Flow and Congestion Controls for Datacenter Networks - 1

L2 Flow Control

A Converged Enhanced Ethernet-centric View of Physical and Virtual DCNs

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FCC Tutorial @ HSPR'14 Vancouver

Outline #1: Link Level Flow Control for DCN / SDN

1. Why lossless?

2. Flow control 101: FC schemes
    1. On/Off Grants (PAUSE); Credits, abs. & incremental;Rate

3. Practical LL-FC, i.e., standard
    1. Ethernet: from .3x PAUSE to .1Qbb PFC

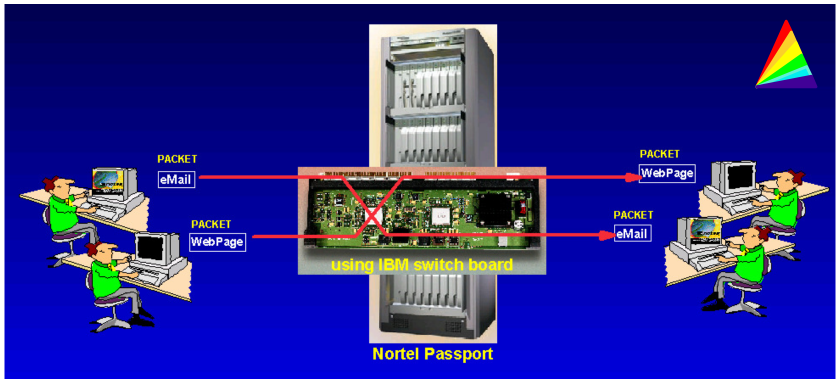
* PFC Benefits and Drawbacks (extras, refs)

1. PFC in CEE: App. and TCP impact (Short&Fat, TCP Incast)
2. PFC in Virtual DCNs: zOVN as fix to SDN losses
3. *All things considered: The good; Bad/HOL/sat-tree; Ugly/DLK... (transition to CC?)*

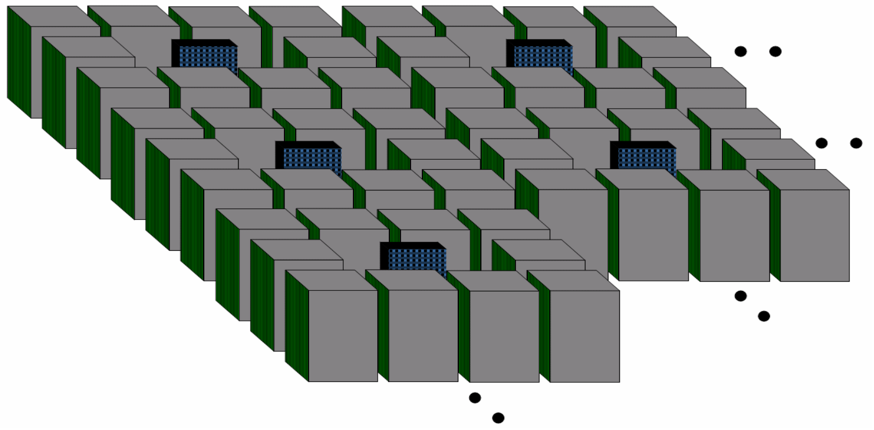
Why lossless?

- Qual. : Must-have, or,
    - When Comp & Comm meet (2 views of the e2e argument)
    - “Wire-once” convergence: ICTN->HPC...->SAN...-> LAN
- Quant.: The Terra-gap from BER to pkt loss rate

Computer Interconnects vs. Communication Networks

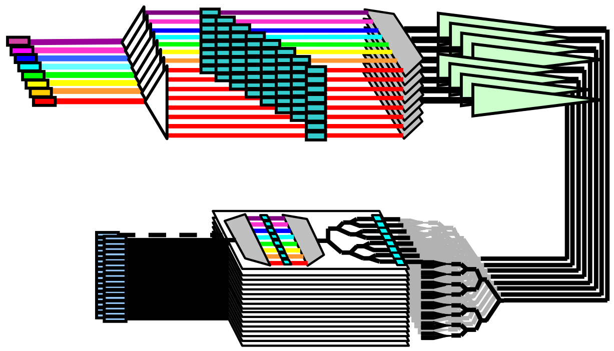


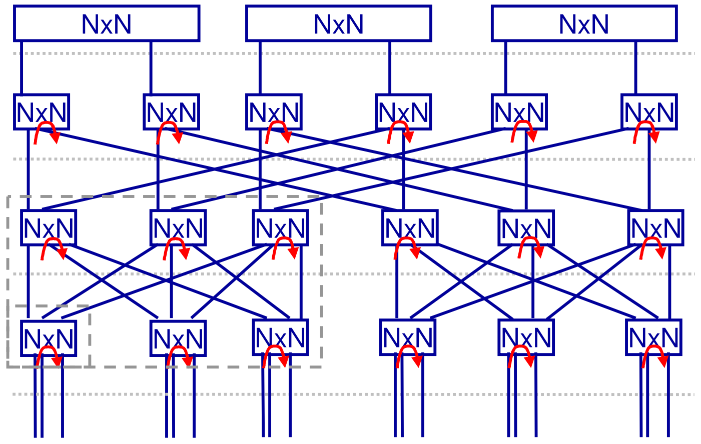
Communication switches
(Prizma generation 1 + 2)



HPC (PERCS, Mare Nostrum/Incognito)

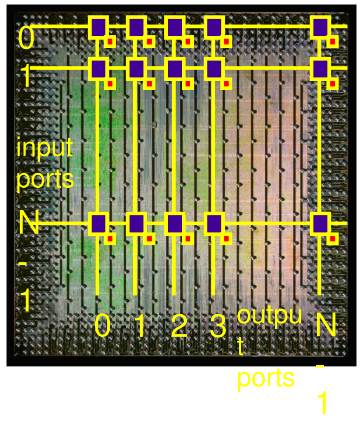
Optical Switching
Osmosis





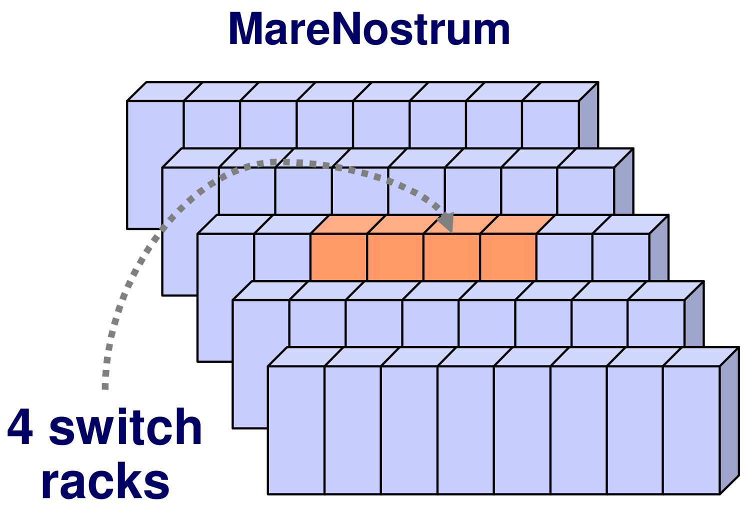
BNT Datacenters,
SDN, Storage

PRIZMA C
(opto electronic - gen. 3)



