A Real-Time Multicast Routing Scheme for Multi-Hop Switched Fieldbuses

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Content


Demand


Background


Problem Definition and Complexity


Heuristic Algorithm


Evaluation


Related Work

Fieldbus is fundamentally different from the Internet, hence requires different solutions.

Specialized networks used in industrial, mining, medical, vehicular, avionic environments

Fieldbus:	**The Internet:**
Hard Real-Time	Best Effort
Periodic Stable Traffic	Random Bursty Traffic
Bounded w/ Global Info	Unbounded w/o Global Info

Fieldbus is evolving from shared medium to multi-hop switched due to scalability needs.

Concord

1976

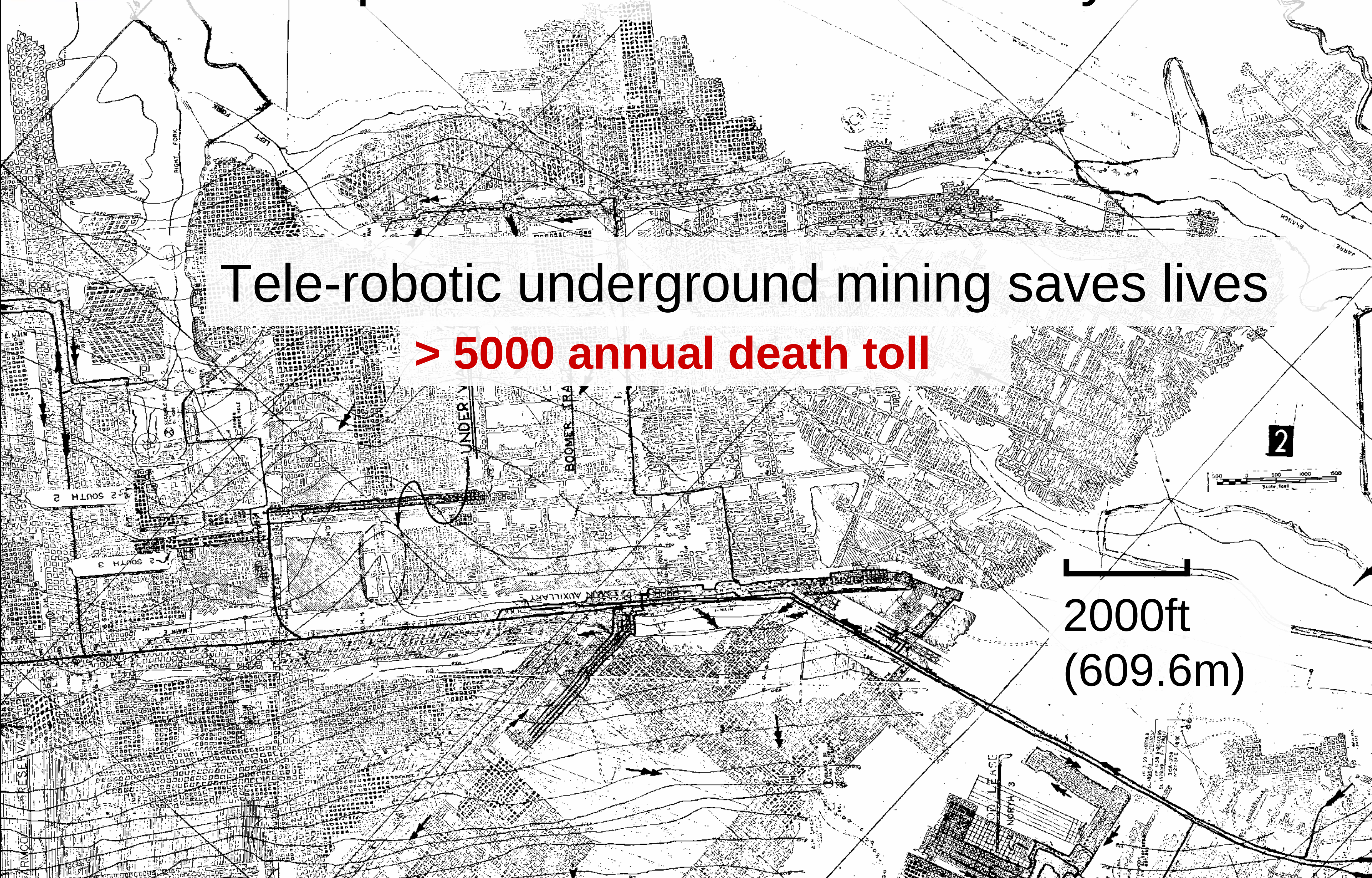
Fieldbus is evolving from shared medium to multi-hop switched due to scalability needs.

A380

2007,

Several Hundreds of computing nodes

Fieldbus is evolving from shared medium to multi-hop switched due to scalability needs.



Tele-robotic underground mining saves lives

> 5000 annual death toll

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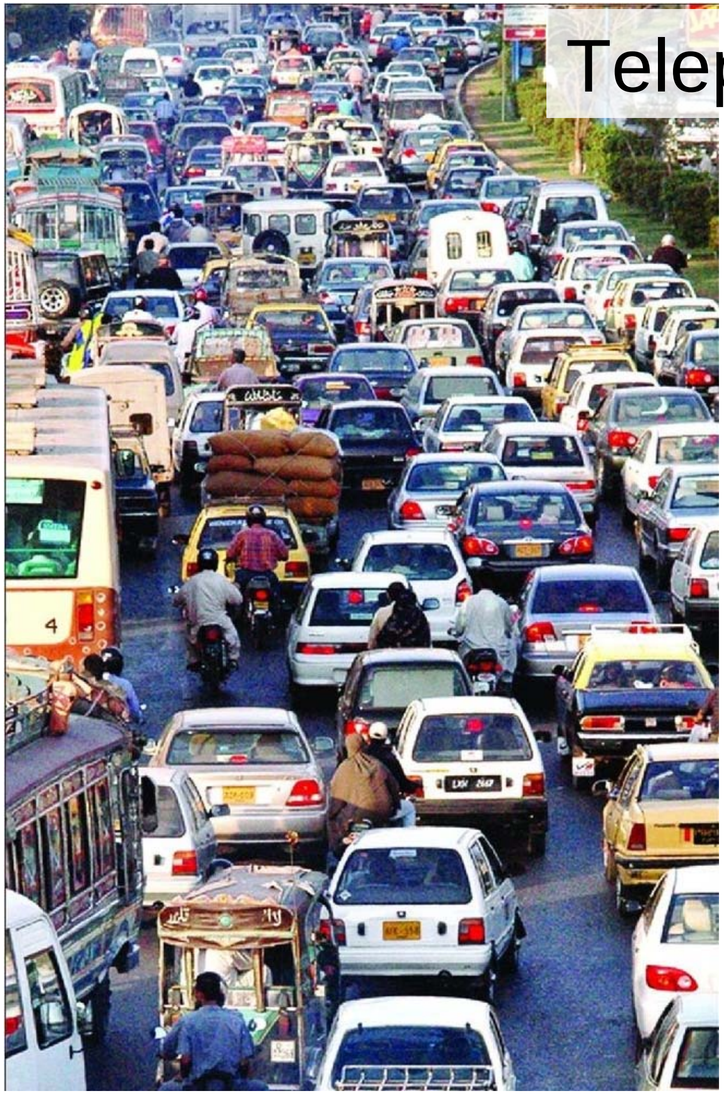
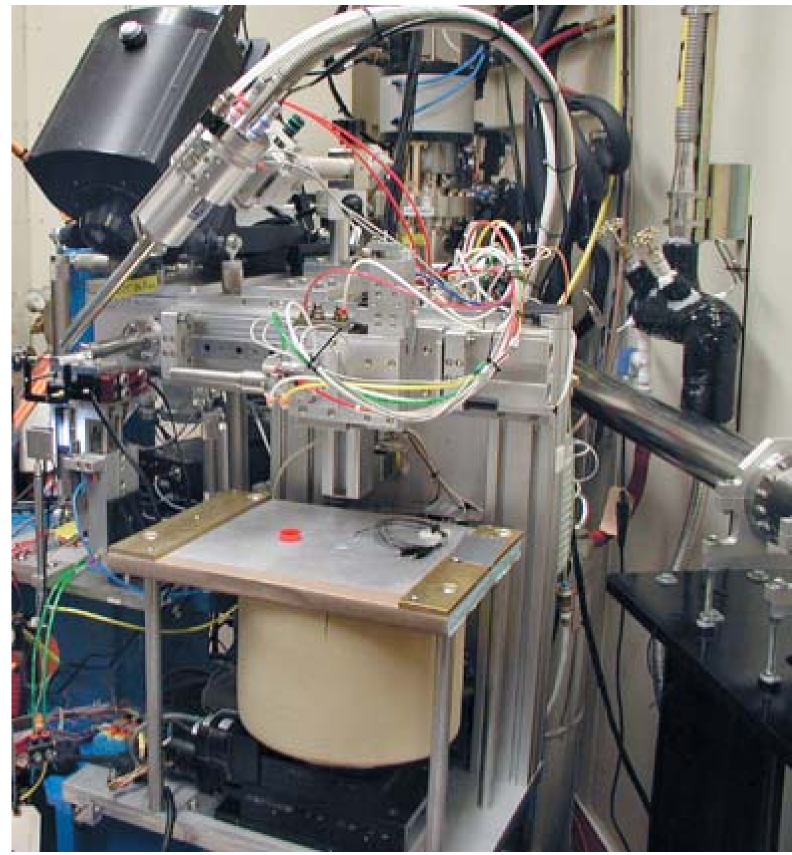


Telepresence

Fieldbus is evolving from shared medium to multi-hop switched due to scalability needs.

Robotic Manufacturing



Shared medium → multi-hop switched: real-time multicast becomes a problem.

$$\dot{x}(t)_{n\times 1} = A_{n\times n}x(t)_{n\times 1} + B_{n\times m}u(t)_{m\times 1}$$

$$u(t)_{m\times 1} = -K_{m\times n}x(t)_{n\times 1}$$

Modern control assumes MIMO →
Real-Time Multicast btw
Sensors-Controllers-Actuators/Observers

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Shared Medium Real-Time Multicast: Easy

Multi-Hop Switched Real-Time Multicast: ?

De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA

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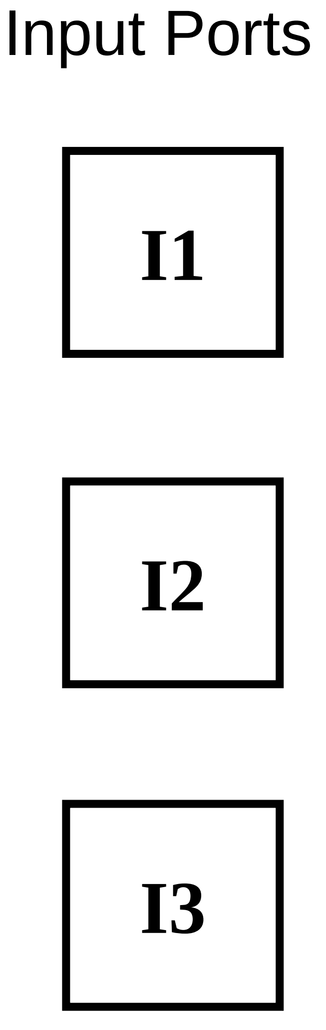

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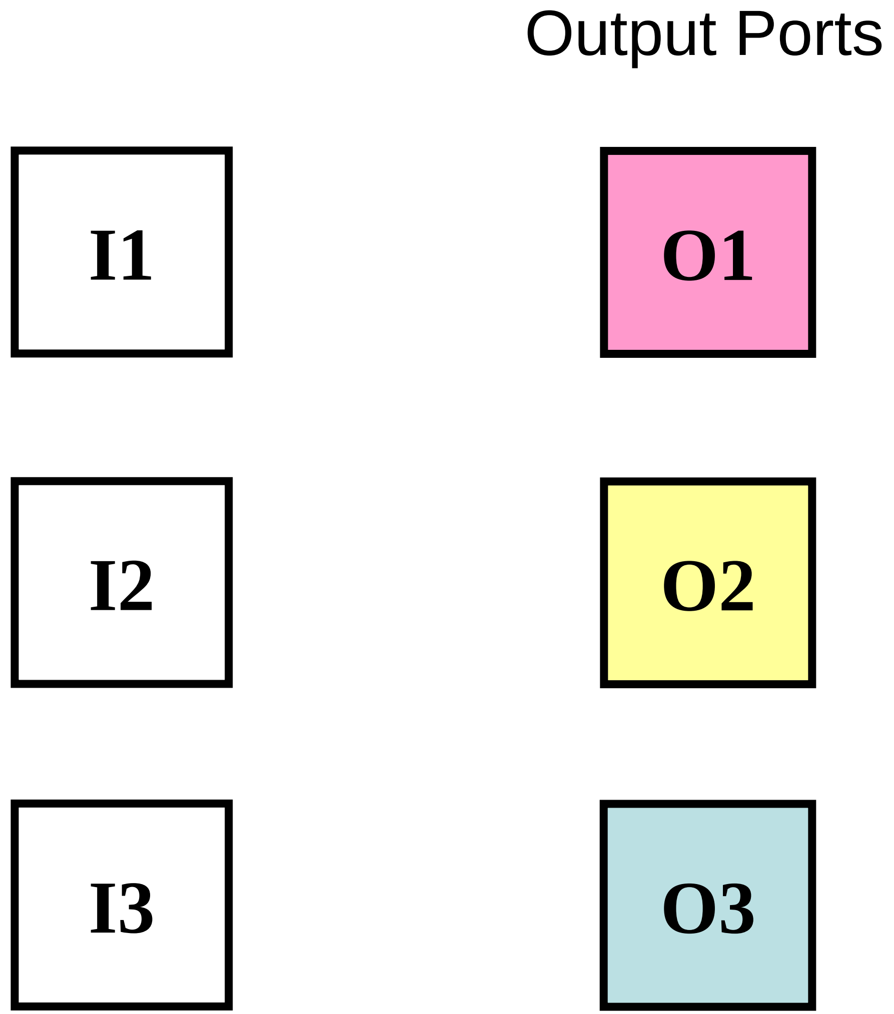

