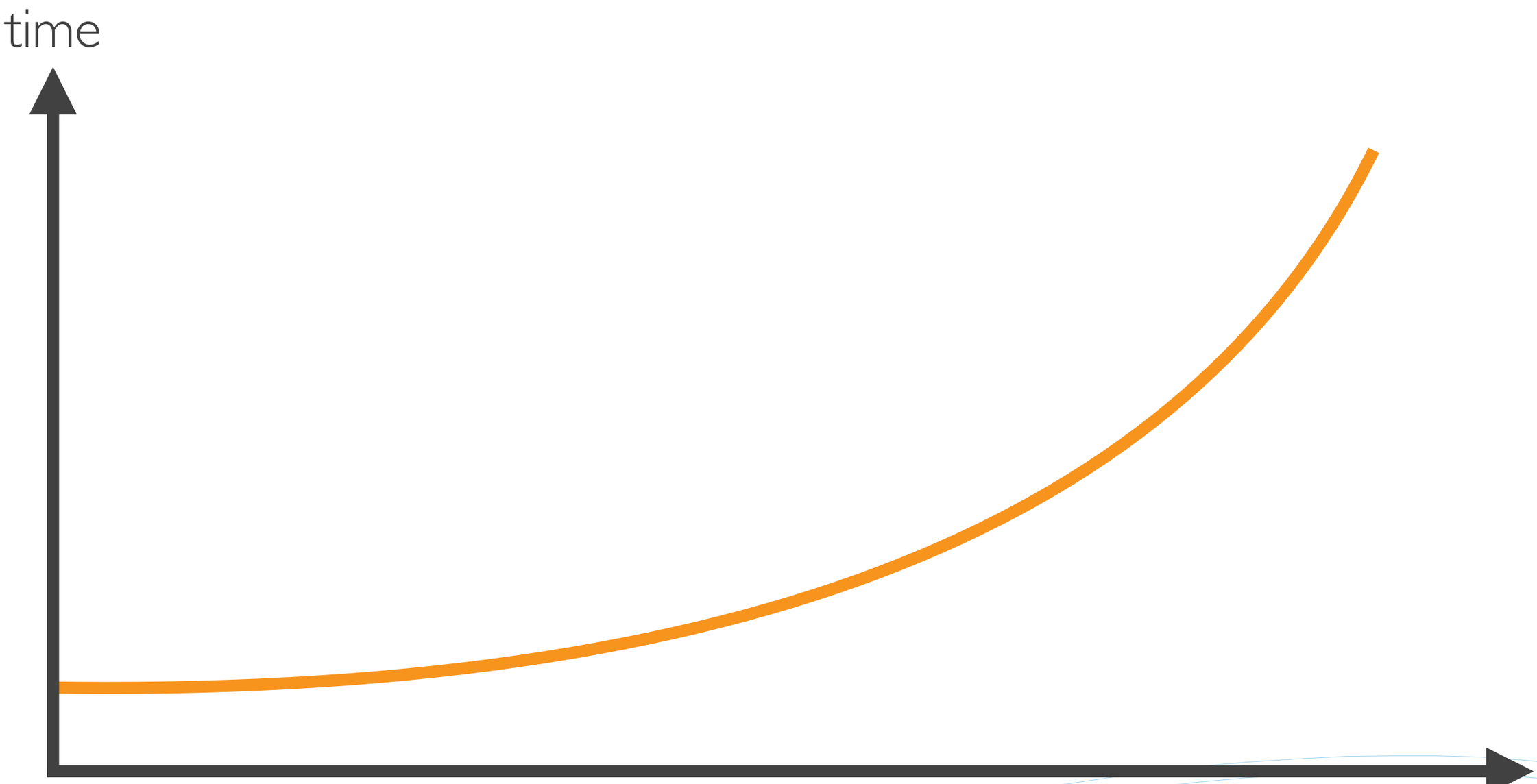
- we are still exponential but scale better for the average case