Comp: From Interconnect to HPC Datacenters

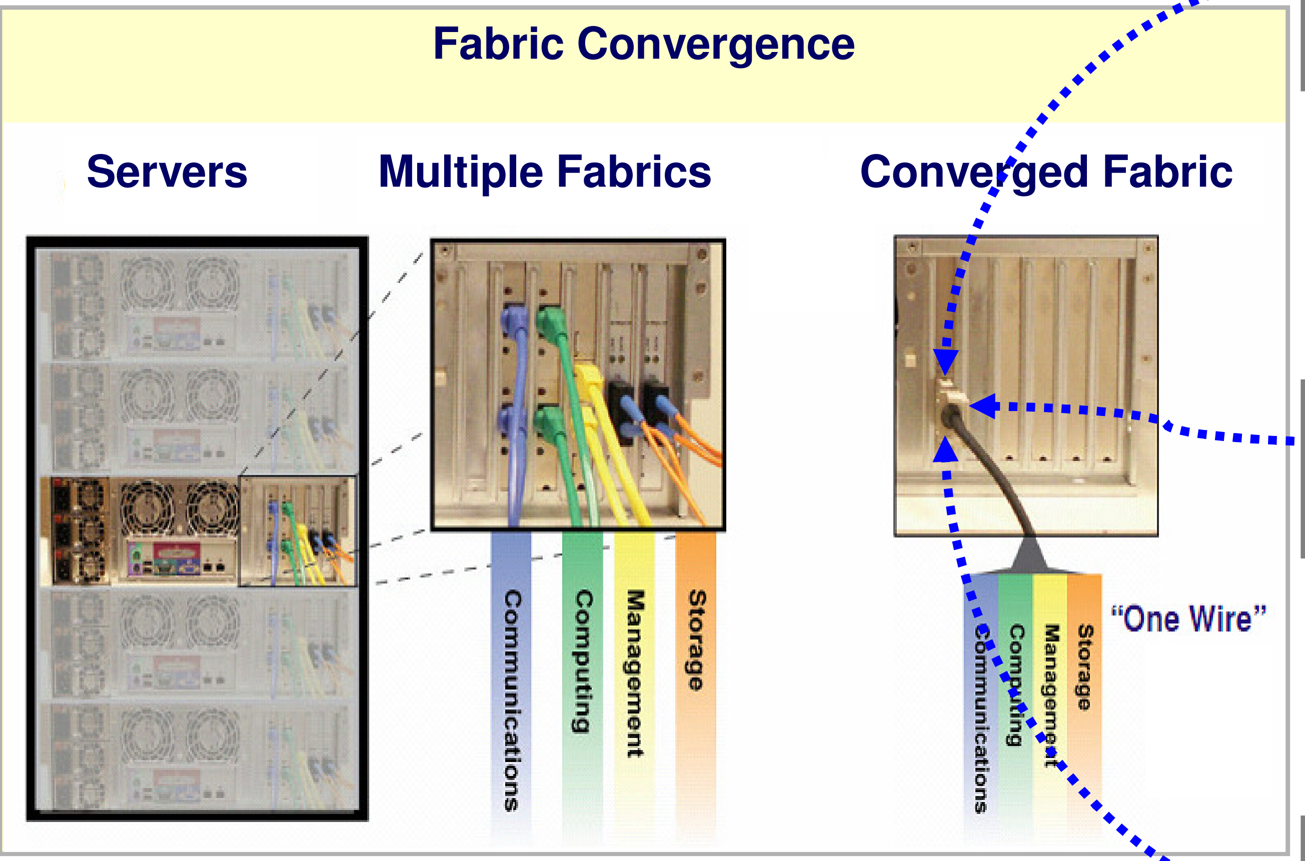
- MareNostrum: IBM BladeCenter computing nodes + SAN/Myrinet + LAN/GigEthernet



- **Nice on the surface**
- Lots of cables, $ and Watt beneath

- **Primary needs**
  - High performance
    - Non-standard network is acceptable
  - Power and cooling
  - Leading edge technology
  - Low capital cost

Datacenter Fabric Convergence → Value Proposition



Simpler Management
Single physical fabric to manage. Simpler to deploy, upgrade and maintain.

Lower Cost
Less adapters, cables & switches
Lower power/thermals.

Improved RAS
Reduced failure points, time, misconnections, bumping.

Requirements of the "DCN"

- Native support for
  - Blades
    - L: ~1us for short messages (IPC, MPI, cache blocks)
    - B_w: min. 10, roadmap to 400+ Gbps; low half-power point (ideal < 100B)
    - 0 loss = core idea of DC-ICTNs (mission-critical)
  - Storage
    - SCSI (if frame loss => 2-3 minutes timeout)
    - RDMA (TOE, iWARP) @ L2: light and reliable LL transport
  - LAN-like mgnt.
    - Virtualization
    - QoS: VL separation per traffic type (IPC, IO, storage, IP) and class (high / low prio) => support for both lossless and lossy traffic
  - TCP-friendly flows => fairness, RTT-dependency
  - Cost ~ (10s-100s) $/port @ 10/40/100/... Gbps
  - Power
  - Open: Standard (L0-L2) & Source (L3-7)

Red Shift in the Datacenter: Migration to Layer 2

1. **Aggregated ➔** Converged Enhanced Ethernet (IEEE 802 DCB)
   - FCoE: FC over CEE +
   - ROCE: RDMA over CEE +
   - HPC, IB, Myrinet, SCSI... etc. "over E"

   UNIFIED WIRE = CEE L2 "wire once"

2. **Virtualized**: Multi-tenants share the $ DCN
   - Overlaid: Maintain IP connectivity + VM mobility
   - SDN-ed : Flexibility and freedom ☺
   - OF-ed: Centralized, distributed? Pendulum swings...

3. Reliable, aka "**Lossless**"
   - via L2 Priority Flow Control (PFC, 802.1Qbb)
4. Work conserving (ETS)
5. Multipath load-balanced (ECMP/LAG+), congestion managed (QCN)

Quantitative Reasons for Lossless Links

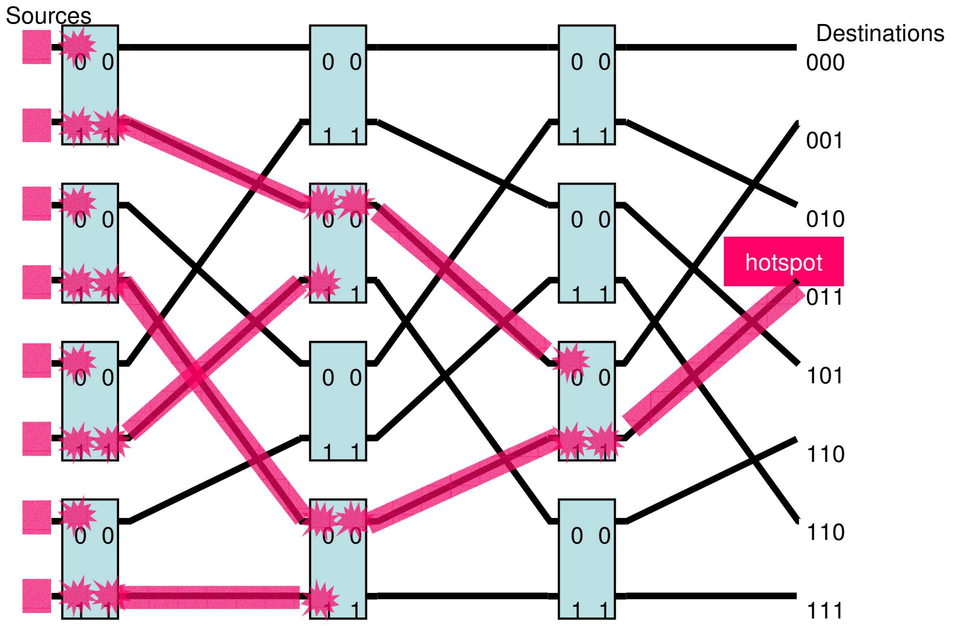
- Performance
  - ➢ The Terra-gap from BER to pkt loss rate

- Typical BER: ~ $10^{-12..-15}$
  - ➢ Few errors/min @ 40Gbps
- Pkt (tail) drop ratios: ~ 0.01 – 5% (up to 70% in SDN)
  - ➢ Many drops/us @ 40Gbps

- While no link is perfect, the distance from BER to the RED pkt loss could be drastically reduced by LL-FC

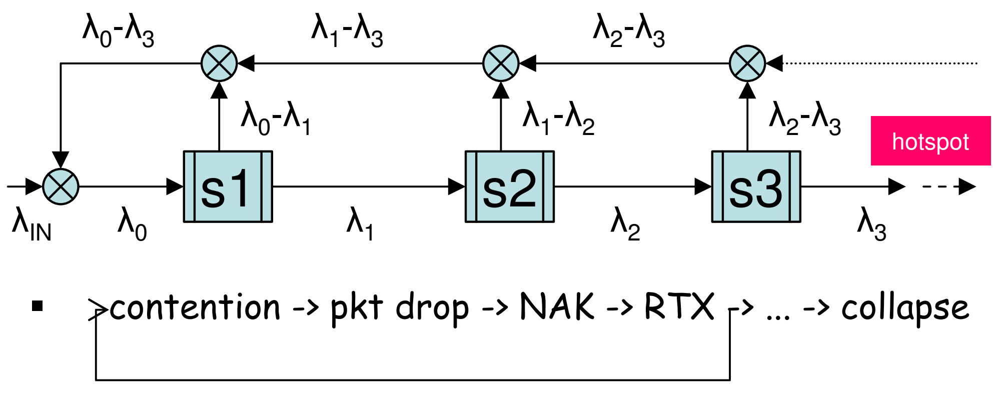
Lossless ICTN or Best-Effort Ethernet + TCP/IP?

A tale of two collapses: ICTN vs. BE Ethernet (w/ TCP)



- Persistent oversubscription of a resource: $\tau > 5x\ RTT_0$
- Flow interference -> HO-HOL blocking -> saturation tree -> 'catastrophic' collapse (Pfister '85) => the $ of LL-FC…!