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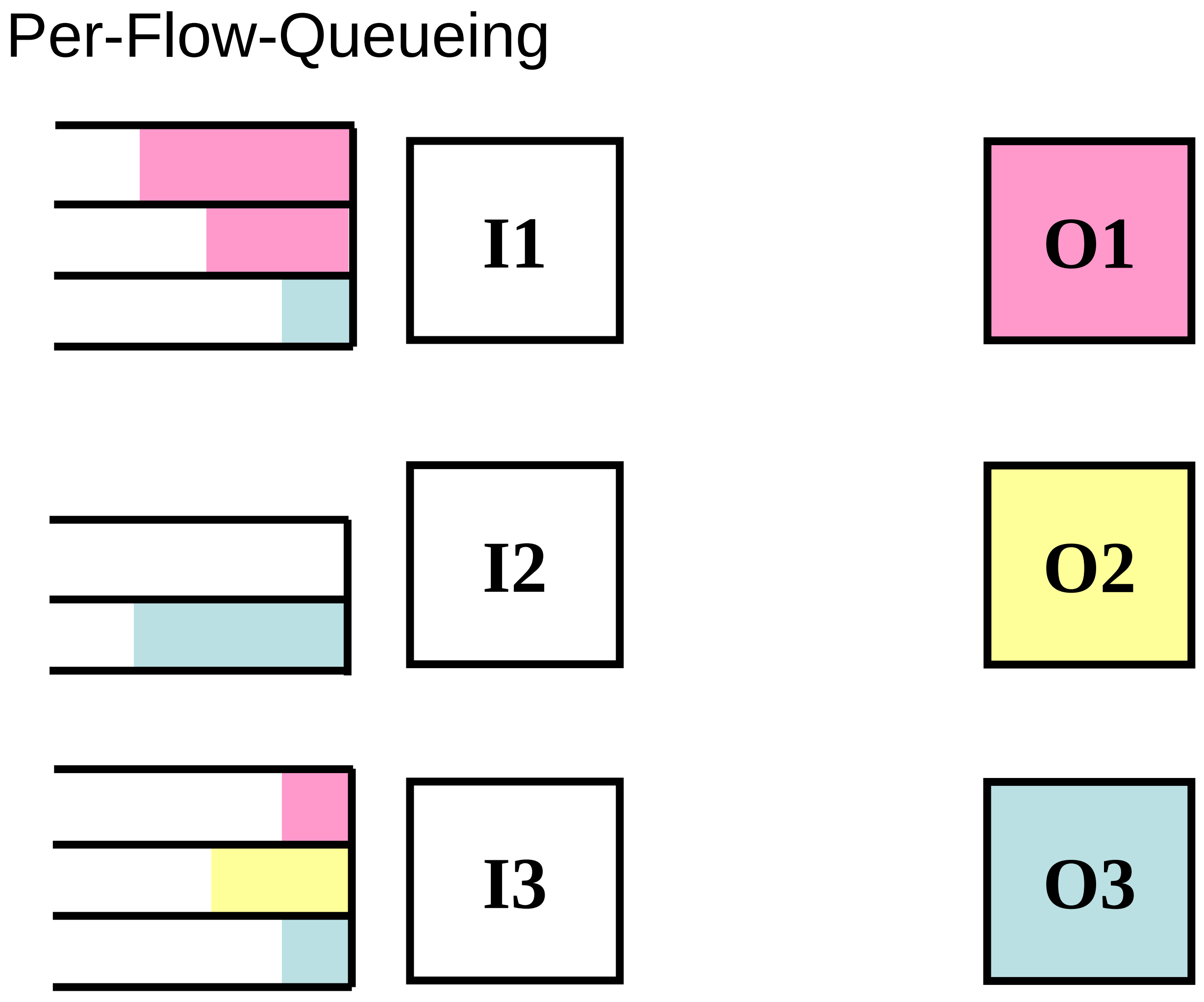

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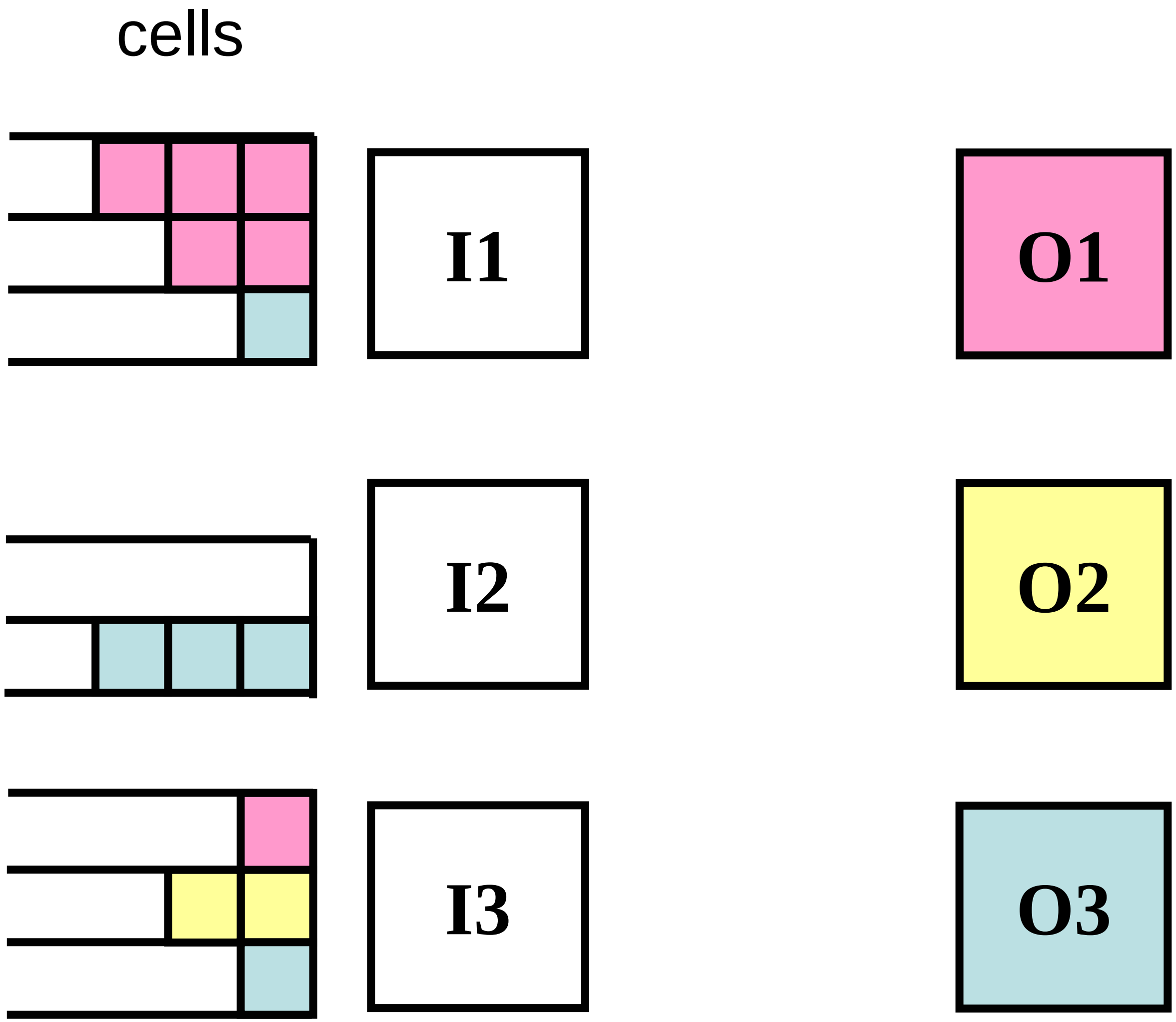

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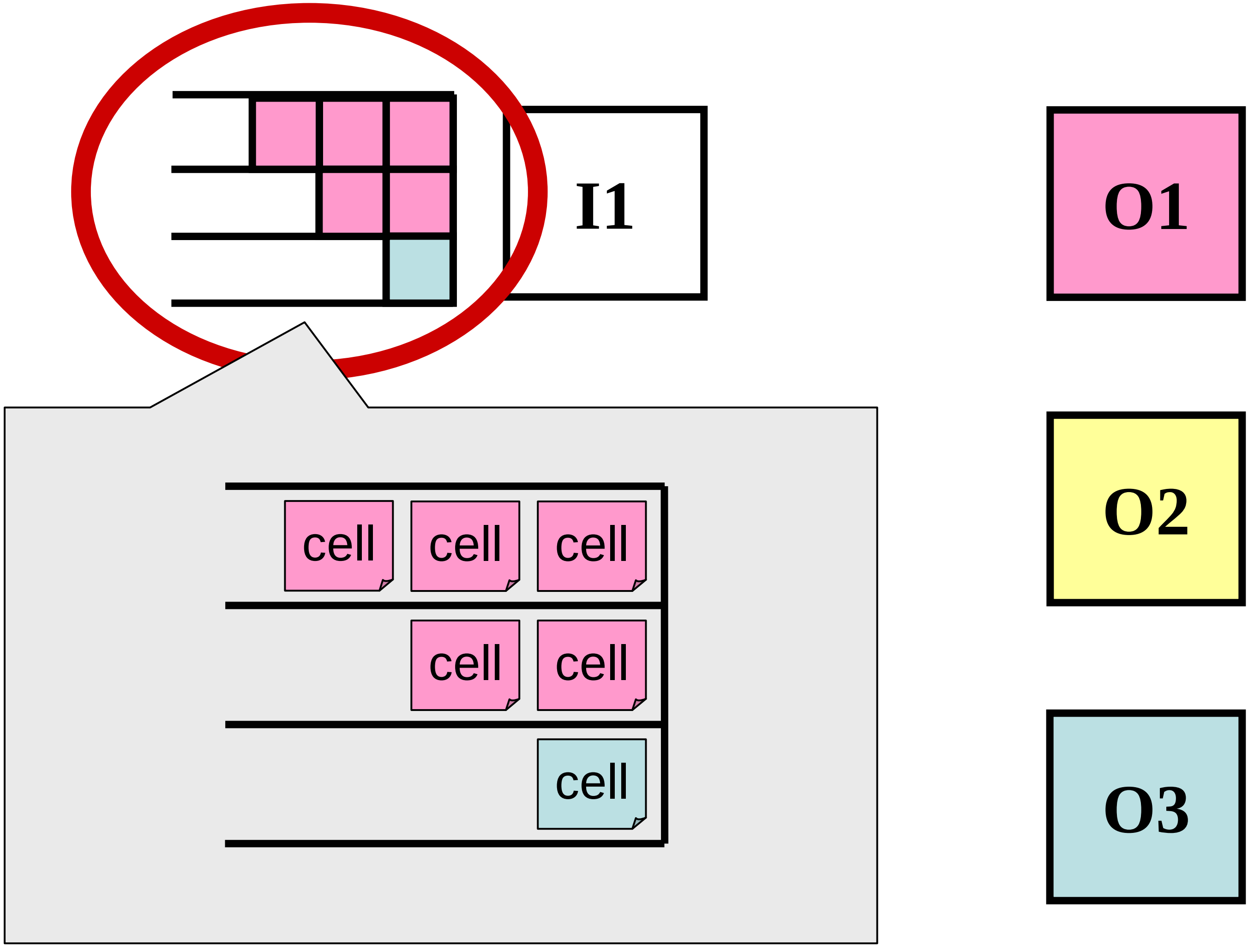
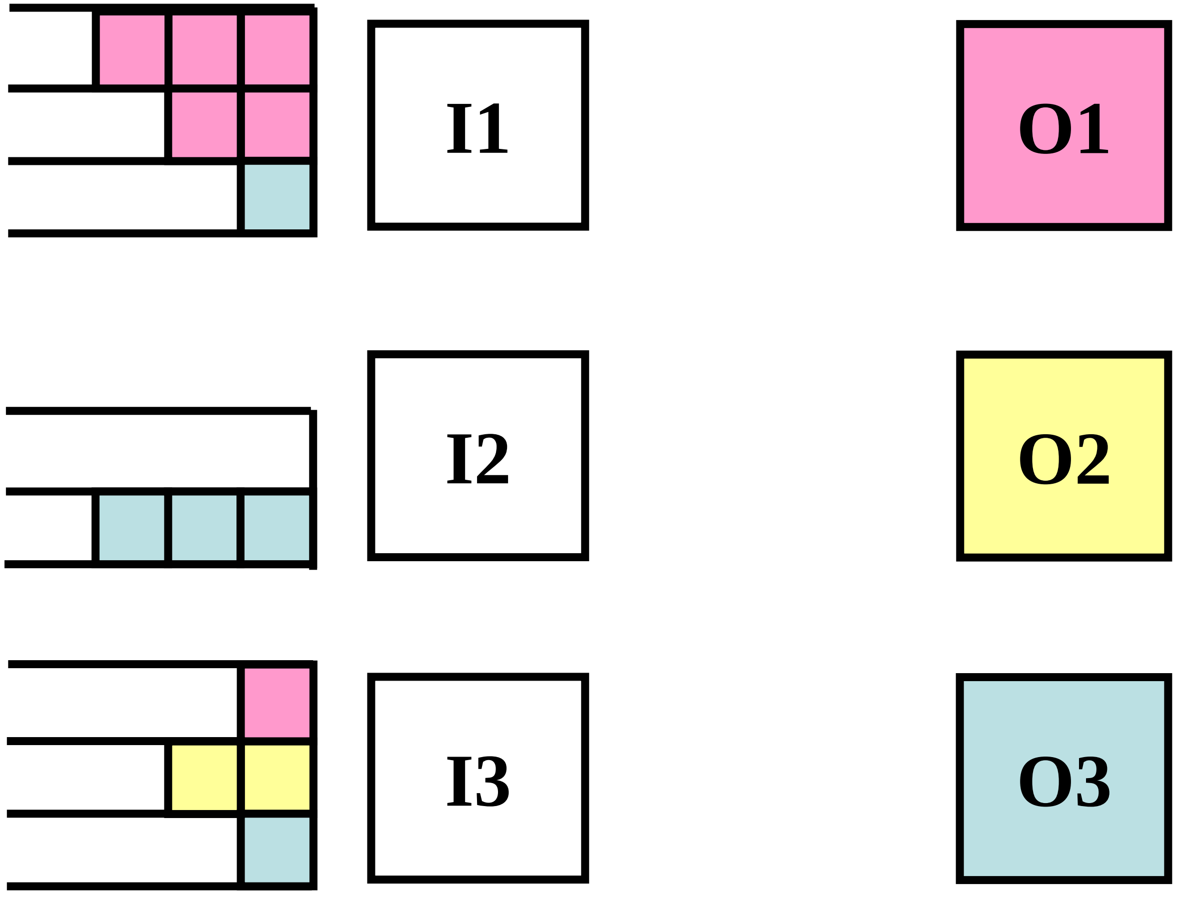