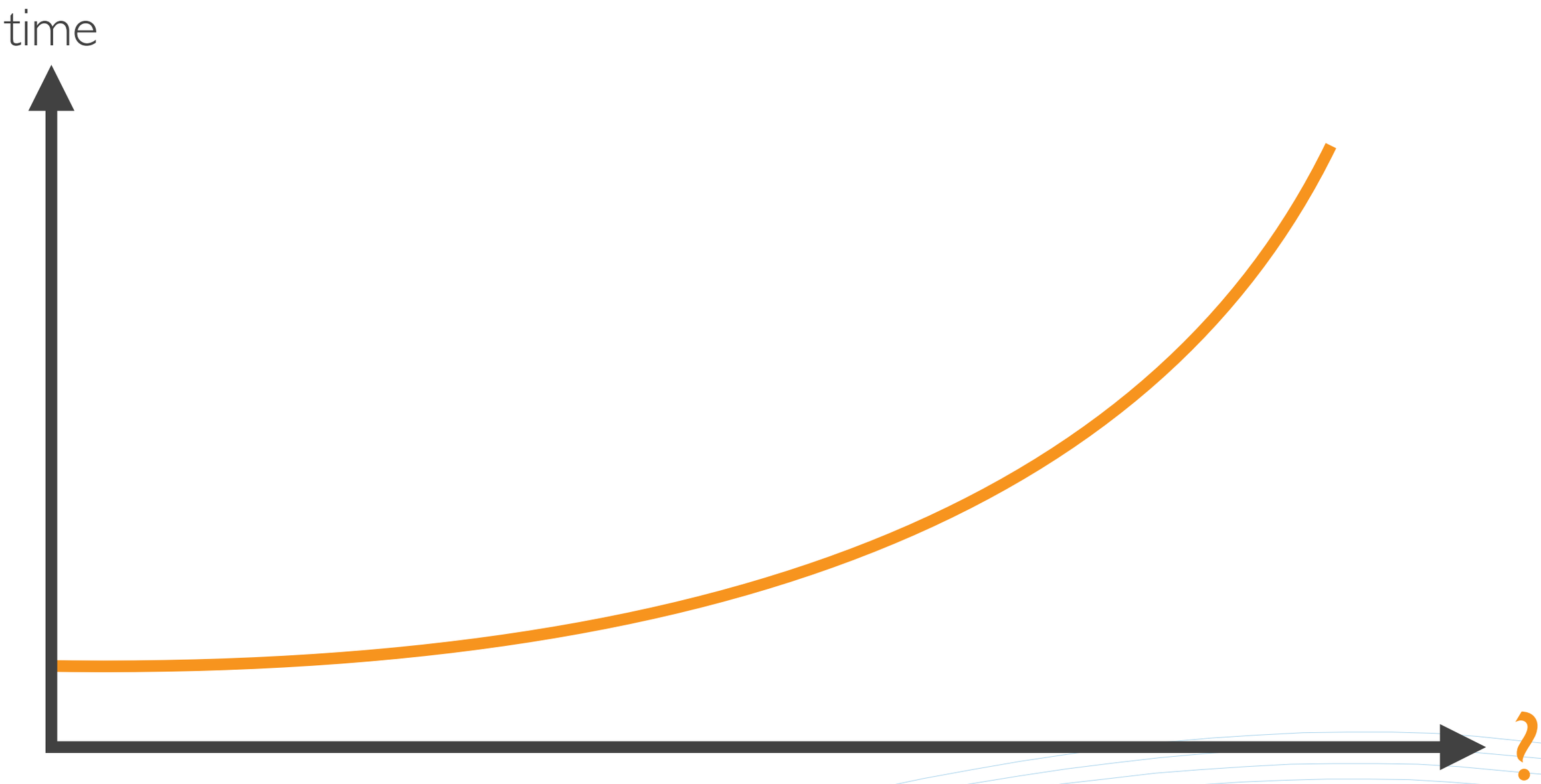
Evaluation

Evaluation

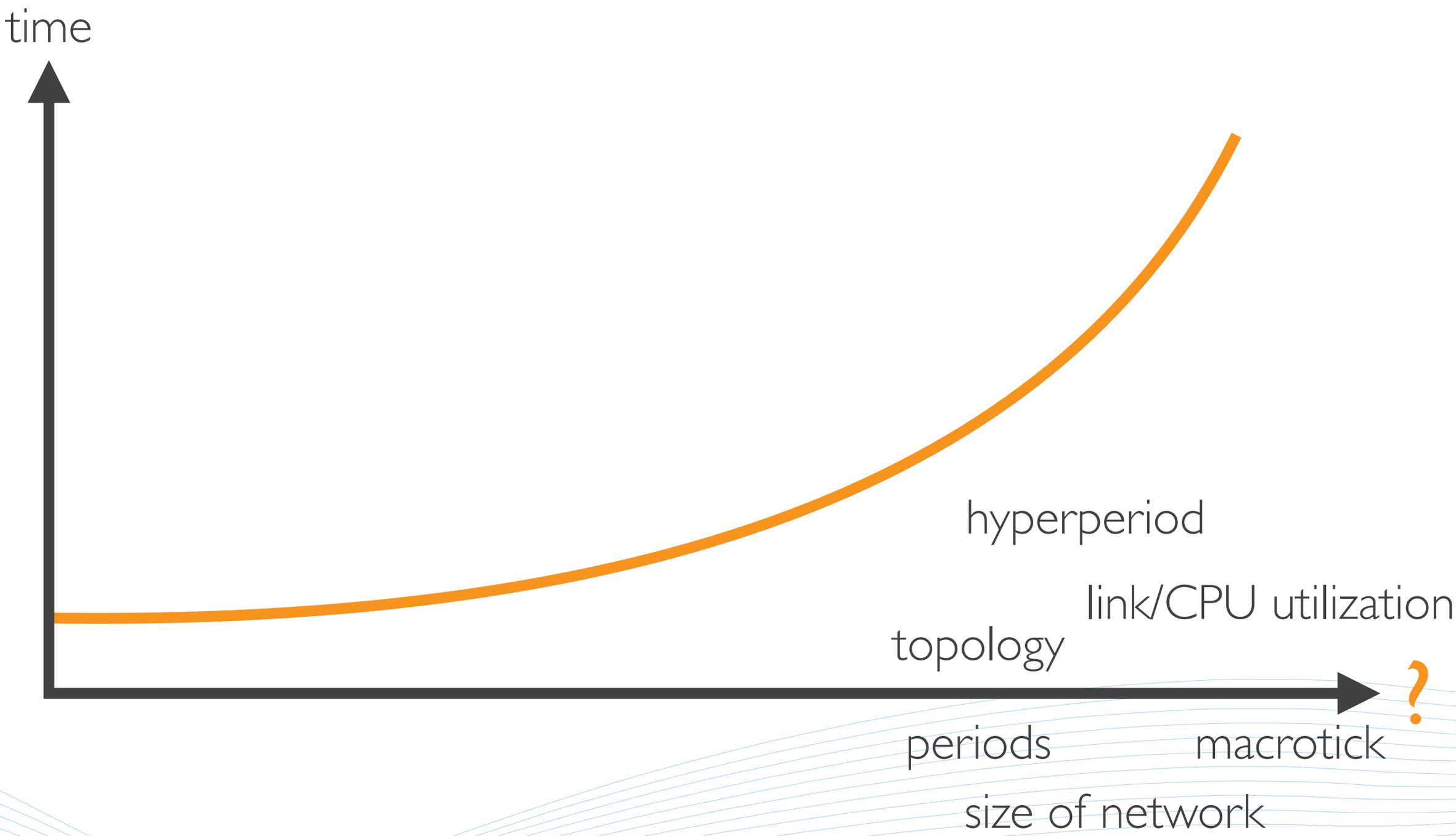
Evaluation



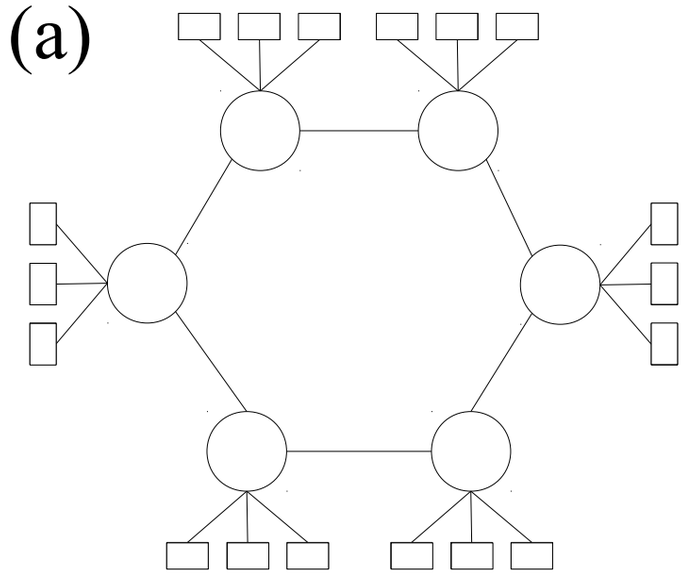
Evaluation

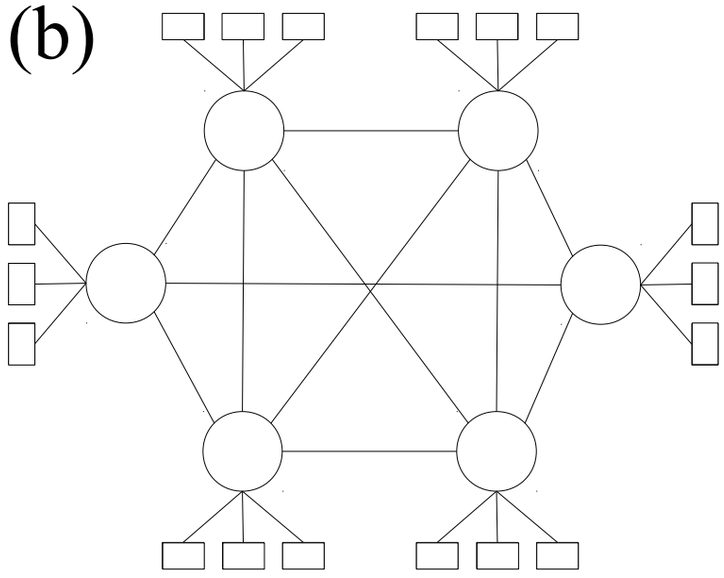


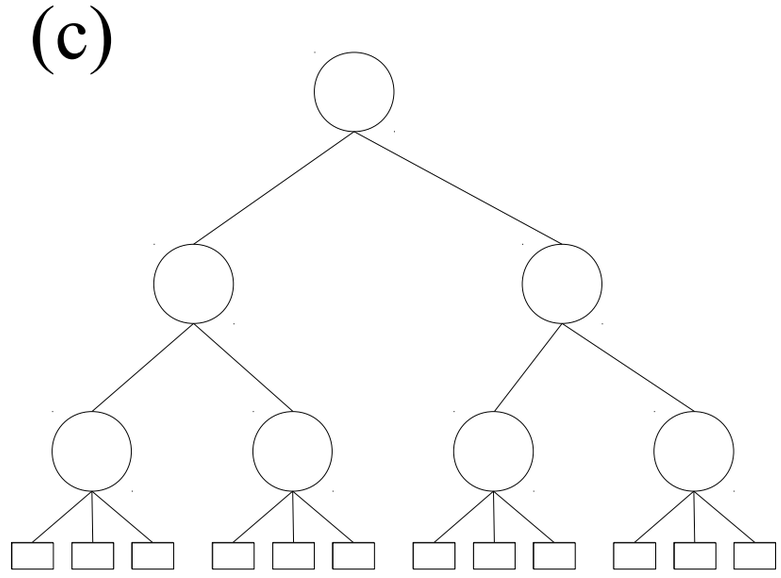
Evaluation



Topologies