- With uniform traffic
  - ➢ ICTN remains stable (linear in Tp and L) for $\lambda_{IN} > .6$
  - ➢ Adaptive routing and FC can extend stability > . 7 (.9)
  - ➢ CM handles congestion only



- contention -> pkt drop -> NAK -> RTX -> … -> collapse

$$\lambda_{i+1} = 1 - (1 - \lambda_{i+1} / n)^n$$

Switch degree	$Tput_{max}$
2	.52
8	.41
32	**.38**
256	.37

- idealized queuing model
- instant retransmissions (RTX)
- up to 40% optimistic Tput ->

- **Latency**

1st dependency on RTX, not flight + switching + queuing =>

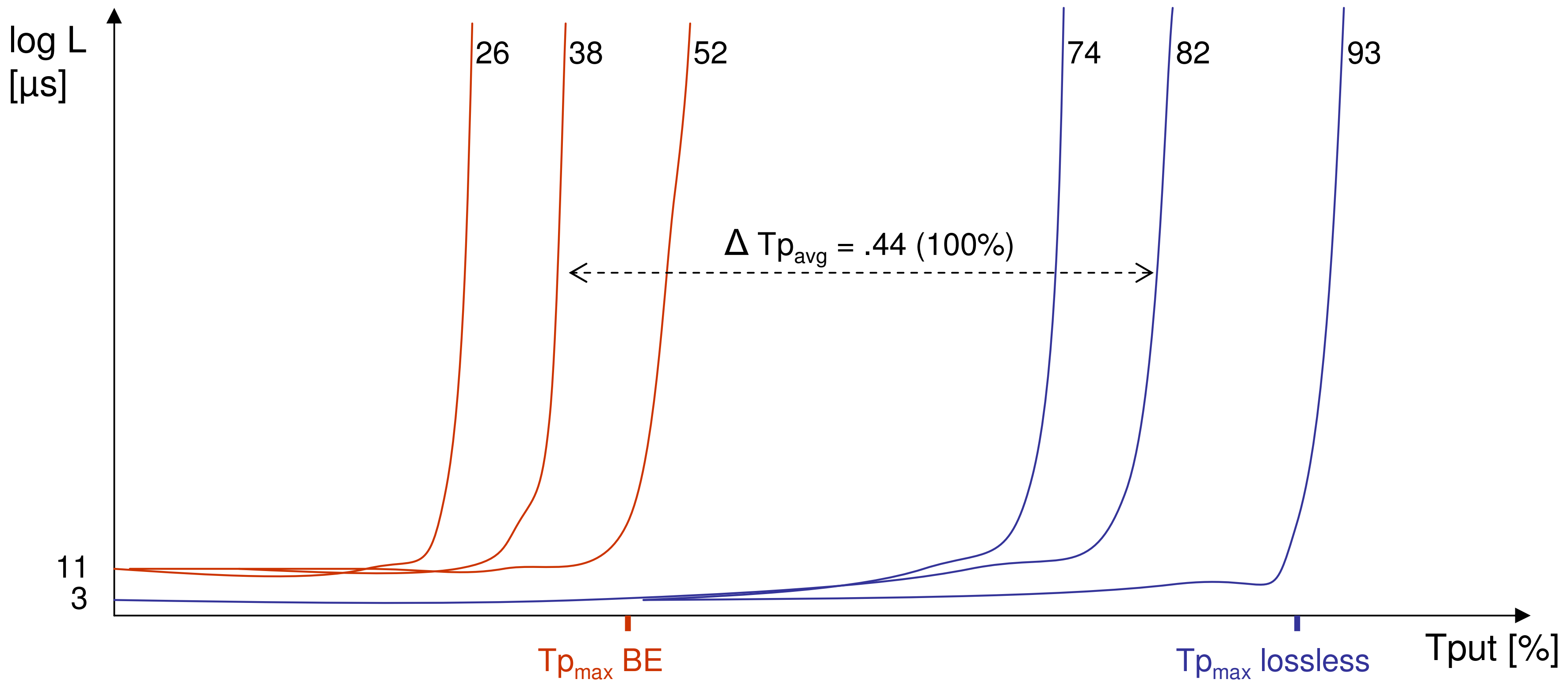
Prob. pkt dropped K-times = F(RTX fraction) = $F(\lambda_0-\lambda_3) / \lambda_0)$

The above is with uniform traffic. What if a hotspot…?

If bottleneck on S3 egress:

λ_3 -> 0 => RTX fraction -> 1.0 => **λ_{IN} -> 0**

Best Effort Ethernet vs. Lossless ICTN?



Best effort Ethernet

- high latency, low Tput

⇒ Bw and power wasted on re-re-transmissions

yet POPULAR…

Lossless ICTN / CEE

+ solves Ethernet RTX => LL-FC

+ separates functions

1. Linear region: (adaptive) routing, FC
2. Congestion: use of dedicated CM…

L2 Flow Control Foundations

1. The basic concept of TX-RX flow control
2. FC schemes
   1. On/Off Grants (PAUSE)
   2. Credits, abs. & incremental
   3. Rate
3. Props and features
4. Grants vs. credits (and rate)

The Flow Control Principle: No Buffer Overflow

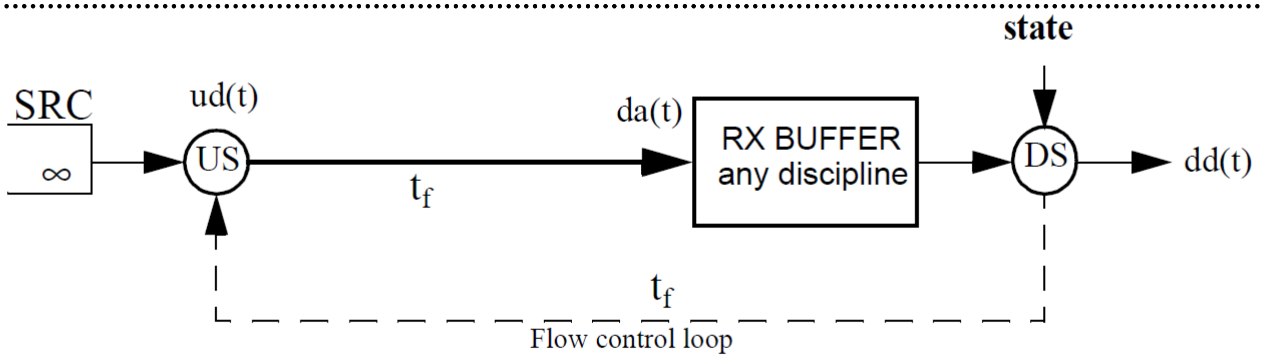


Figure 1. Flow-controlled communication system.

The producer side consists of an infinite source queue followed by an Upstream Server (US) process producing *upstream departures* with rate ***ud(t)***, injected into an ideal communication channel. After *time of flight* t_f the coressponding *downstream arrivals* ***da(t)*** are enqueued in the reception queue "RX_BUFFER"; it is important to note that its service discipline is arbitrary, i.e., FIFO, RAM etc. From here onward the packets awaiting service in the RX_BUFFER are forwarded by the Downstream Server (DS) process at a rate of ***dd(t)*** *downstream departures*. Channel bandwidth is Bw_{max} and all the departure rates can vary between 0 and Bw_{max}. According to the control of dynamic systems, the US process is controlled by DS by means of flow control events - e.g., grants (on/off) or credits - that can temporarily suspend the US process. We make no assumptions regarding the traffic patterns between US and DS, their probability distributions and the specifics of each FC protocol - except what is explicitly stated.

$$\alpha\big|_0^\tau = (ud\max - dd\min)\big|_0^\tau = Bw\max\big|_0^\tau \qquad (3d)$$

$$\alpha\max = Bw\max \cdot \tau \qquad (3e)$$

Since τ = RTT, the maximum RX_BUFFER occupancy at any moment in time is upper-bounded by Bw_{max} *RTT. This result is independent of the buffer service discipline and FC protocol, provided that the fundamental time constant of the dynamic system is not changed. Accordingly, equation (3e) provides the necessary and sufficient condition of lossless communication in a closed-loop system. It also generalizes in the continuum domain the results of [1, modeled by discrete state-time variables] because among other issues it decouples the memory service from the downstream departure scheduler, i.e., no need for lock-stepping in FIFO order through the stored downstream arrivals.