De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA

Synchronous periodic cell forwarding

Cell-Time



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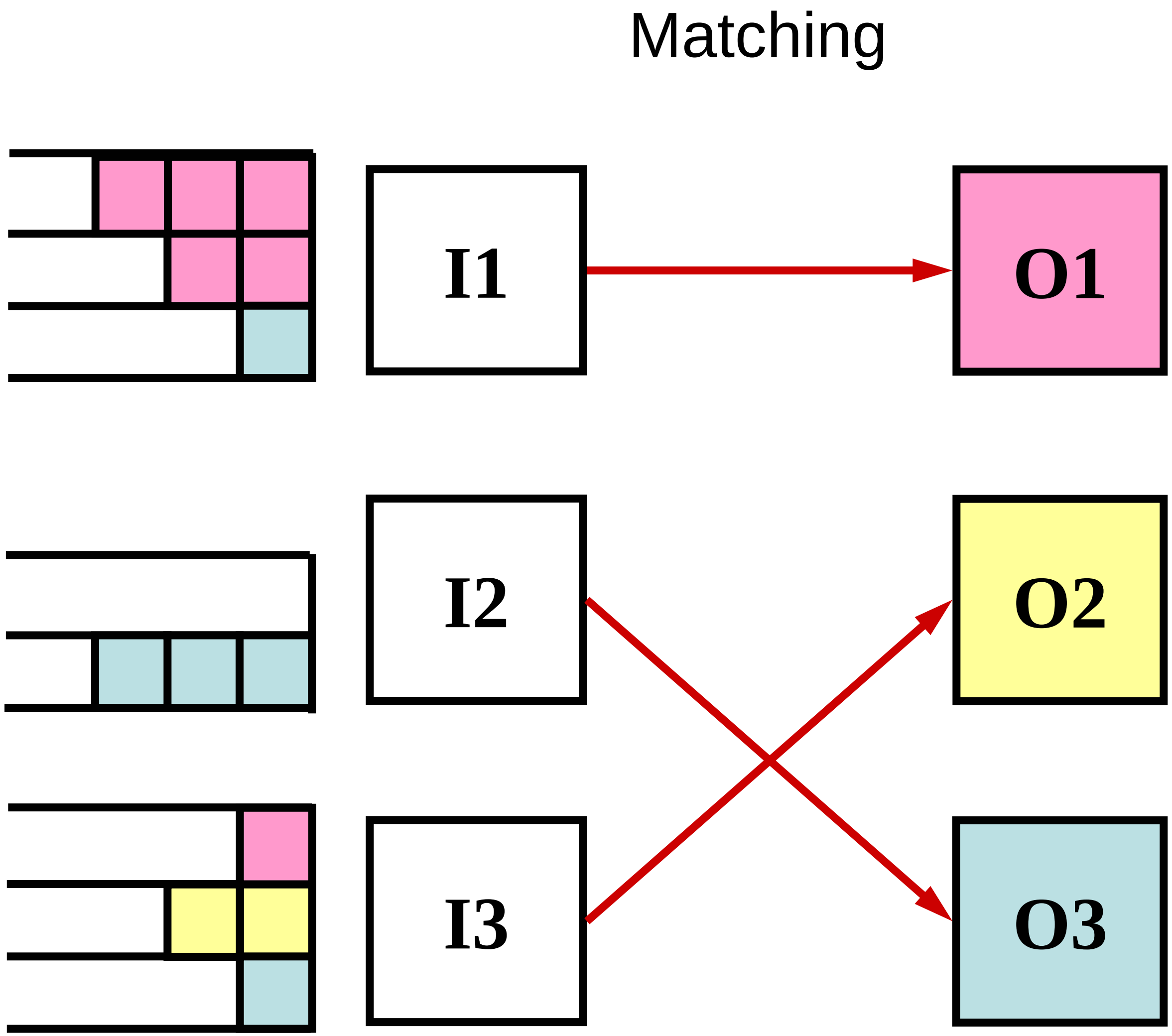
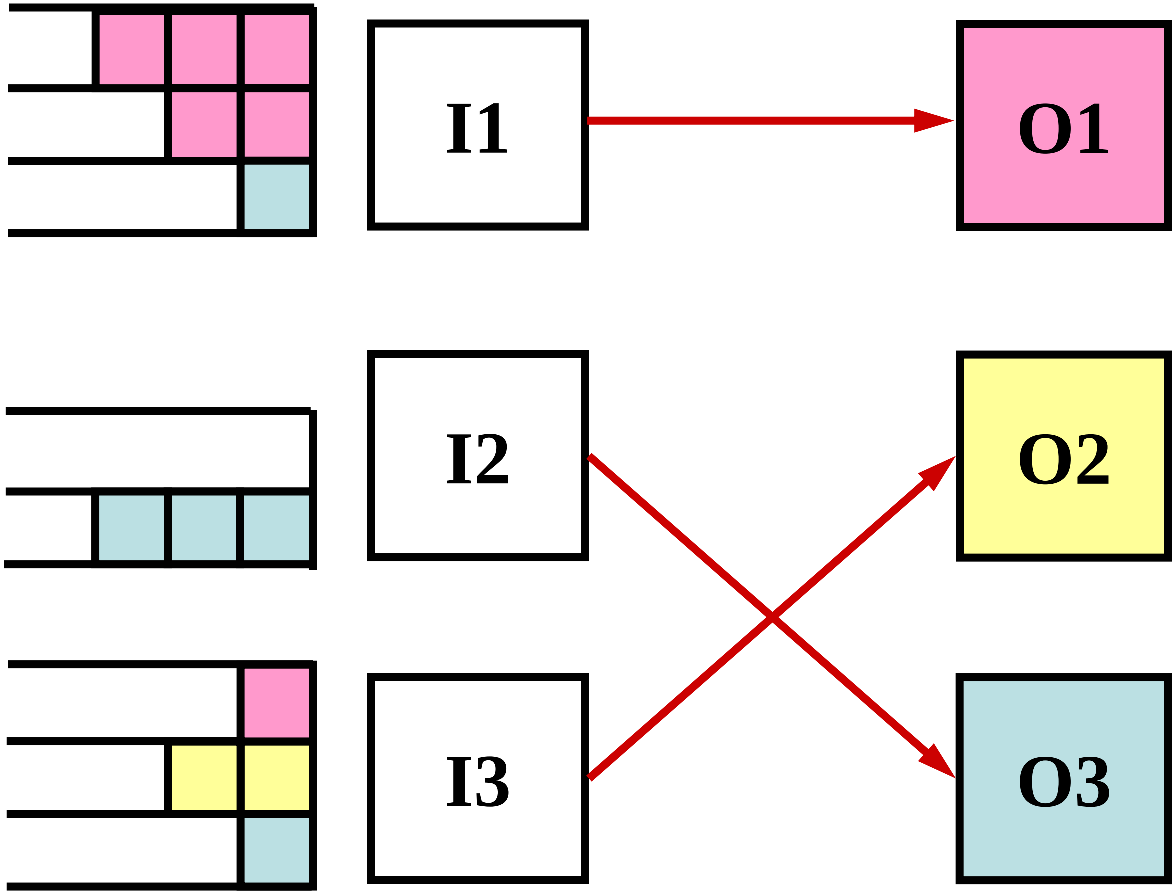


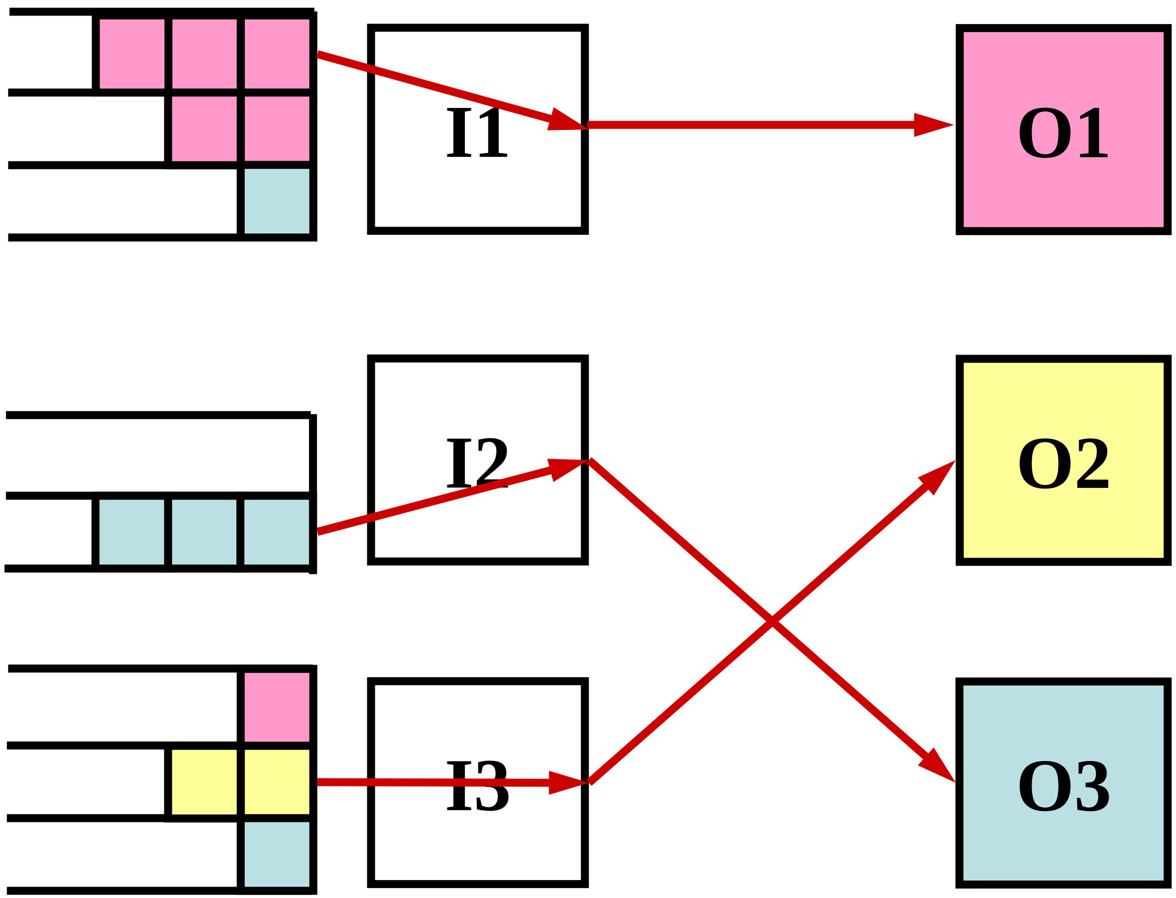
De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA

Why Matching? An input/output can only send/receive one cell per cell-time



De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA

Internal Matching: if an input has multiple per-flow-q for the same output, only one is picked every cell-time.