Periods {10,20,25,50,100}, {10,30,100}, {50,75} ms

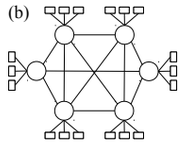
1usec network link granularity

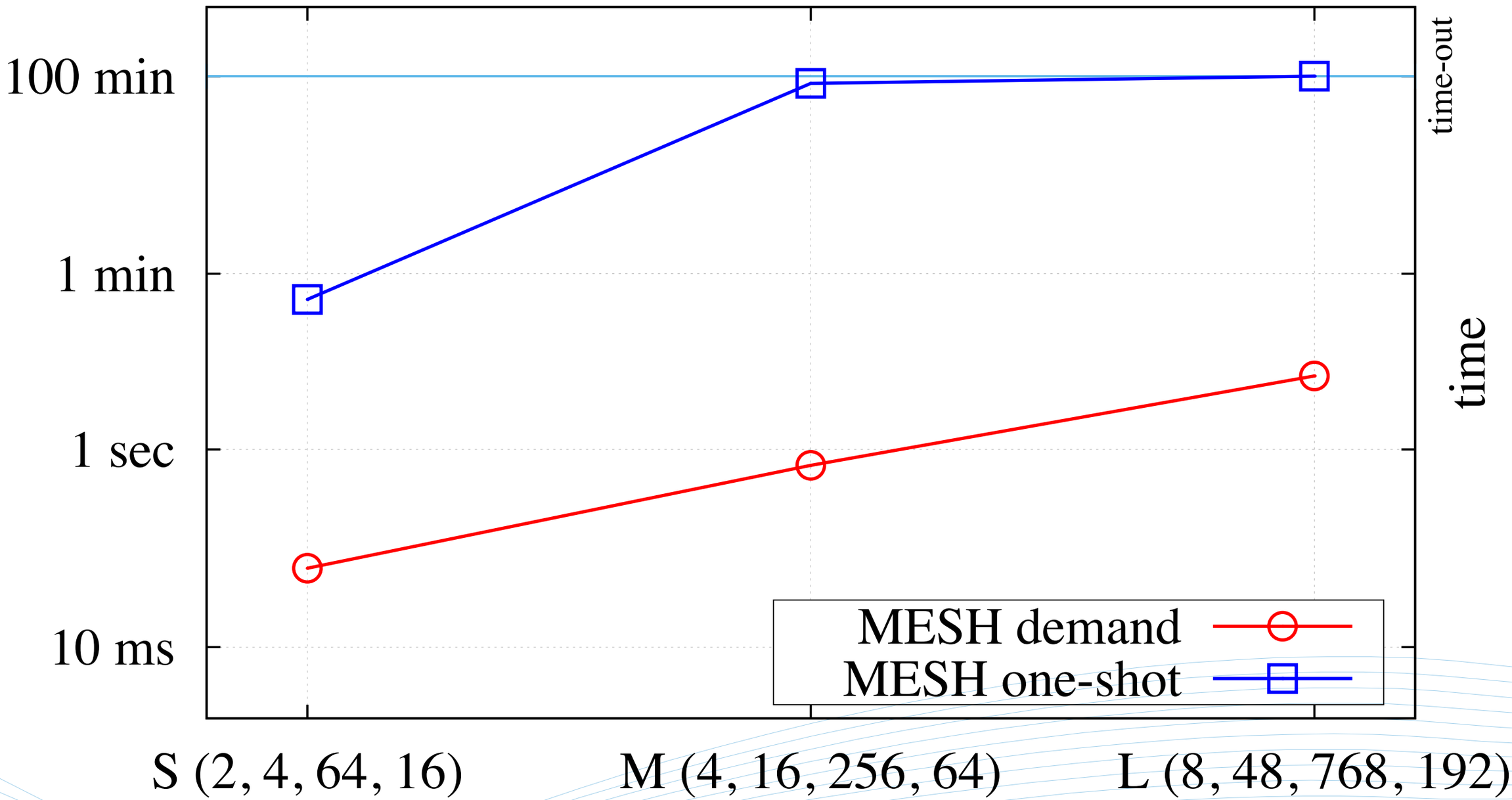
100Mbit/s and 1Gbit/s

random message size and virtual links

different macrotick and utilization configurations