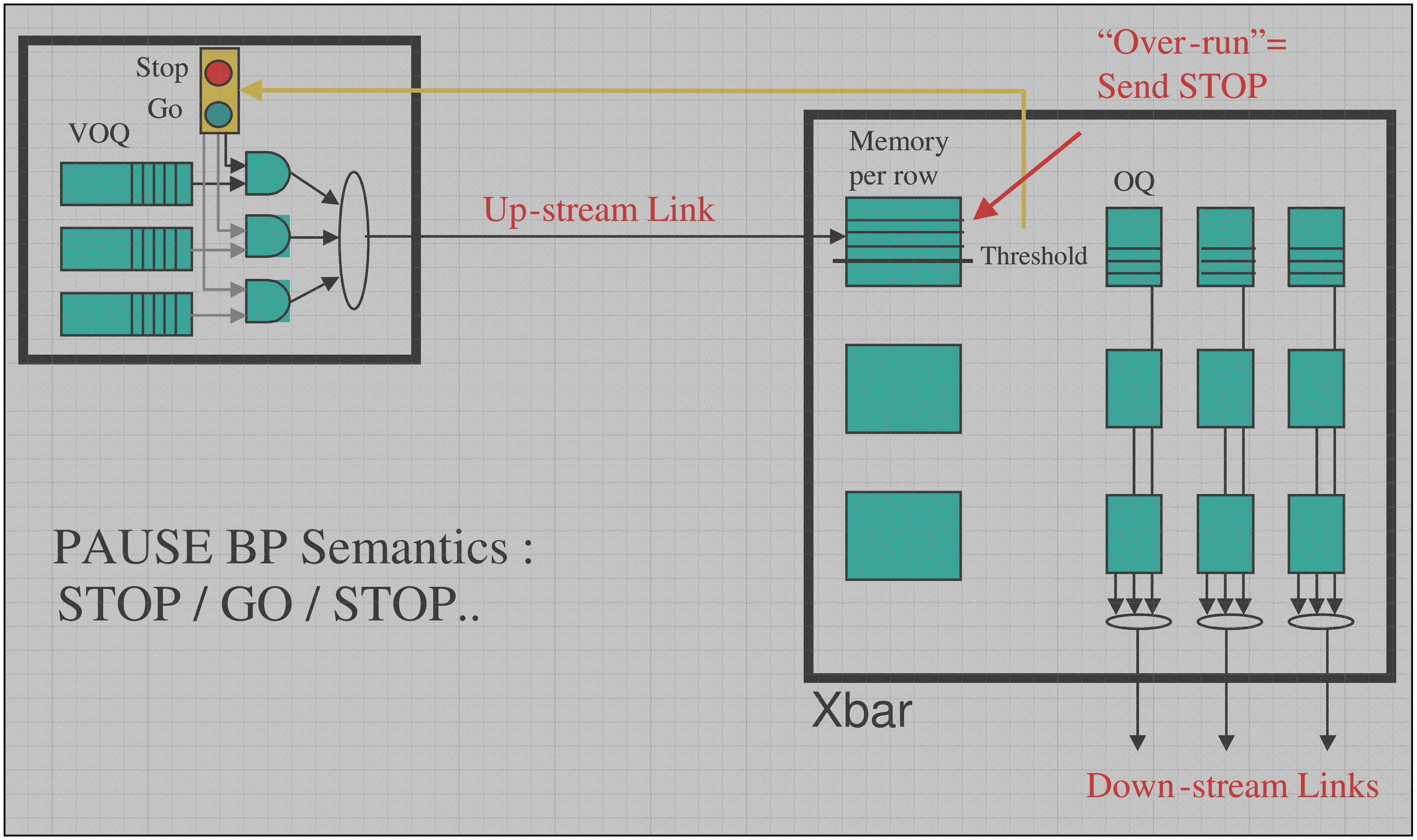
Comparison of Lossless LL-FC Schemes

- Main LL-FC methods: On/Off Grant, Credit, Rate
  - ACK/NACK w/ RTX not considered on L2 (as done by TCP)

- Evaluation of the 3 FC candidates
  - Practically feasible implementations
  - Similar conditions of correctness and memory (M)
  - Core schemes only, without optimizations which may boost the performance of either scheme:
  - link RTT = 4 MTUs (normalized to pkt size)

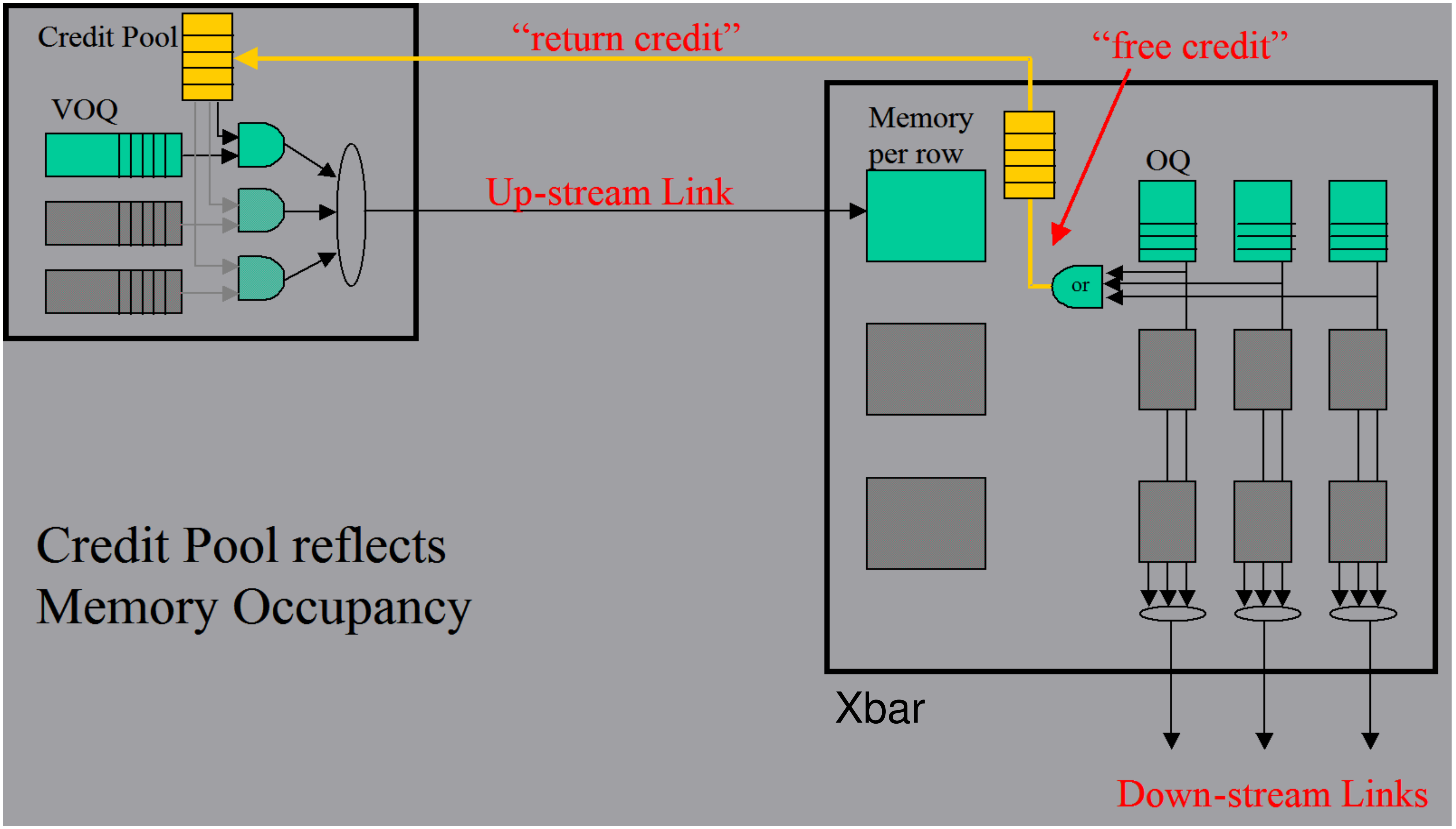
    *Note: rate is harder to fairly compare in correctness, performance and complexity.

FC-Basics: On/Off Grants (PAUSE)



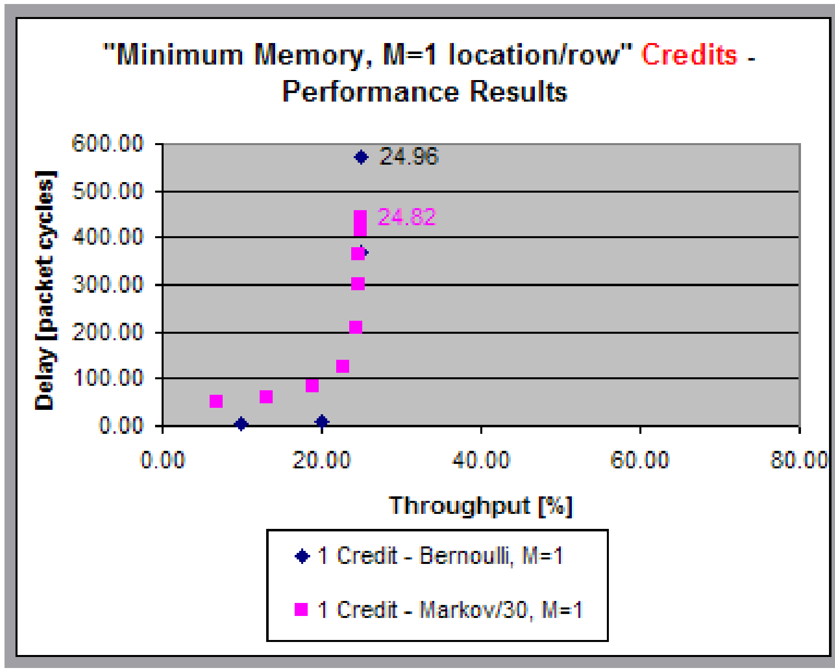
PAUSE BP Semantics :
STOP / GO / STOP..