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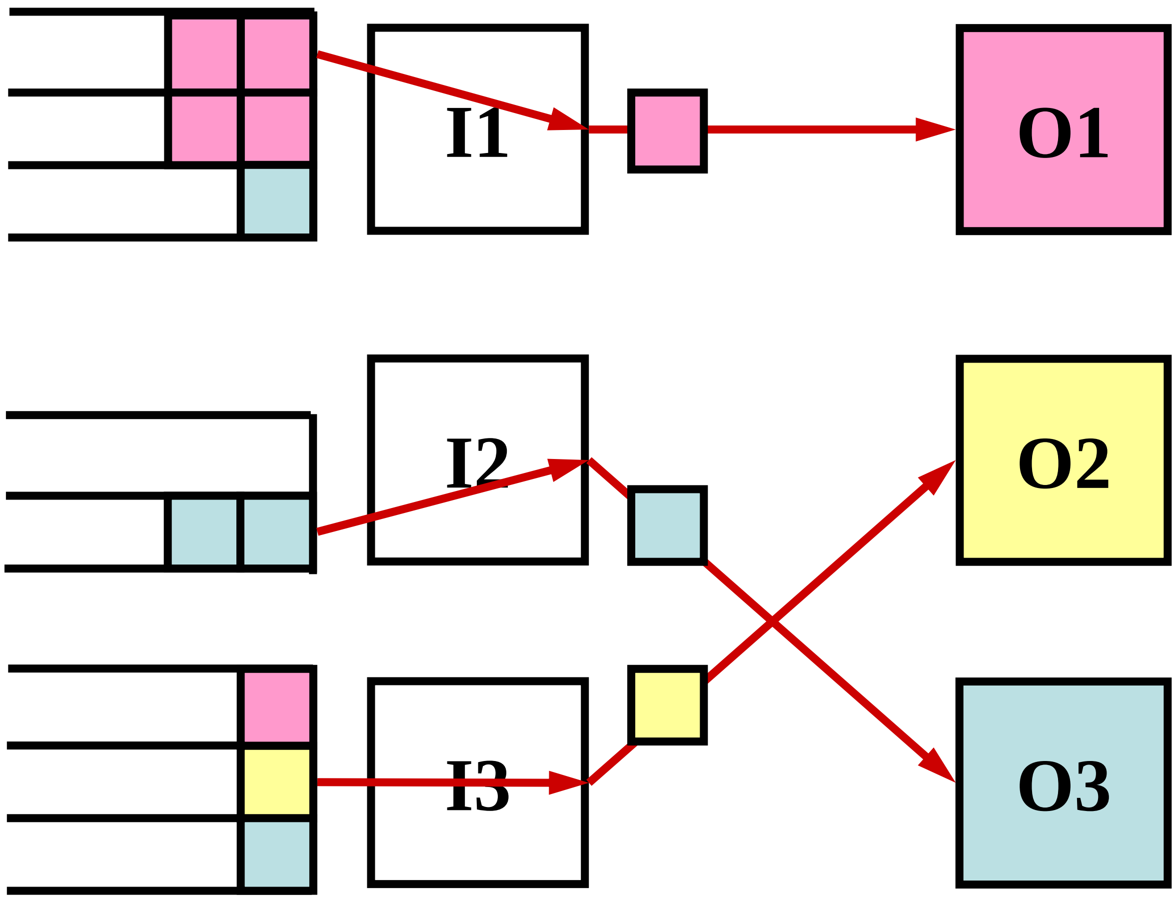

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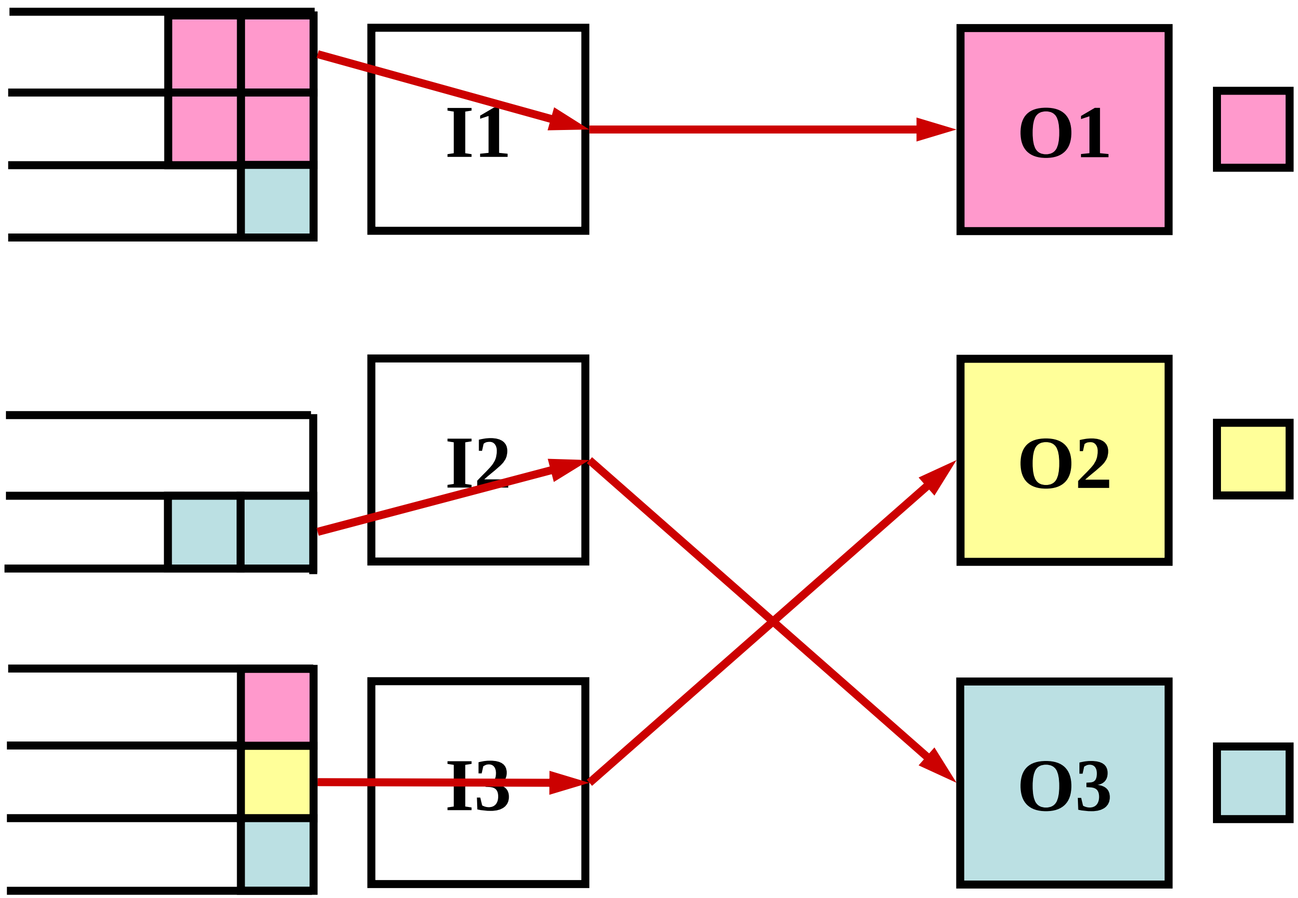

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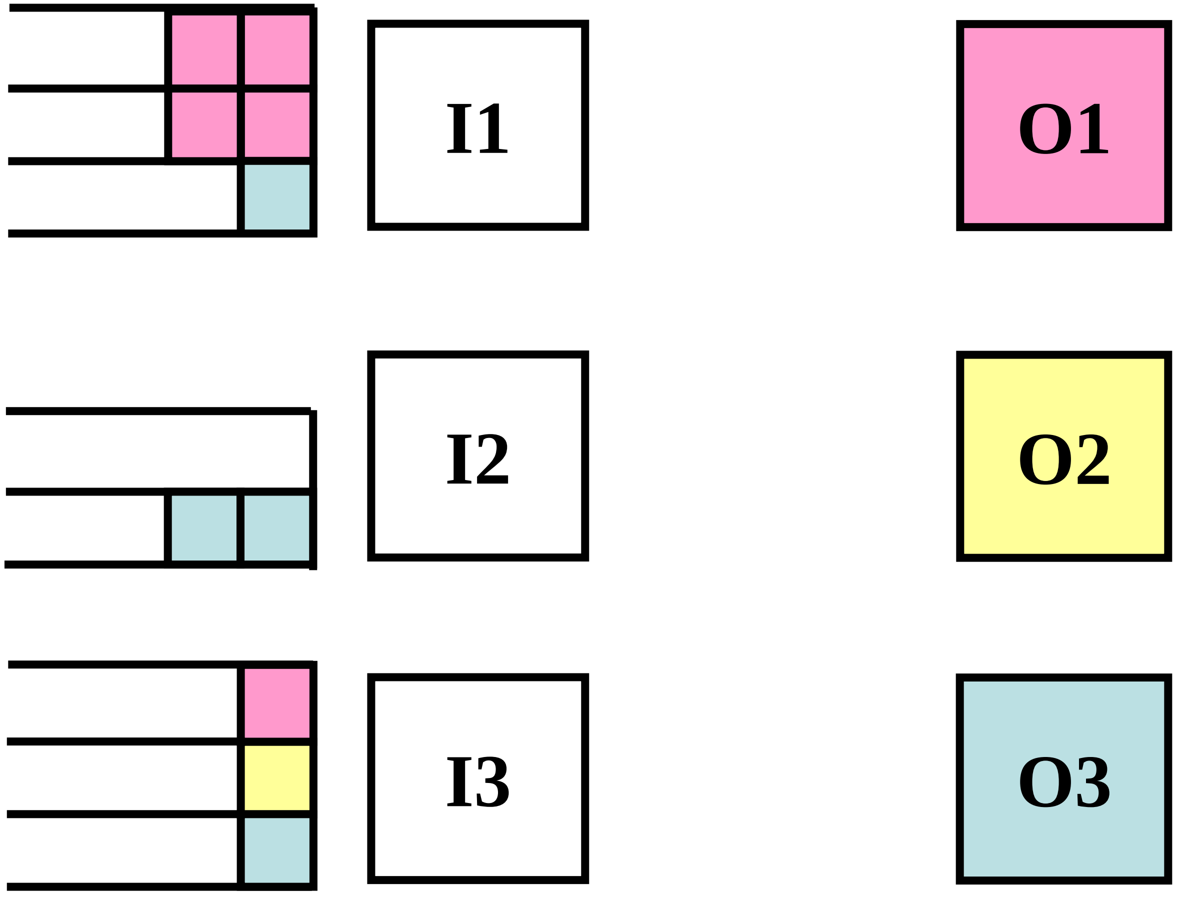
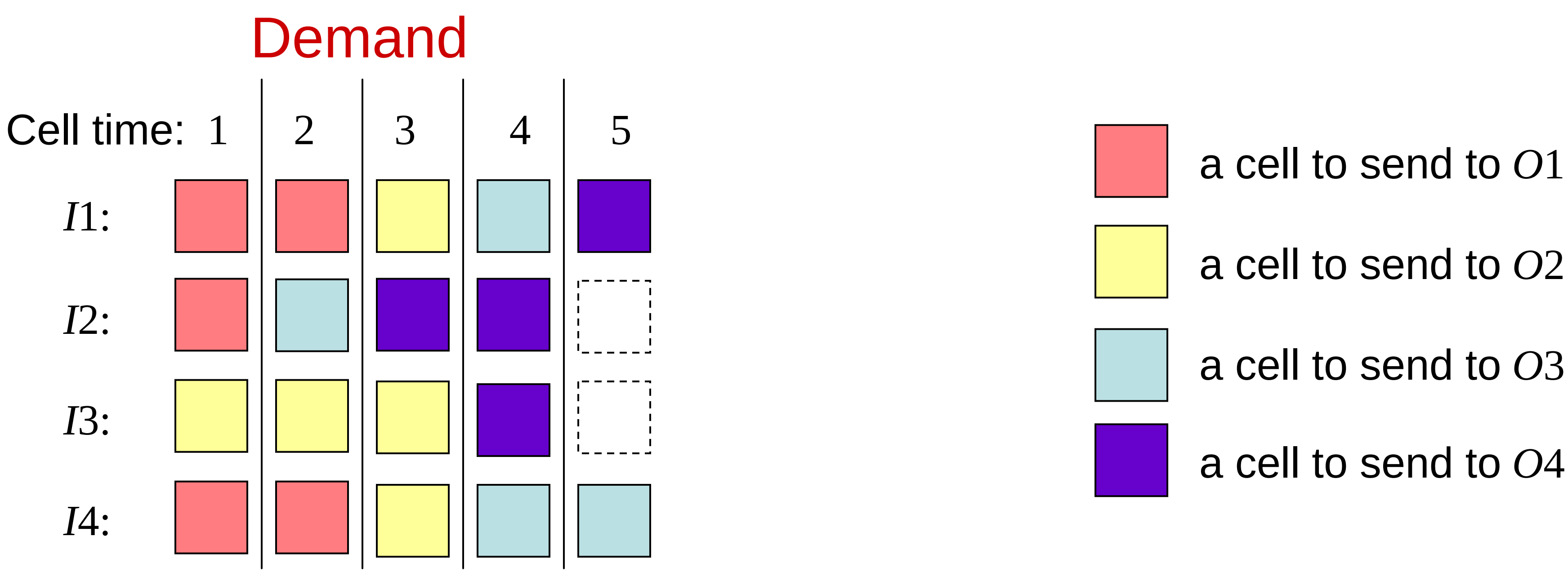


De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA

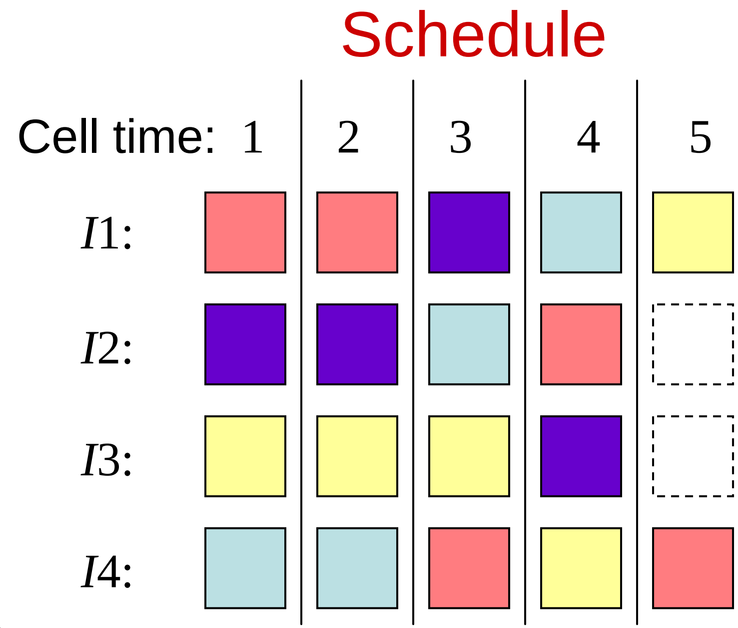
TDMA scheduling frame of $\boldsymbol{M}$ cell-time, e.g., $\boldsymbol{M} = 5$