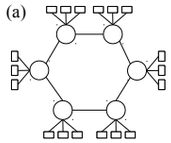
Mesh

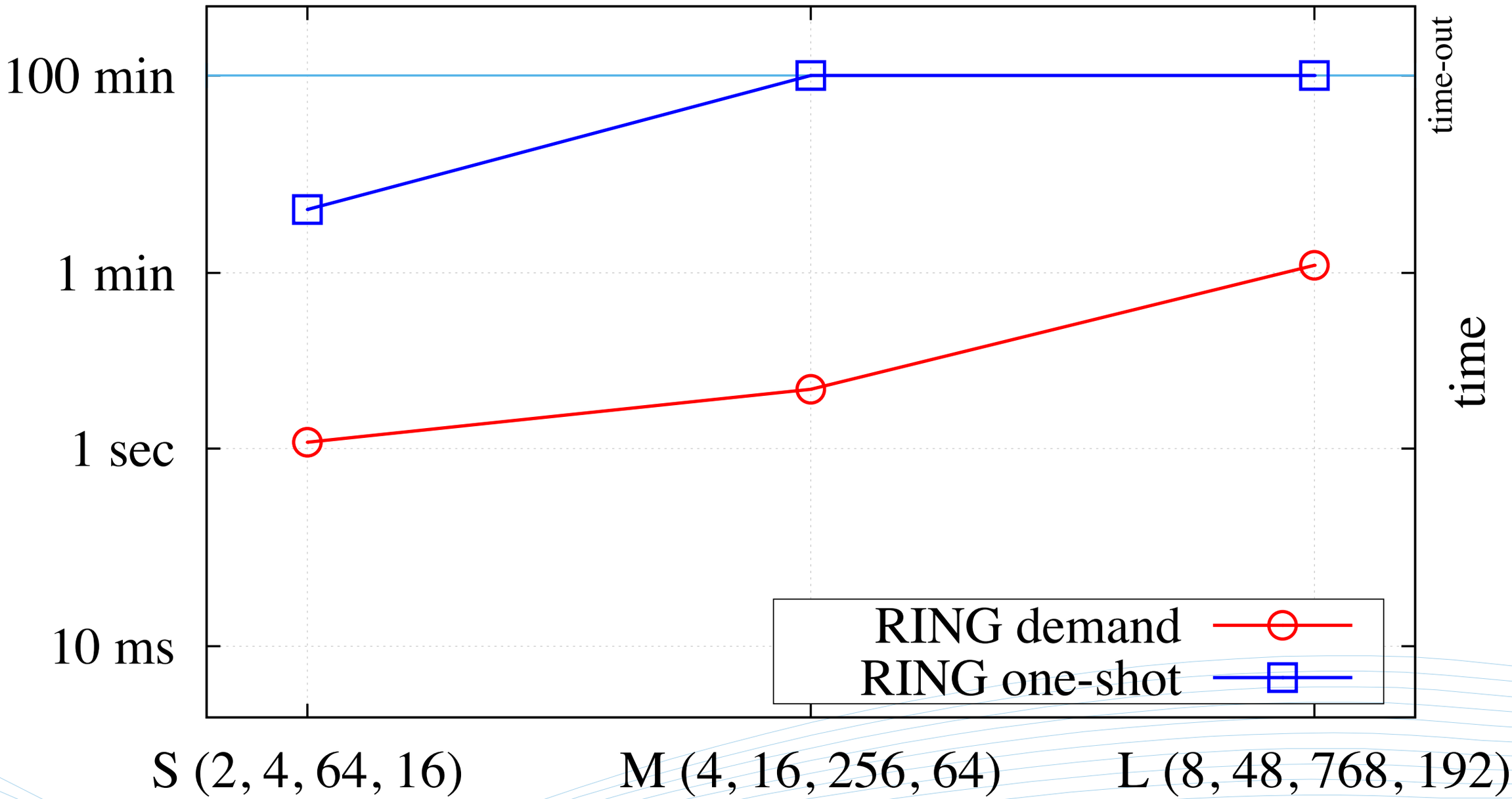




Periods {10,20,25,50,100} ms

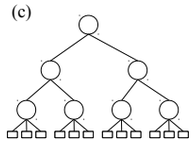
Ring

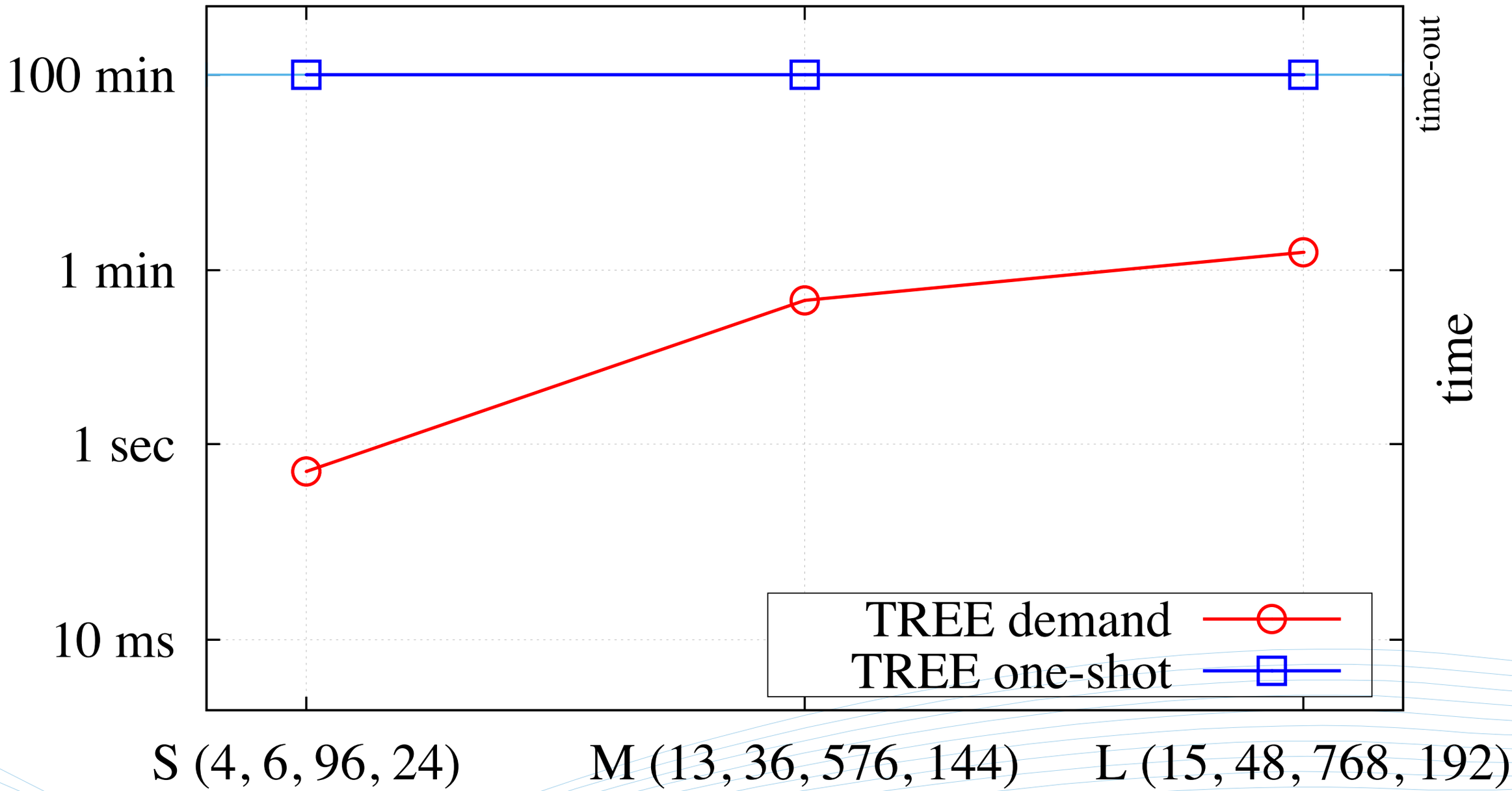




Periods {10,30,100} ms

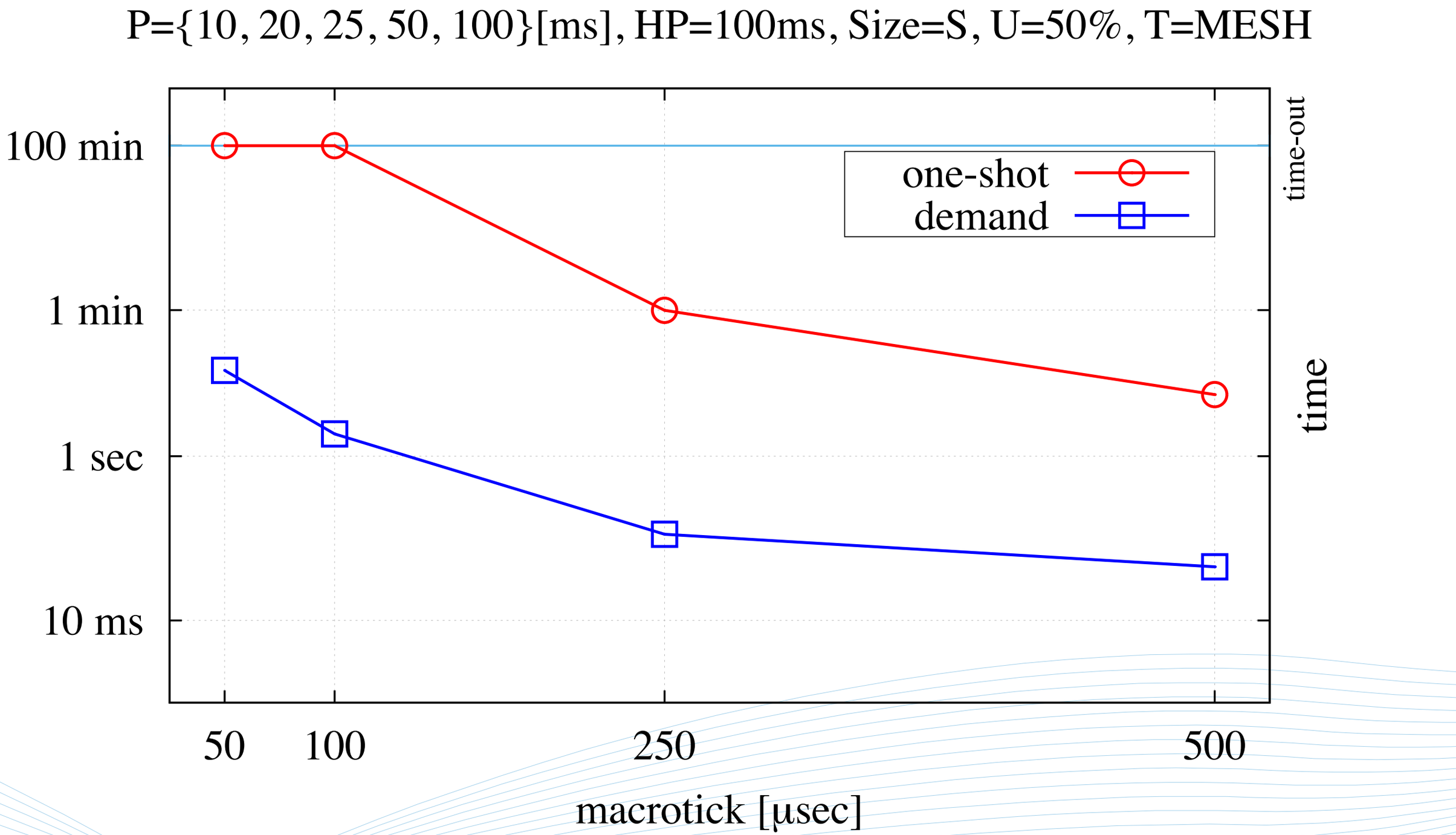
Tree



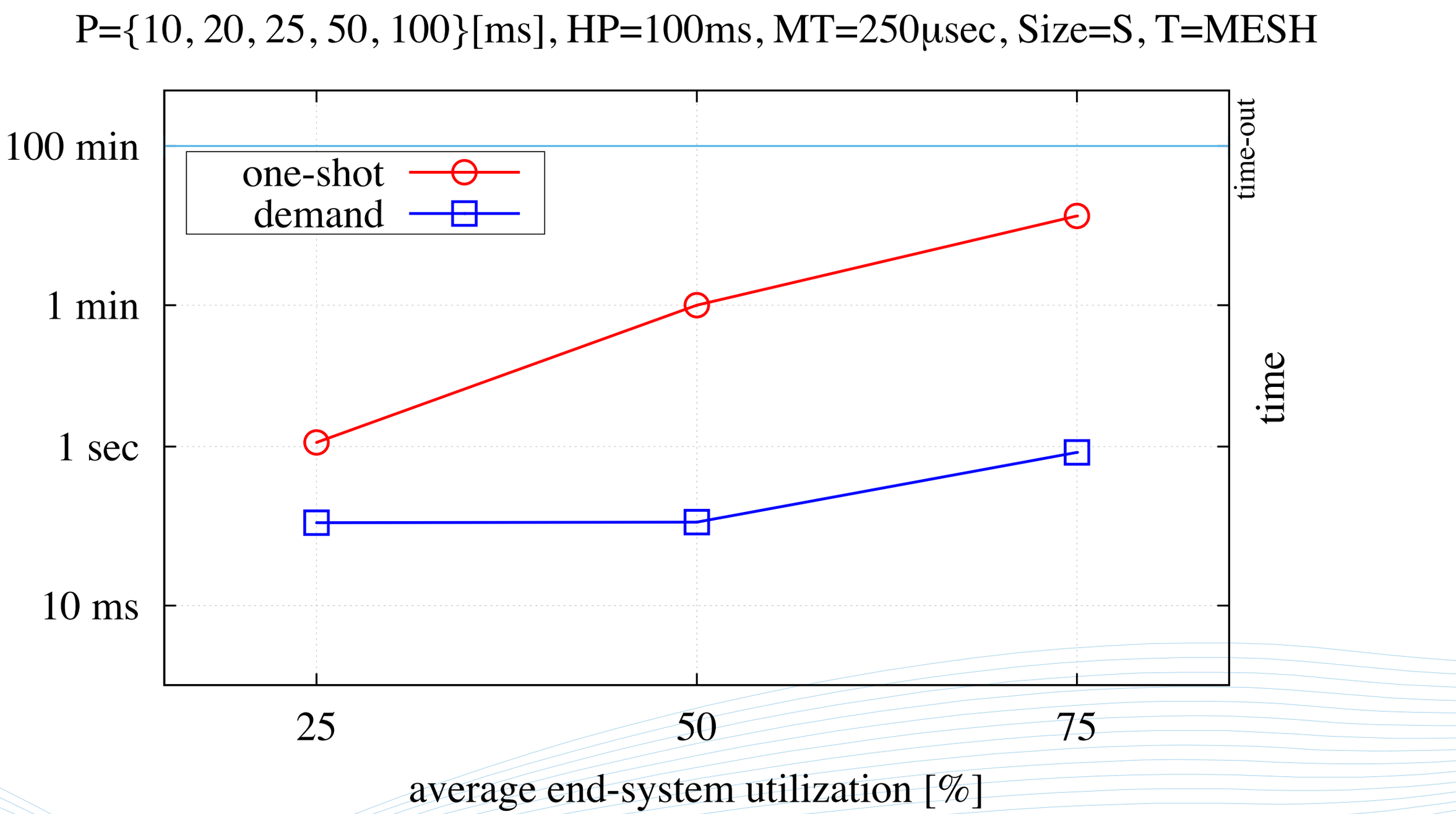