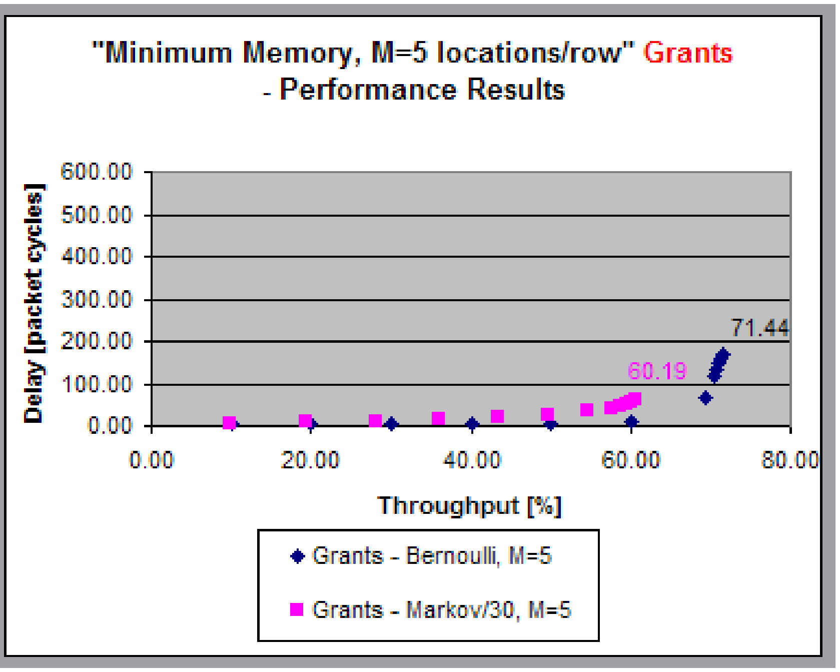
FC-Basics: Credits



Credit Pool reflects Memory Occupancy

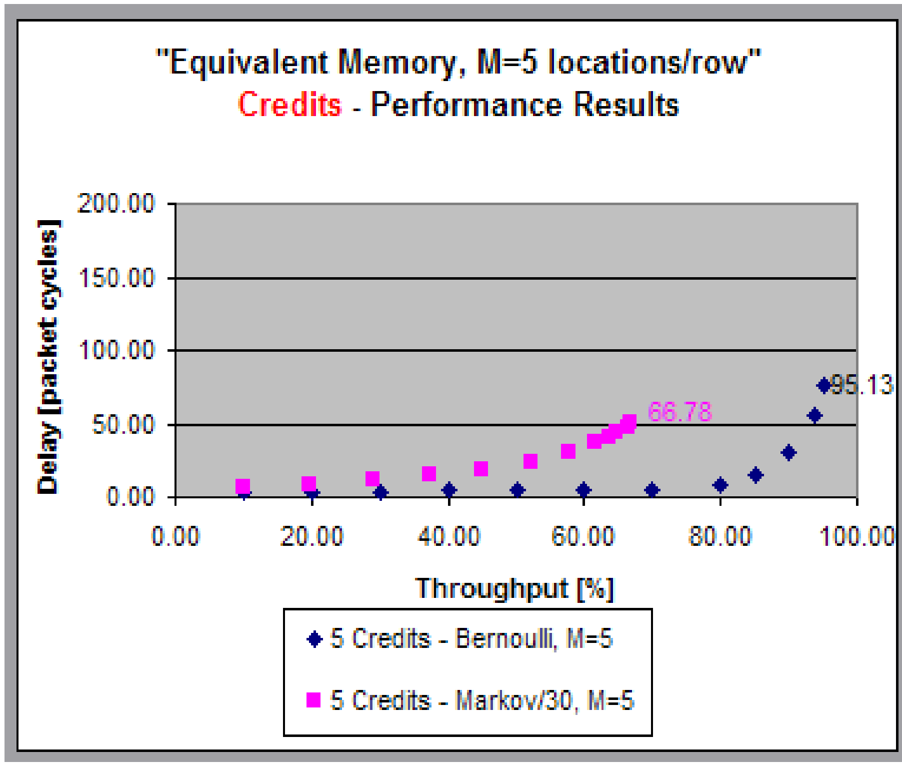
Correctness: Min. Memory for “No Drop” @ BDP=4

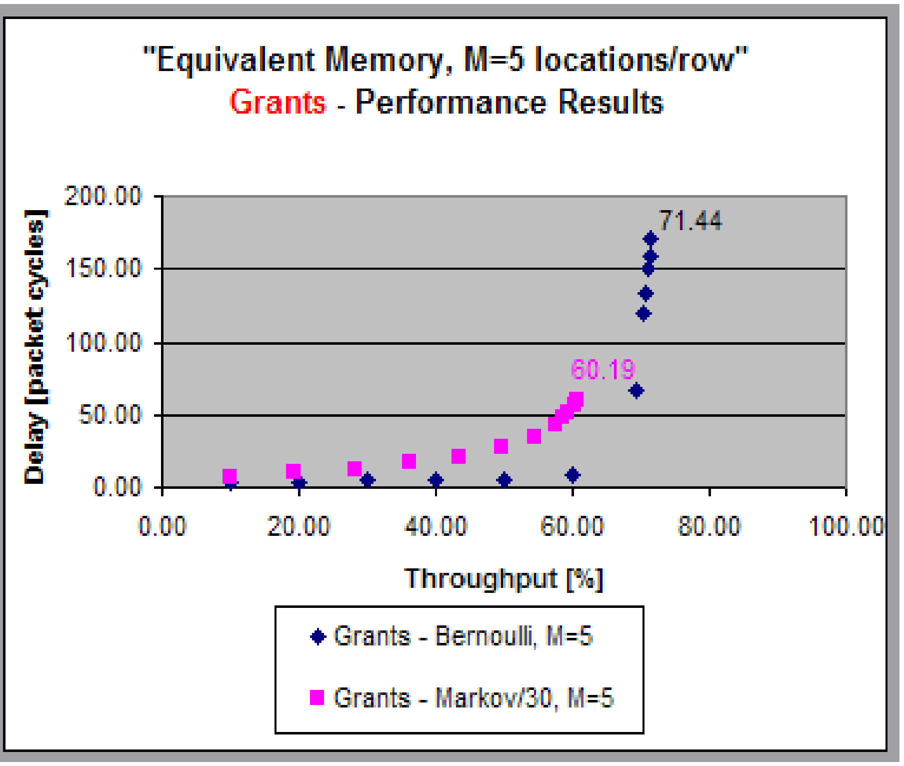




- "Minimum“: to operate lossless => O(RTT$_{link}$)
  - Credit : 1 credit = 1 memory location
  - Grant : 5 (=RTT+1) memory locations
- Credits
  - Under full load the credit is circulating constantly
  - RTT=4, therefore the maximum performance determined by up link utilisation = 25%
- Grants
  - Determined by slow restart (poor up link utilisation) : GO, if last packet has left switch needs RTT until next packet arrives at switch