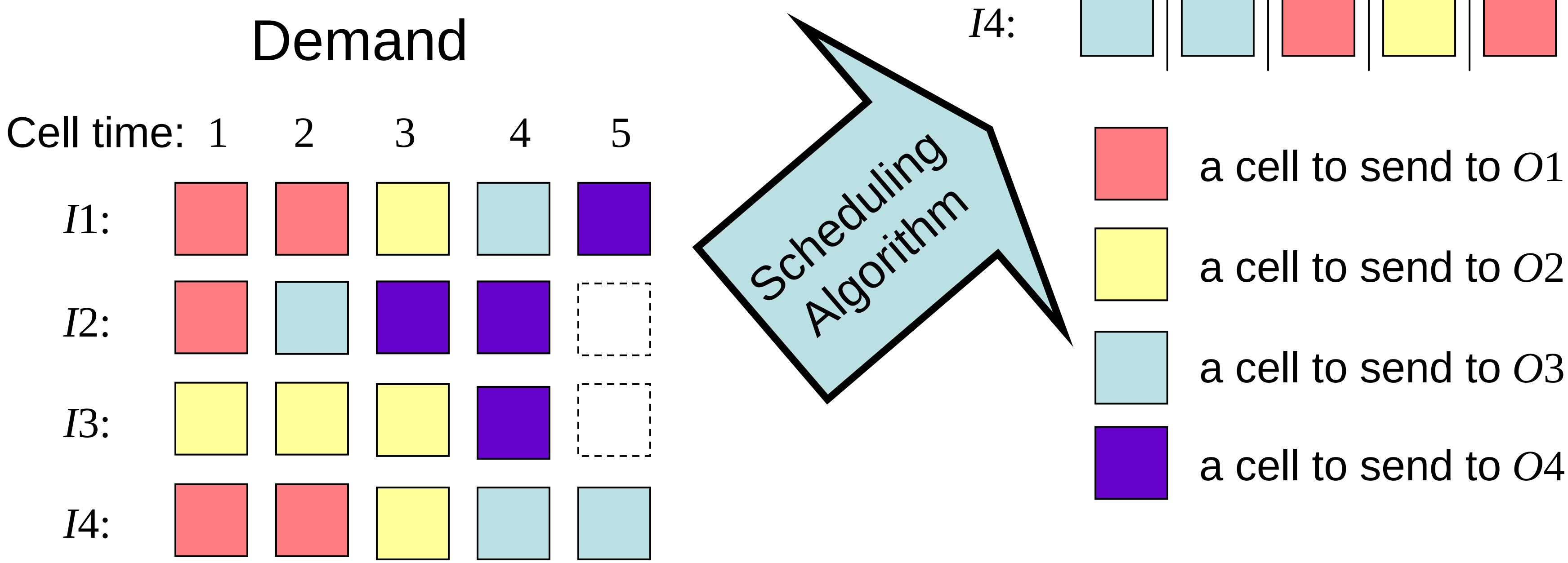
Fit all real-time flows' periods into frame,
e.g., (11, 3) → (5, 2), i.e., (10, 4)



De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA

Theorem 1: If demand matrix' every color $\leqslant \boldsymbol{M}$ cell, then have config. time scheduler with $O(N^4)$ time cost [wang10].





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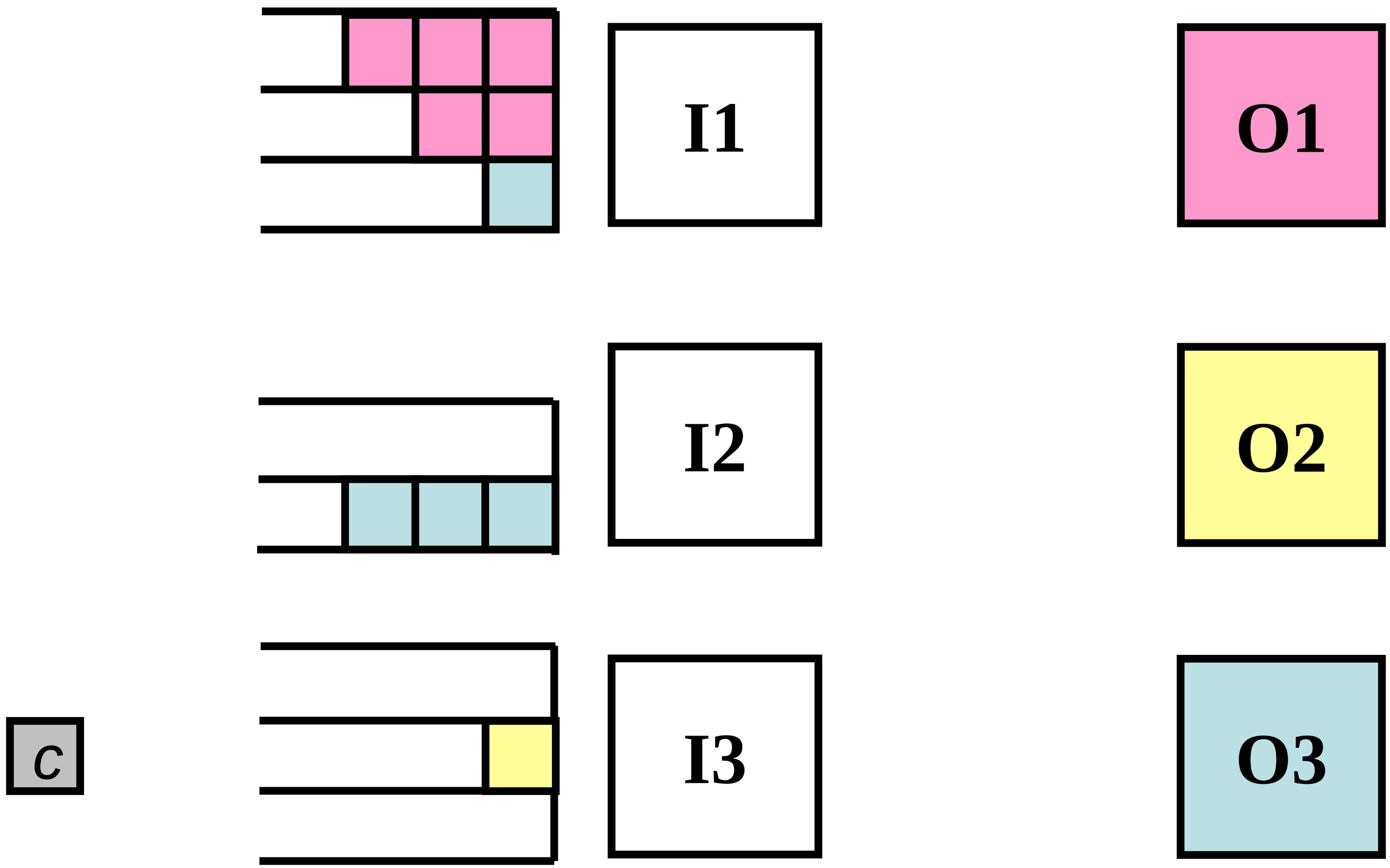
Support for Multicast



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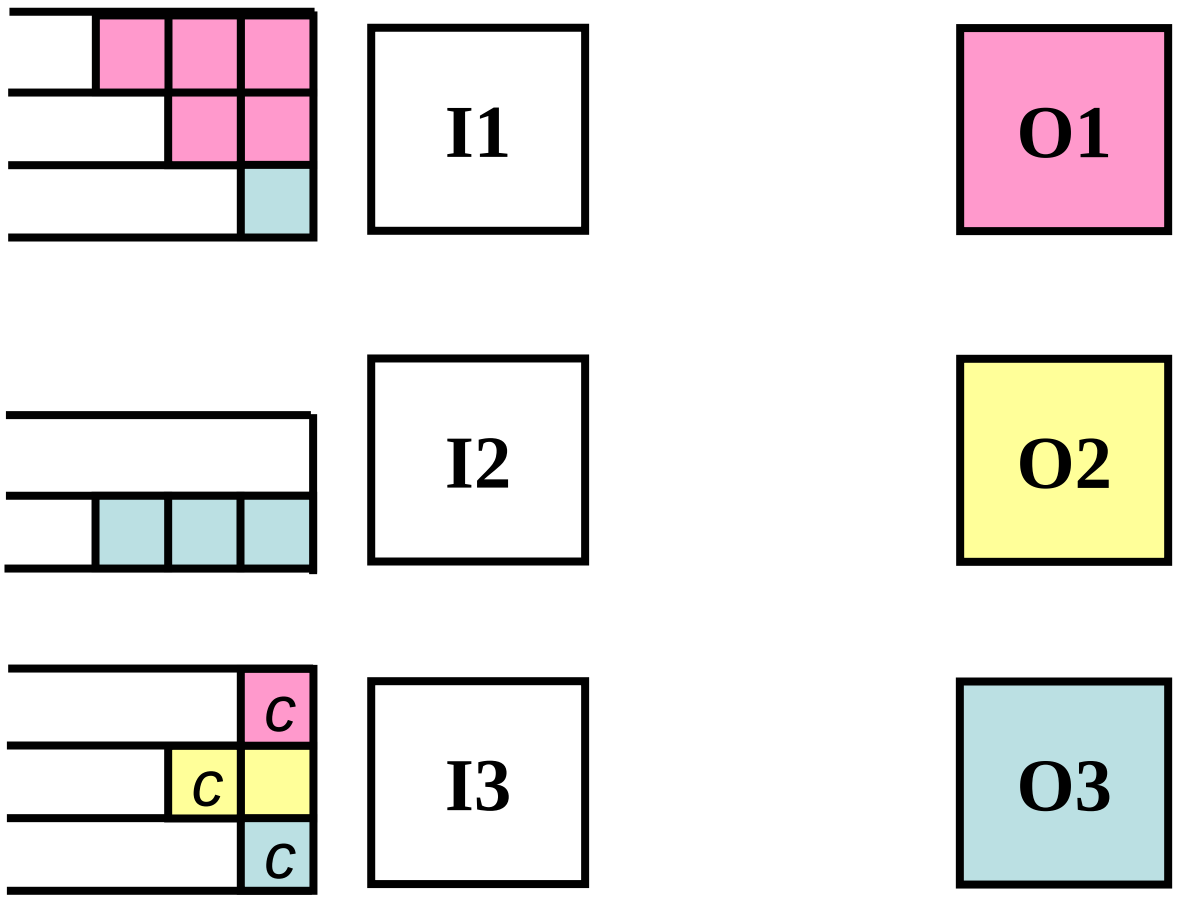

Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

$$\vec{G}(V,\vec{E})$$

$$m=(s,D,w,T,H)$$

$$\mathcal{M}=\{m_i\}$$

$$q=(\vec{G}(V,\vec{E}),\mathcal{M})$$

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Graph of the switched real-time network (fieldbus)

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Graph of the switched real-time network (fieldbus)

Switches (nodes) of the network

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Graph of the switched real-time network (fieldbus)

Switches (nodes) of the network

Edges of the network

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A (real-time) multicast group

$$\mathcal{M}=\{m_i\}$$

$$V,\vec{E}),\mathcal{M})$$

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Source End

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$$m = (s, D, w, T, H)$$

Destination Ends

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Source End

Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

Destination Ends

$$m = (s, D, w, T, H)$$

A (real-time) multicast group

Source End

Cells to multicast every period

Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

$$m = (s, D, w, T, H)$$

- m: A (real-time) multicast group
- s: Source End
- D: Destination Ends
- w: Cells to multicast every period
- T: Period (unit: cell-time)

Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

$$m = (s, D, w, T, H)$$

- Destination Ends (D)
- Period (unit: cell-time) (T)
- Deadline (relative, unit: cell-time) (H)
- A (real-time) multicast group (m)
- Source End (s)
- Cells to multicast every period (w)

Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

$$\vec{G}(V,\vec{E})$$

$$m=(s,D,w,T,H)$$

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Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

$$\vec{G}(V, \vec{E})$$

The set of all real-time multicast groups

$$= (s, D, w, T, H)$$

$$\mathcal{M} = \{m_i\}$$

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Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

$\vec{G}(V,\vec{E})$

An instance of RTMS problem

$= (s, D, w, T, H)$

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Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

An instance of RTMS problem

The network(fieldbus) topology

$$q = (\vec{G}(V, \vec{E}), \mathcal{M})$$

Real-Time Multicast Scheduling (RTMS) problem in multi-hop switched fieldbuses

An instance of RTMS problem

The network(fieldbus) topology

The set of RT multicast groups that user demands

$$q = (\vec{G}(V, \vec{E}), \mathcal{M})$$

RTMS Problem: Given a q, how to schedule each switch s.t. every m_i meets needs?

$$\vec{G}(V, \vec{E})$$

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RTMS Problem: Given a q, how to schedule each switch s.t. every m_i meets its needs?

Theorem 2: RTMS Problem is NP-Hard.

$$\vec{G}(V, \vec{E})$$

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M-slot Periodic RTMS: a subset of RTMS problems.

$$\mathcal{Q} = \{q \mid q \text{ is an RTMS instance}\}$$

$$\mathcal{Q}' = \{q' \mid q' = (\vec{G}, \mathcal{M}) \in \mathcal{Q},$$
$$\mathcal{M} = \{m_i\}, m_i = (s_i, D_i, w_i, T_i, H_i),$$
$$\text{and } \forall i, T_i \equiv M\}$$

M-slot Periodic RTMS: a subset of RTMS problems.