Periods {50,75} ms

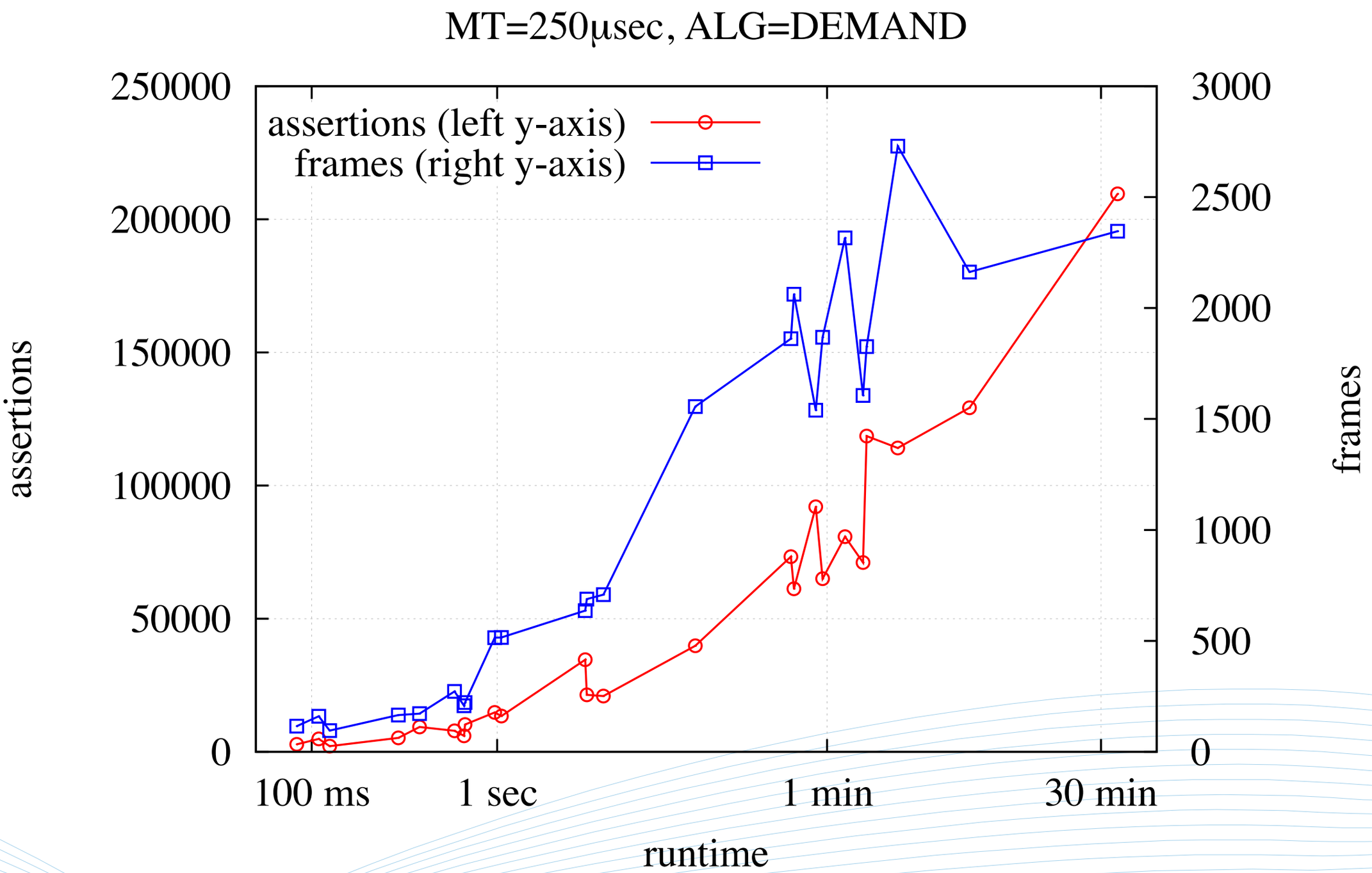
Macrotick



Utilization



SMT assertions



Conclusions

Ensuring Reliable Networks TTTech

Conclusions

Ensuring Reliable Networks TTTech

co-synthesis of task and message schedules

Conclusions

co-synthesis of task and message schedules

preemptive tasks

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co-synthesis of task and message schedules

preemptive tasks

switched multi-speed TTEthernet networks

Conclusions

co-synthesis of task and message schedules

preemptive tasks

switched multi-speed TTEthernet networks

satisfiability modulo theories

Conclusions

co-synthesis of task and message schedules

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satisfiability modulo theories

demand based approach

Conclusions

co-synthesis of task and message schedules

preemptive tasks

switched multi-speed TTEthernet networks

satisfiability modulo theories

demand based approach

scales for medium to large industrial systems

Thank you!

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SMT-scheduled frames

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