PAUSE vs. Credit @ M = RTT+1



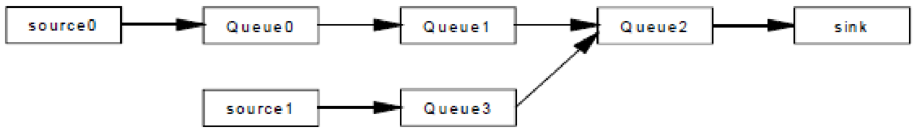


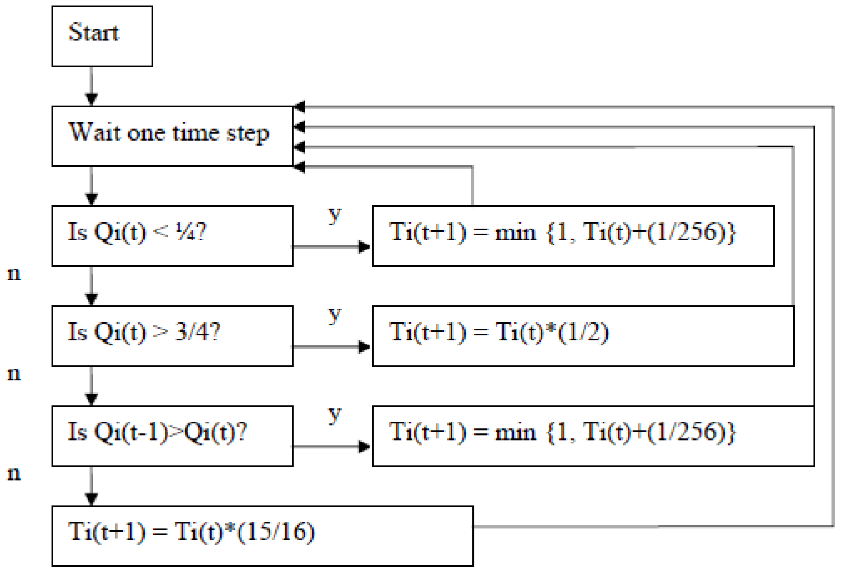
- "Equivalent" = 'fair' comparison
  - Credit scheme: 5 credit = 5 memory locations
  - Grant scheme: 5 (=RTT+1) memory locations
    - Performance loss for PAUSE/Grants is due to lack of underflow protection (pipeline bubbles on restart)

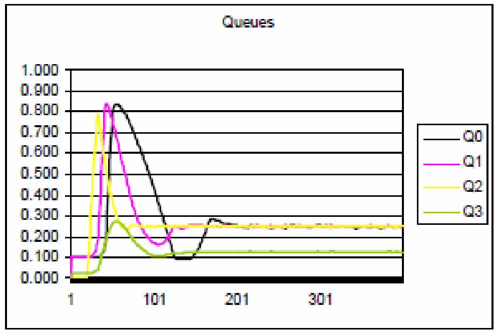
    For equivalent (to credit) performance, M=9 is required for PAUSE

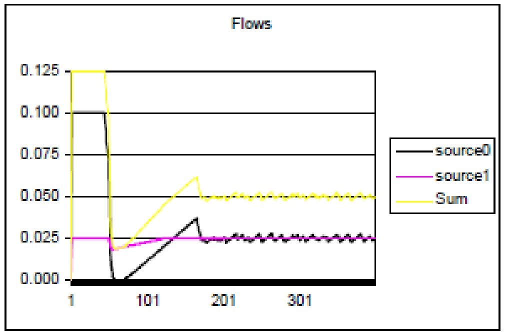
FC-Basics: Rate

- RX queue Qi=1 (full capacity).
- Max. flow (input arrivals) during one timestep (Dt = 1) is 1/8.
- Goal: update the TX probability Ti from any sending node during the time interval [t, t+1) to obtain the new Ti applied during the time interval [t+1, t+2).
- Algorithm for obtaining Ti(t+1) from Ti(t) ... =>
- Initially the offered rate from source0 was set = .100 , and from source1 = .025. All other processing rates were .125. Hence all queues show low occupancy.
- At timestep 20, the flow rate to the sink was reduced to .050 => causing a congestion level in Queue2 of .125/.050 = 2.5 times processing capacity.
- Results: The average queue occupancies are .23 to .25, except Q3 = .13. The source flows are treated about equally and their long-term sum is about .050 (optimal).









Which LL-FC Scheme is "Better"? It depends...

- **<u>Grant / PAUSE</u>**
  + simple
  + scalable (lower overhead of signalling)
  - 2x M=BDP size required
- **<u>Credits</u>** (absolute or incremental)
  + are always lossless, independent of the RTT and memory size
  + adopted by virtually all modern ICTNs (IBA, PCIe, FC, HT, ...)
  - not trivial for buffer-sharing (incr.)
  - protocol reliability (incr.) ➔ census of ghosts and zombies
  - scalability and overhead (abs.)
- At equal M = RTT, credits show ca. 30% higher T_{put} vs. PAUSE

- Rate: in-between PAUSE and credits
  + OK for NICs with h/w RLs
  + potential good match for QCN and CCA (e2e CM)
  - complexity (cheap fast bridges)

Practical LL-FC

1. Ethernet: from .3x PAUSE to .1Qbb PFC

Introductory Overview of DCB Ethernet Standardization Activities in IEEE 802

DCB Redshifting: Learning from the higher layer protocols → L2

Ethernet before DCB

- Traditional Ethernet philosophy: ***good enough***
  - KISS, Plug&Play => low cost, to buy *and* to use
  - 30 yrs. of continous development
  - major iteration once every ca. 10-15 yrs

- Good match for TCP/IP stack

- Not optimized for performance, nor for DC / HPC apps
  - Frame loss
  - Latency
  - Throughput
  - Jitter, fairness, no VL, no true QoS (besides .1Q/p)

…and after CEE / 802 DCB

The promise of DCB: 802-standard Ethernet with

1. Low latency, comparable w/ best HPC ICTNs
2. Quasi-Losslessness (zero drop)
3. Traffic class differentiation (e2e SLA)
4. Congestion (aka delay/Tput) mgnt
5. Bw sharing (ETS, prio grouping)
6. DC capability detection and exchange (DCBX)

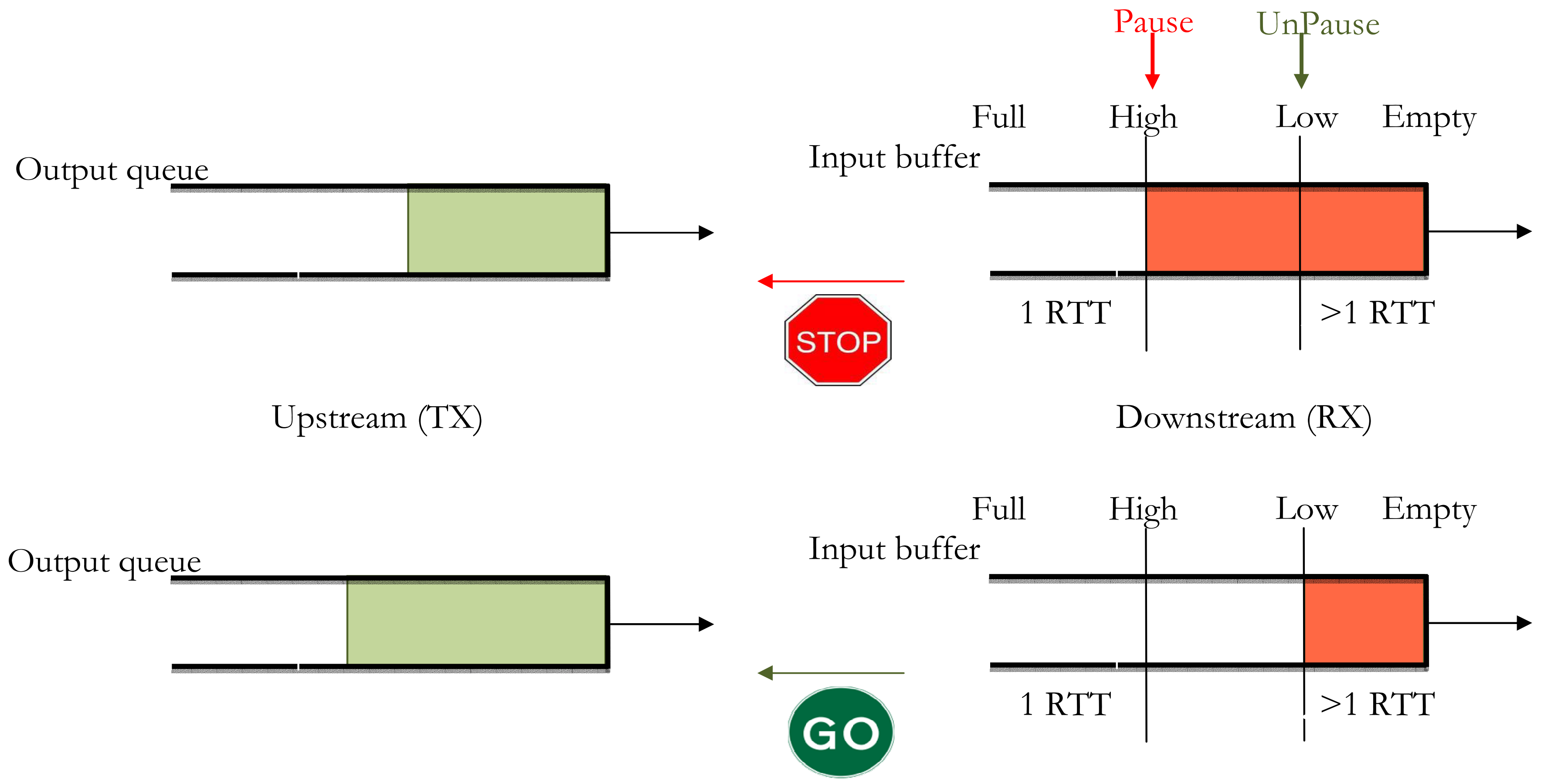
- Vendor specific
  - Deadlock mgnt
  - Load balancing, adaptive routing, intelli-hashing for LAG
  - Schedulers
  - ….