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Proposition 1: M-slot Periodic RTMS is NP-Hard.

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Search for Heuristic Solutions.

$\text{and } \forall i, T_i \equiv M\}$

Transform an M-slot Periodic RTMS instance into a Real-Time Multicast Routing (RTMR) instance.

Given

$$q' = (\vec{G}, \mathcal{M}) \in \mathcal{Q}',$$

where $\mathcal{M} = \{m_i\} = \{(s_i, D_i, w_i, T_i(\equiv M), H_i)\}$, define

$$\tilde{q} = (\vec{G}, \tilde{\mathcal{M}}),$$

where $\tilde{\mathcal{M}} = \{\tilde{m}_i\} = \{(s_i, D_i, w_i, T_i(\equiv M), \tilde{H}_i)\}$, and

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RTMR instance

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Max Multicast Tree Height

where $\tilde{\mathcal{M}} = \{\tilde{m}_i\} = \{(s_i, D_i, w_i, T_i(\equiv M), \tilde{H}_i)\}$, and

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RTMScheduling problem becomes a Routing problem.

Given

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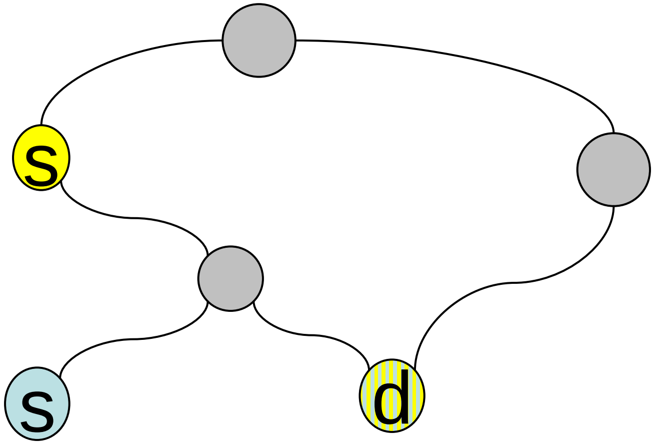
Heuristic Routing Algorithm

Existing mainstream internet multicast routing algorithms become Dijkstra when network is static and global info is available

Dijkstra’s short-coming: only cares about # of hops, ignores congestion.



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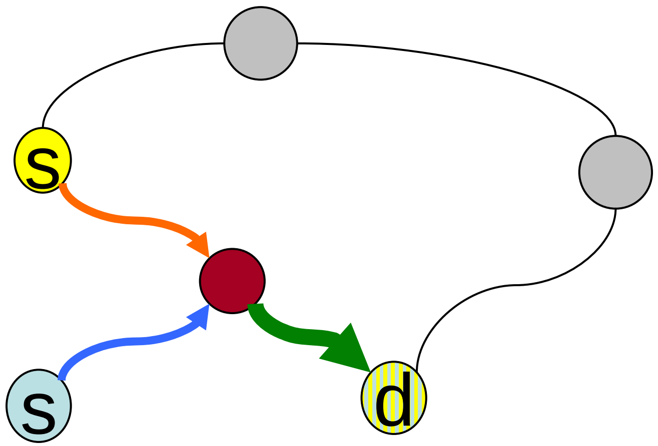

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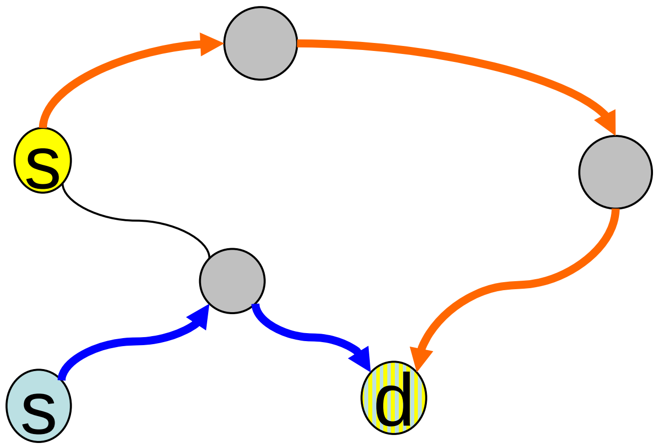
We want a heuristic routing algorithm that considers both (hops and congestion).



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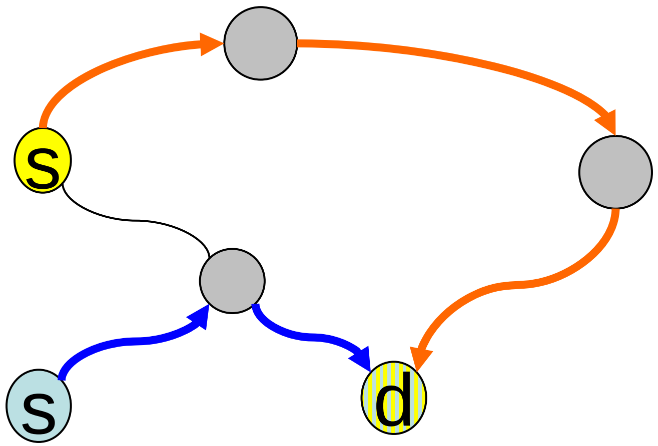


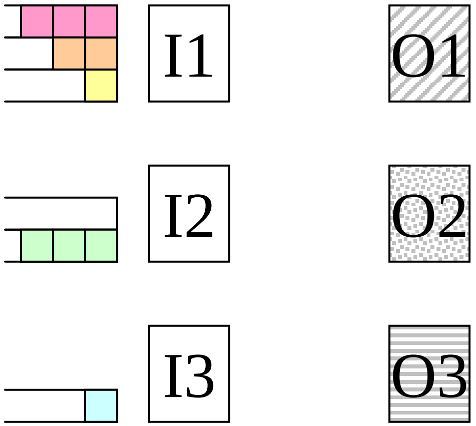
Heuristic Routing Algorithm

Grow the multiple trees simultaneously with multiple iterations.

In each iteration, $\leqslant$1 link is added to each tree.

When multiple tree contends in a same switch, we carry out a job-hunting-like negotiation to let only $\leqslant$1 contending tree grow through an output in this iteration.

The job-hunting-like contention negotiation is itself an iterative algorithm.



different colors for
different trees

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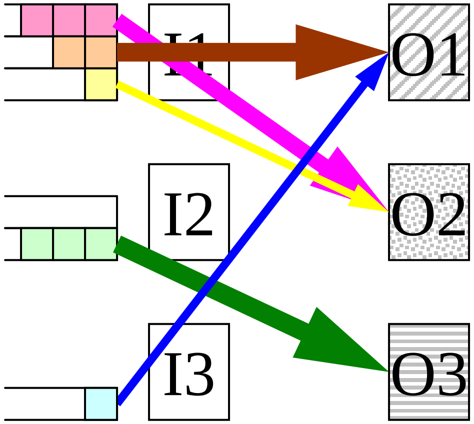

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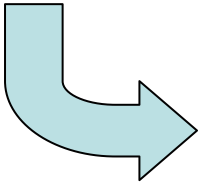
Each tree ranks all outputs and only apply to its favorite output



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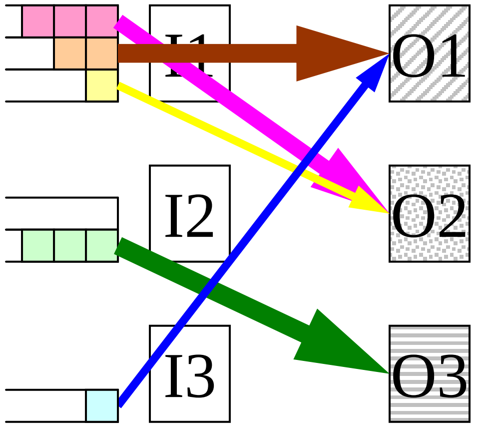

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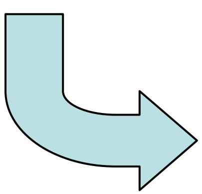
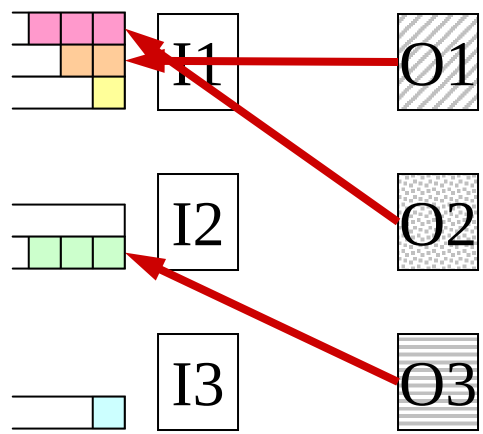
Each tree ranks all outputs and only apply to its favorite output

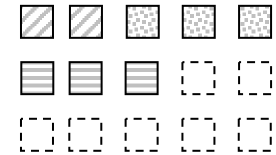


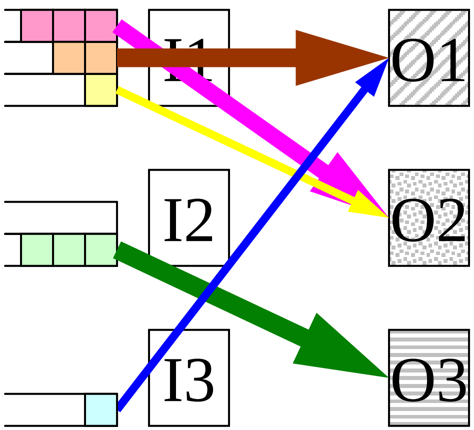


Each output offers job to the most loyal applicant

The job-hunting-like contention negotiation is itself an iterative algorithm.

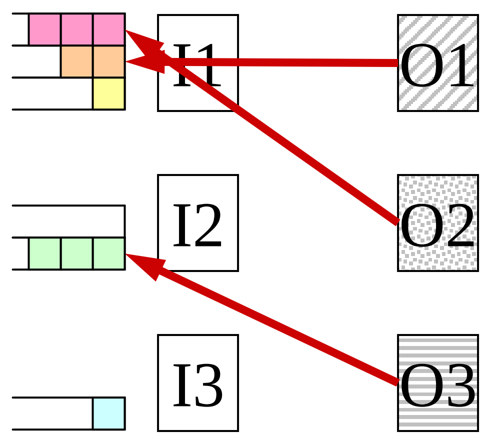
updated demand matrix





different colors for different trees

Each tree ranks all outputs and only apply to its favorite output



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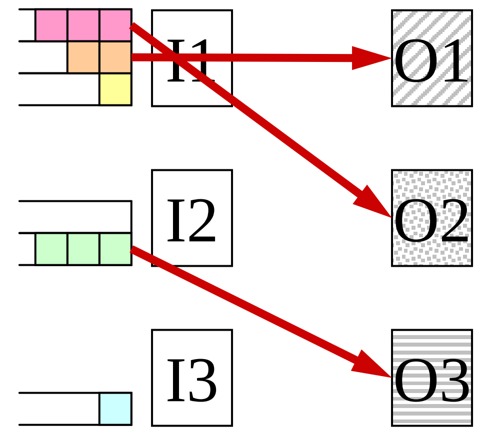

Accept job by reserving corresponding frame slots.

Ranking function design: considers both E2E delay (hops) and congestion.

$$r_{t,o} = \frac{\gamma_o(\tilde{H} - H(t,v))}{\mathrm{dis}(v, t.target)}$$

$$\gamma_o = \begin{cases} 1 & (\text{if } \max_{j \in \mathcal{O}_u}\{N_j\} \\ & = \max_{j \in \mathcal{O}_u}\{N'_j\}), \\ \exp(\max_{j \in \mathcal{O}_u}\{N_j\} & (\text{otherwise}) \\ - \max_{j \in \mathcal{O}_u}\{N'_j\}) & \end{cases}$$

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rank of o to tree t

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congestion↑ ⇔↓

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Definition of "favorite", a.k.a., "loyalty".

$$r_{t,o} = \frac{\gamma_o(\tilde{H} - H(t,v))}{\mathrm{dis}(v, t.target)}$$

$$o^{(t,1)} \stackrel{def}{=} \mathrm{argmax}_{o \in \mathcal{O}}\{r_{t,o}\}$$

$$o^{(t,2)} \stackrel{def}{=} \mathrm{argmax}_{o \in \mathcal{O} - \{o^{(t,1)}\}}\{r_{t,o}\}$$

$$r_{t,o^{(t,1)}} - r_{t,o^{(t,2)}}$$

t 's loyalty to $o^{(t,1)}$

Evaluation Setup.

4x4 port real-time switches

15x15 square grid network topology

Per port capacity: 1Gbps,

M = 2000 (cell/frame), 1 cell = 500 bit

10000 Trials, in each trial:

- Random number of multicast groups,
- w_i = 1~20 cell/frame (500K~10Mbps)

Evaluation Setup.

4x4 port real-time switches

15x15 square grid network topology

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10000 Trials, in each trial:

- Random number of multicast groups,
- w_i = 1~20 cell/frame (500K~10Mbps)

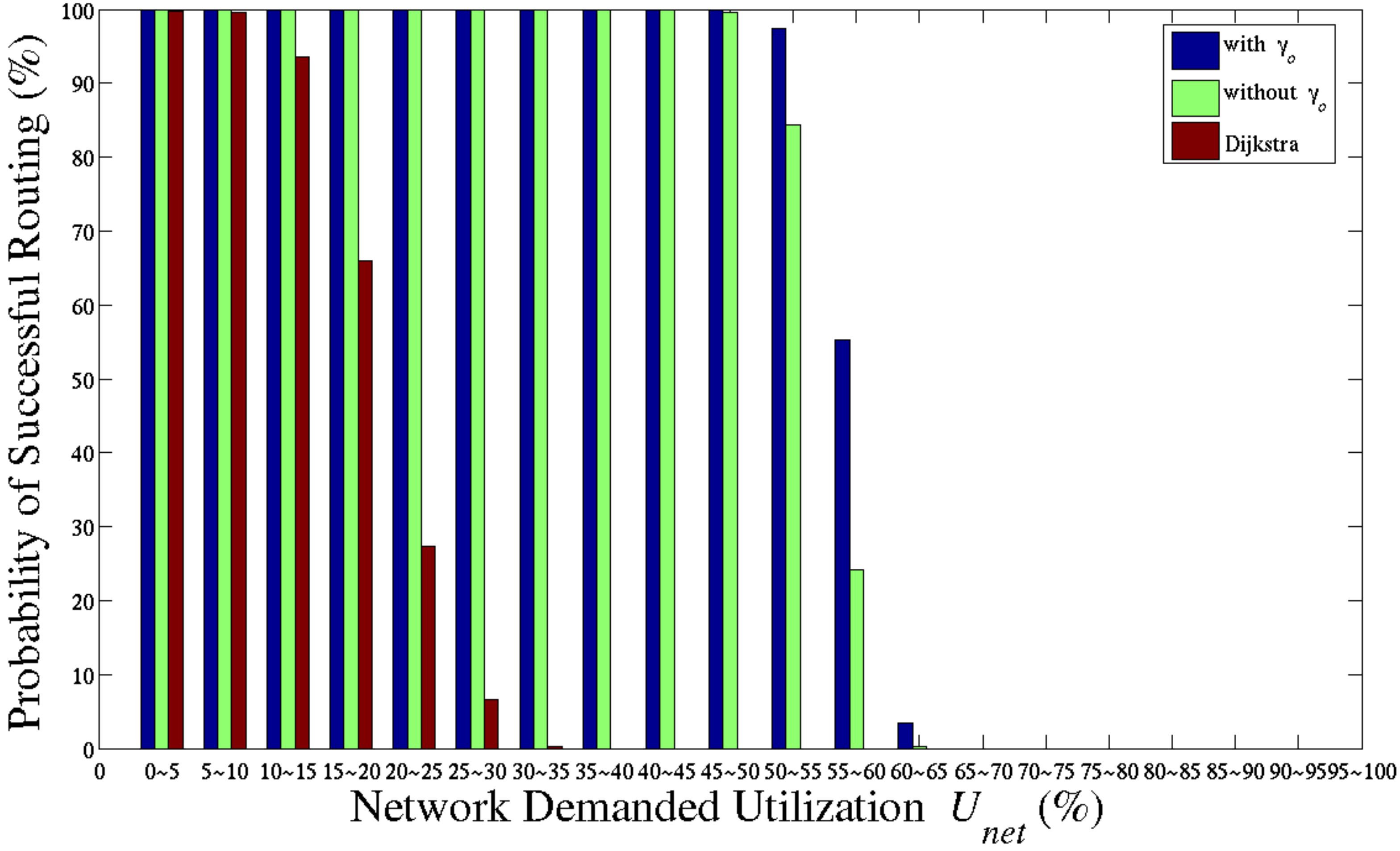
Evaluation Setup.

$$\tilde{H}_i = \eta H_i$$

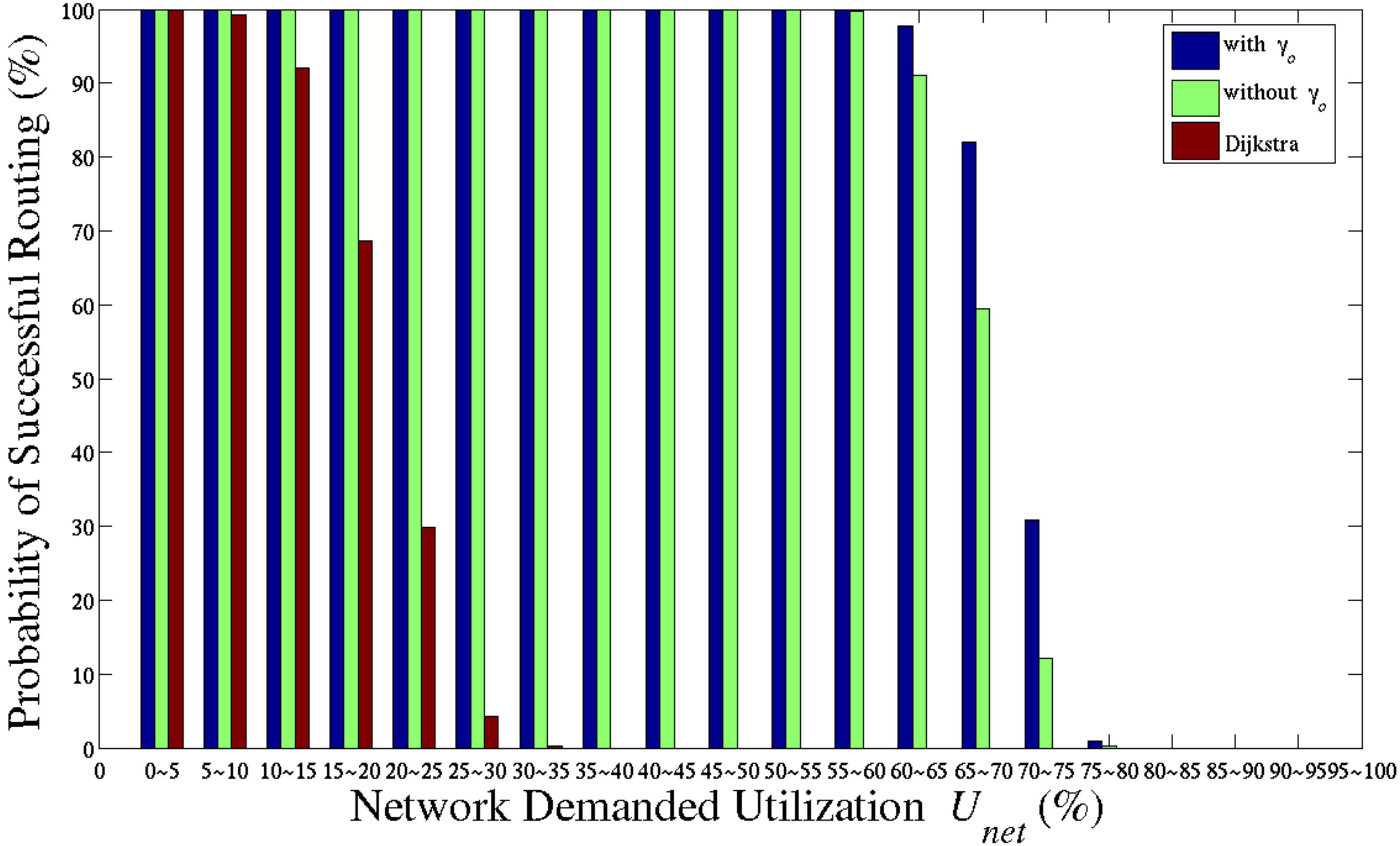
Network Demanded Utilization
(Application Layer E2E Utilization)

$$U_{net} \stackrel{def}{=} \frac{\sum_i (|D_i| w_i)}{|\bigcup_i \{D_i\}| M}$$

Evaluation Results: η=3



Evaluation Results: η=9



Mainstream Internet multicast routing algorithms mainly concern about dynamic distributed group management.

Reverse Path Broadcasting/Multicasting (RPB/RPM) [semeria97]

Truncated Reverse Path Broadcasting (TRPB) [semeria97]

Distance Vector Multicast Routing Protocol (DVMRP) [waitzman88]

Multicast Extension to Open Shortest Path First (MOSPF) [moy94a][moy94b]

Protocol Independent Multicast (PIM) [fenner06][adams05]

Core-Based Tree Multicast Routing (CBT) [ballardie97]

Mainstream Internet multicast routing algorithms become Dijkstra for static network with global info.

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Others

P2P and Overlay Network Multicast are concerned with statistical performance instead of hard real-time E2E delay bound.

Thank You!

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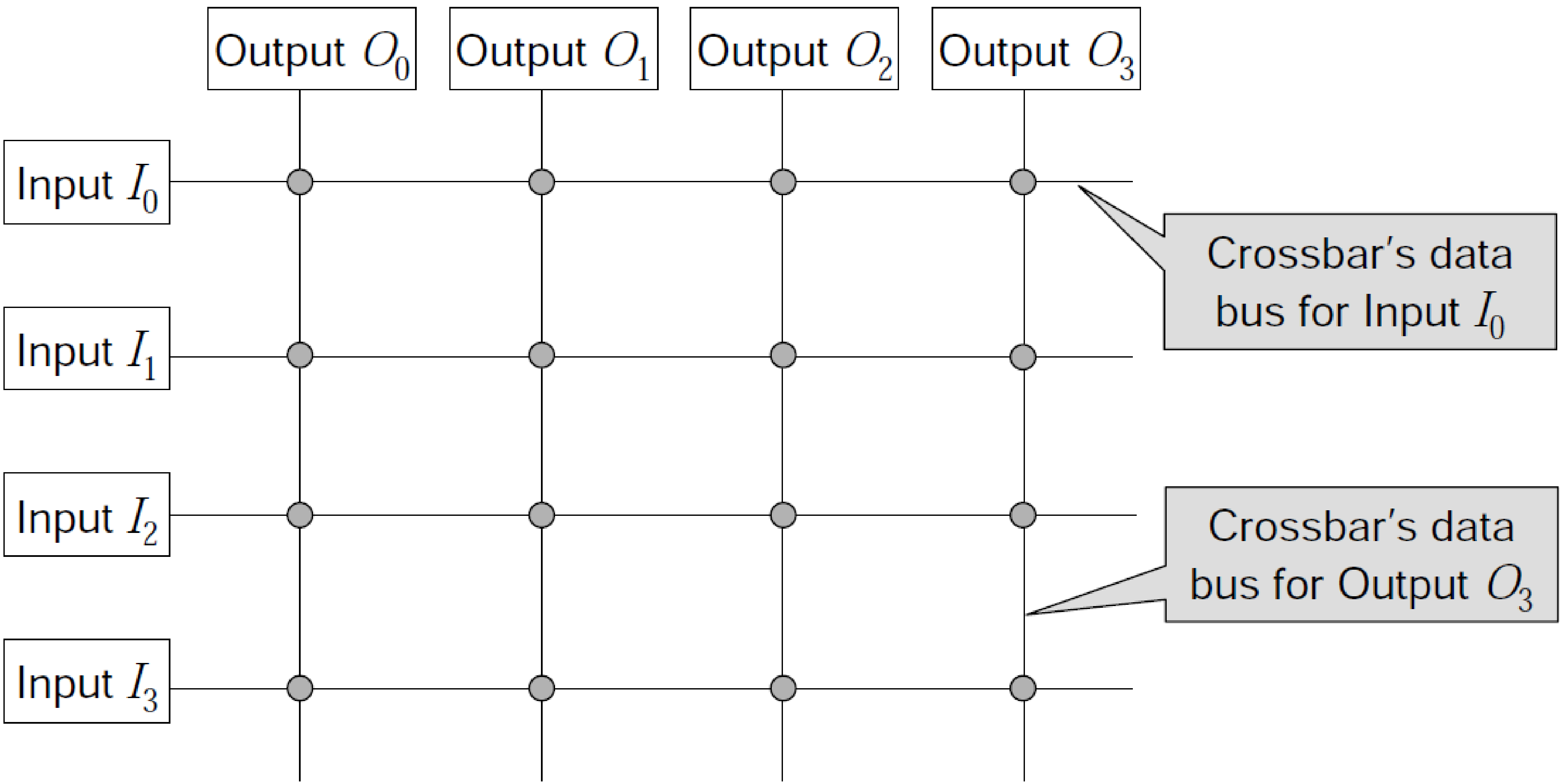
De facto standard (real-time) fieldbus switch architecture: crossbar per-flow-q TDMA