PFC = Per Priority Flow Control

8x worse than PAUSE...?!

802.3x ➔ .1 Qbb Priority Flow Control

- Conventional Ethernet is PnP, yet it drops pkts (fixed by L4)
- Layer 2 flow control: 802.3x PAUSE ➔ 802.1Qbb PFC



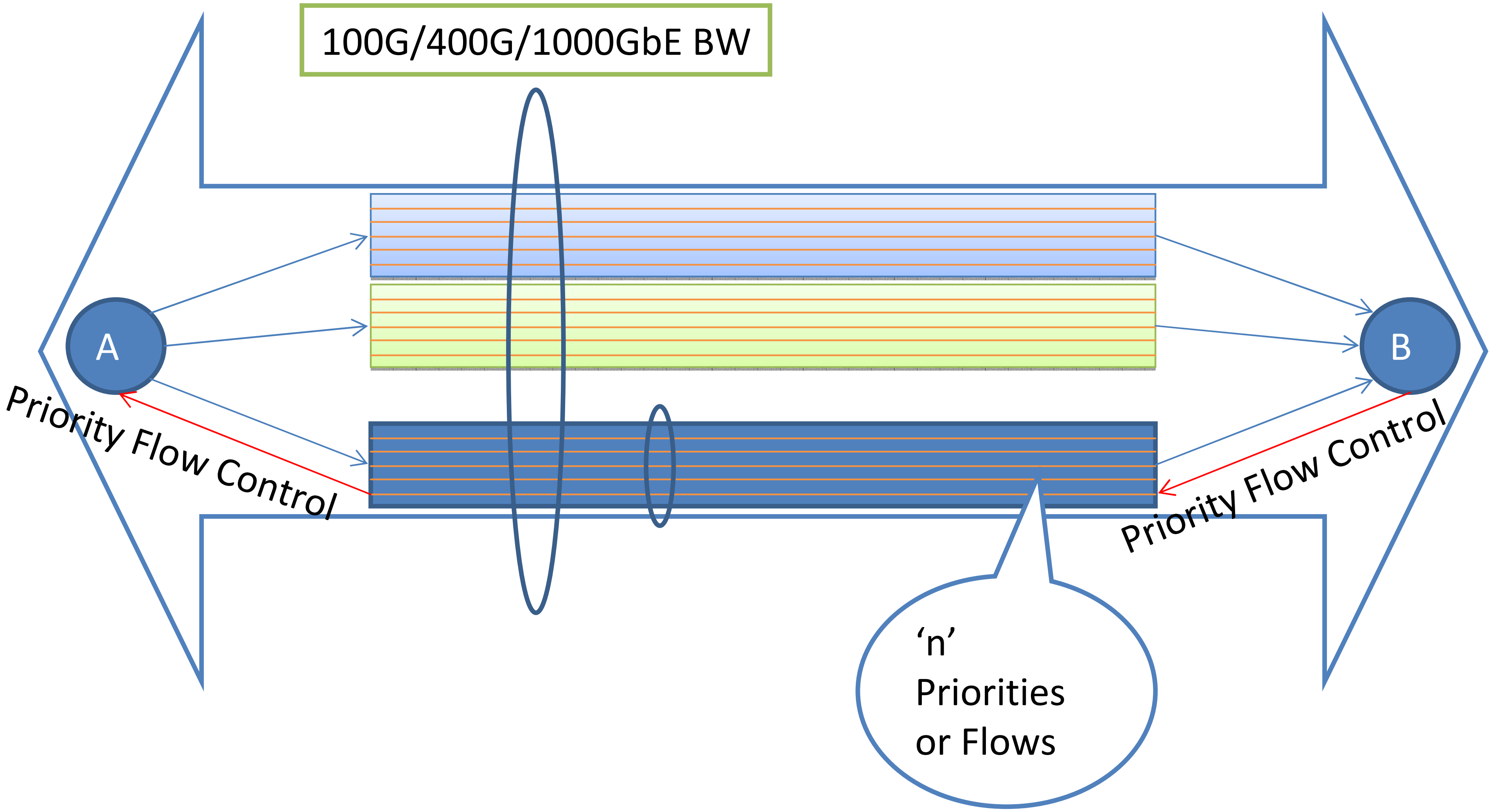
PFC: 802.1Qbb - Priority-based Flow Control

- Target: Create a VL-like lossless Ethernet (also fix the .3x PAUSE…)
- Why fix a .3 problem in .1?
  - A) .1 has queues, whereas .3 doesn't…
  - B) tightly coupled w/ the other .1 DCB proposals, especially QCN (802 internal dependency) and ETS
- PFC enables
  - flow control per traffic class; TC is identified by the VLAN tag priority values.
  - multiple datacenter networks (DCN), including those serving loss sensitive protocols- - e.g. inter processor communication (IPC), storage (FCoE), etc. to be converged onto an IEEE 802 network.
- PFC is intended to eliminate frame loss due to congestion, thru a mechanism similar to the 802.3x PAUSE, but operating on individual priorities… PFC complements Congestion Notification (aka QCN) in DCB.

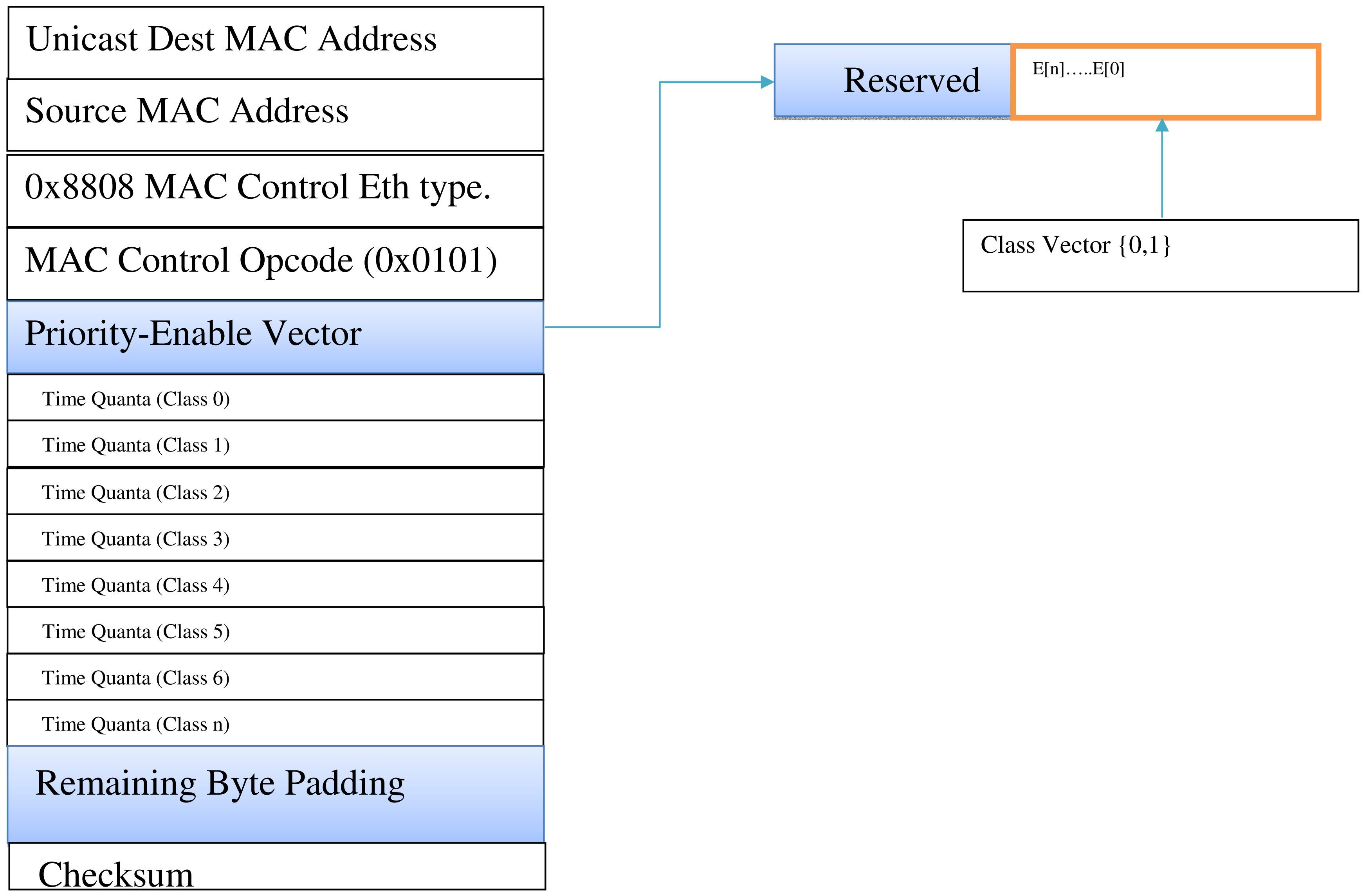
PFC basic operation: A vector of max. 8 Prio PAUSEs w/ explicit timer value/Prio