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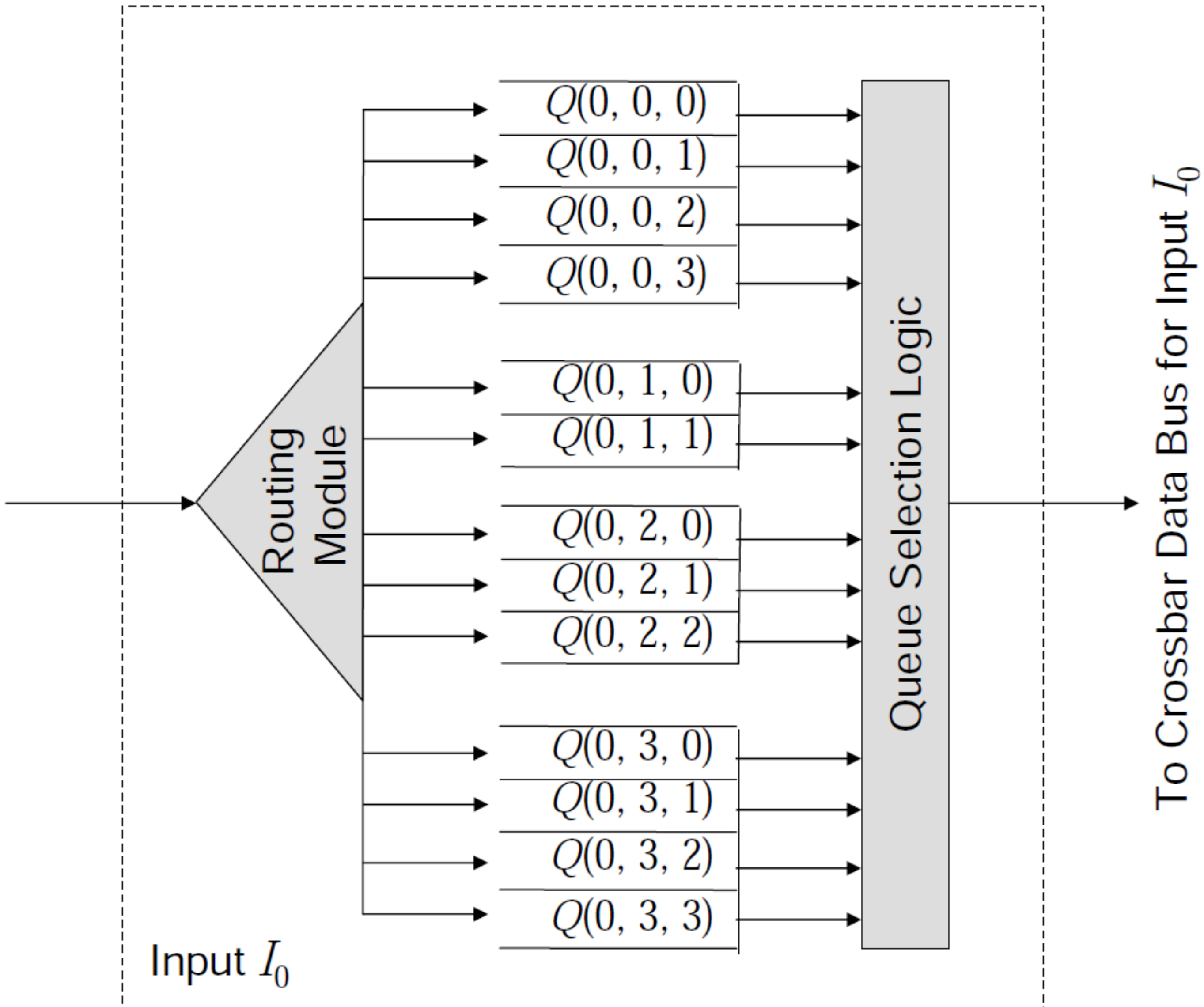

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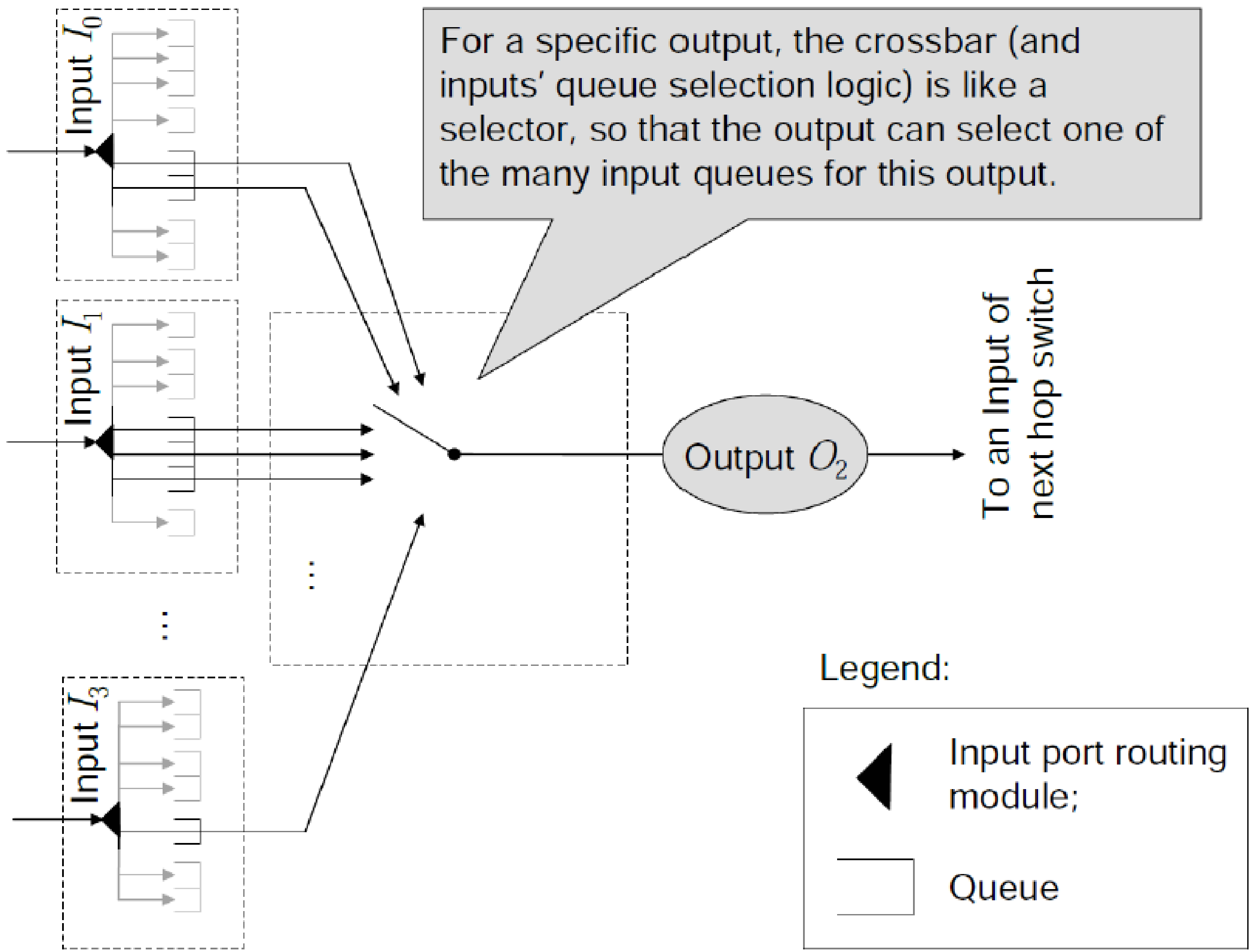

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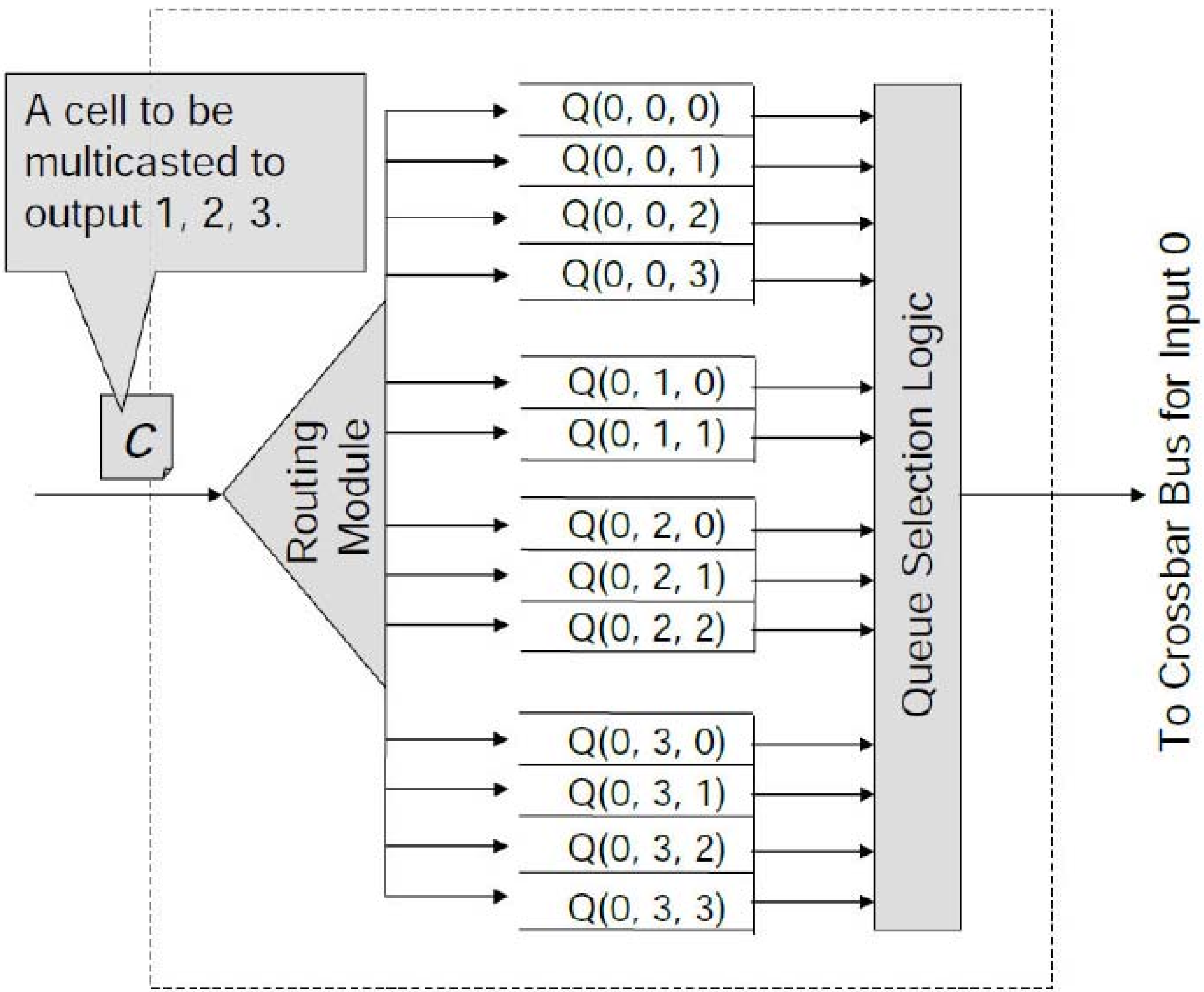

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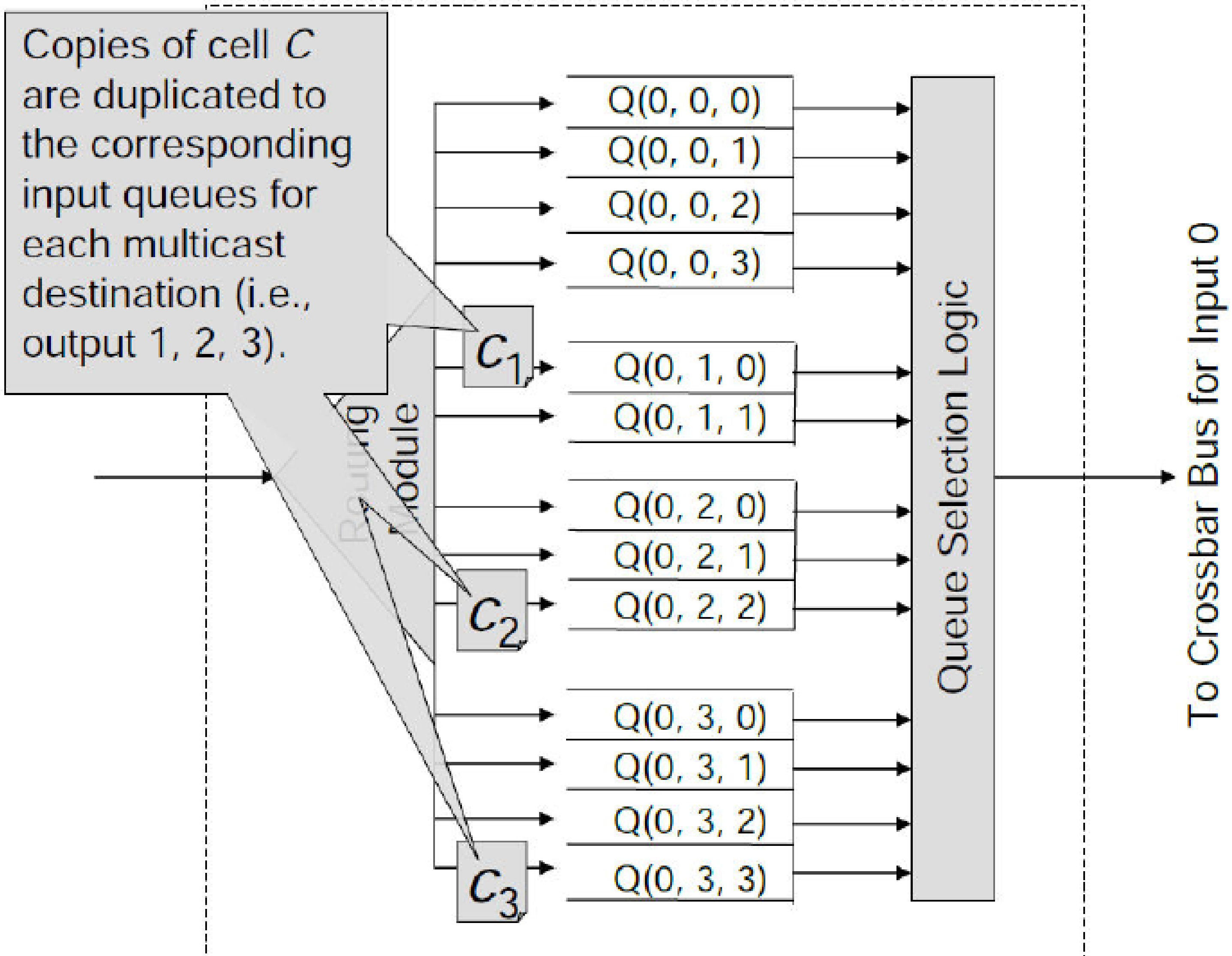

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