- **PFC request_operands = {priority_enable_vector | time_vector}**
  - **priority_enable_vector = { 00000000 | e[7..0] }**
  - **time_vector = 8*2B => 8 * [0..64K] * pause_quanta * 64B (512 bit time)**
  - Common size of RX_Buffer > 10KB (10Gbps, short link)

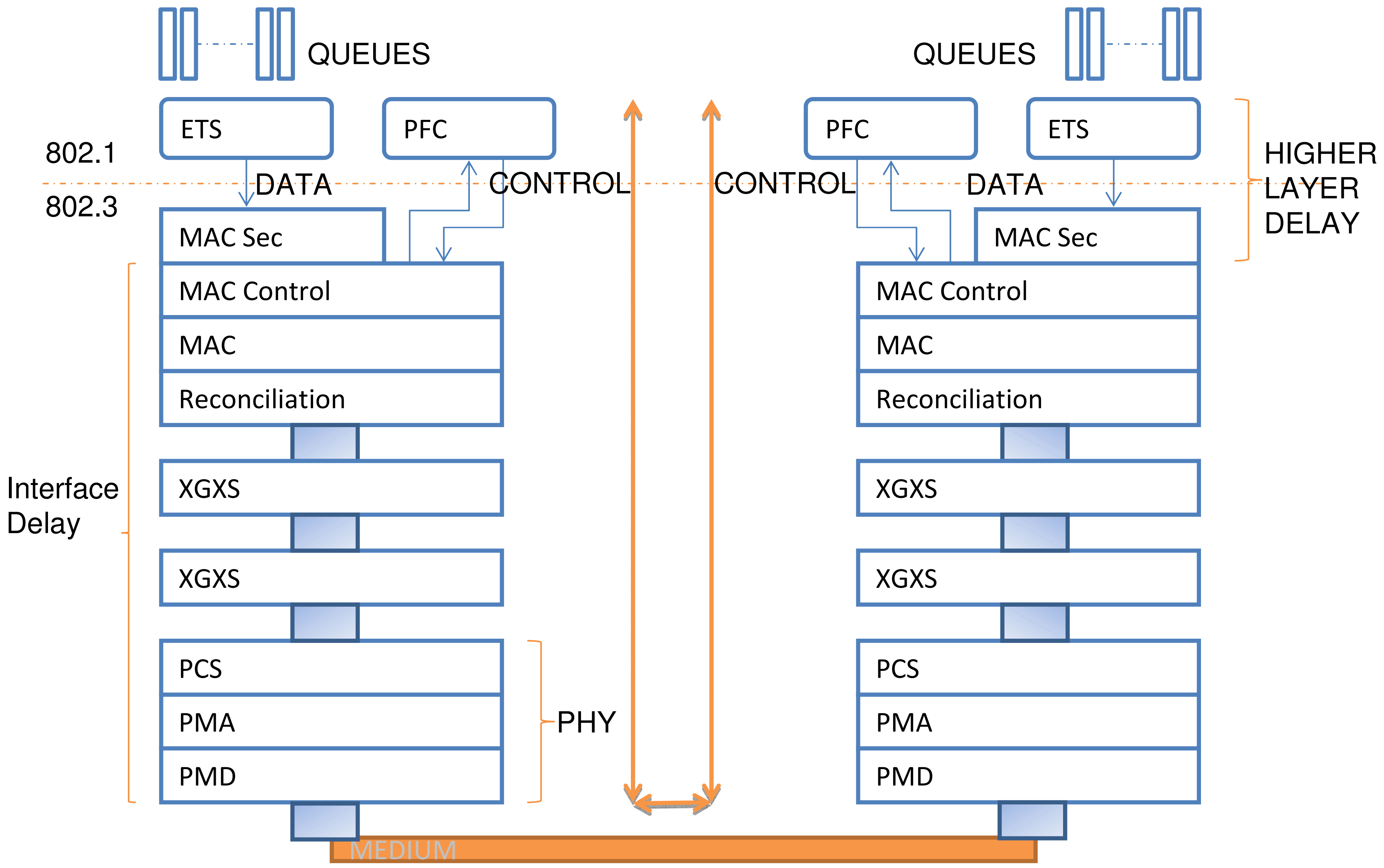
Link Level PFC



PFC Frame Format



PFC Delay Model



PFC Max Total Delay Calculations

Max Total Delay = 2 * (Max Frame Size)
+ PFC Frame
+ 2 * (Cable Delay)
+ 2 * (Interface Delay)
+ (Higher Layer Service Delay)

Cable Delay = Medium Length * 1/(BT * v)
Where BT = Bit Time
v = Speed of light in medium.
Considering, refractive index of optics = 1.467; Speed of light in single mode fiber = 66% of light speed in vacuum (Ether).

Potential PFC Issues

PFC Issue	Problem	Solution
Transient PFC activation: 0.1 – 10 us	Out of order (OOO) w/ Link Aggregation (LAG)	Re-sequencing at destination (RSQ @ DST)
10s to 100s us	Saturation tree hotspot congestion spreading	Adaptive routing & Congestion mgnt. (AR+CM)
Persistent PAUSE or cycles (loops, RQ/Reply)	Deadlocks (DLK)	DLK mgnt: prevention or recovery

Consequences

1. "One sublink being Paused may have a ripple effect on the entire aggregated link"
2. .3az Energy Efficient Ethernet ?
   - Link unavailable during speed change: EEE will produce short term (1ms?) link unavailability
   - Frames will be delayed (blocked) during link unavailability => hotspot (unless discarded, !PFC)
   - Link speed will produce latency variation; speed change affects available bandwidth

- ...

IBA LL Credit Scheme

VL[0..14]

Keshav

- insert 3-5 foils

PFC Final Toughts

Advantages :

•Link level losslessness.
•Priority based buffer management.
•Priority based traffic management.
•Simple.
•Works beautifully well ☺.

Short-comings :

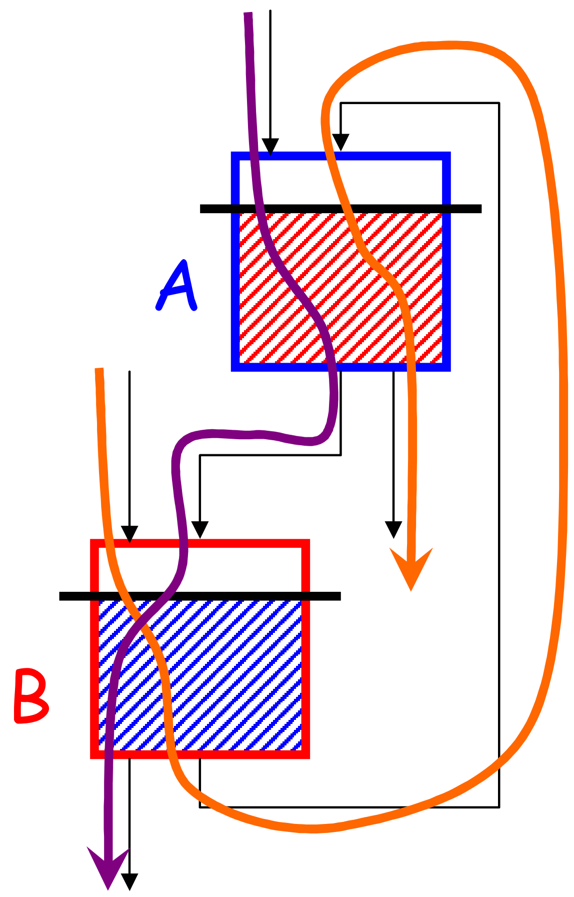
•Head of line blocking within priority groups.
•XON/XOFF like behavior, although delay quanta are programmable.
•Higher Buffer requirements [$\propto$ ort Speed and Cable length.]
•Lacks flow control at virtual port level. Does not enable flow control at smaller slices of bandwidth.
•Suffers due to RTT delays.
•Was not built into original Ethernet standard. Thus not backward interoperable.

LL-FC Deadlocks
aka, the Preventable Ugly

VL[0..14]

M2M Circular Dependency Deadlocks

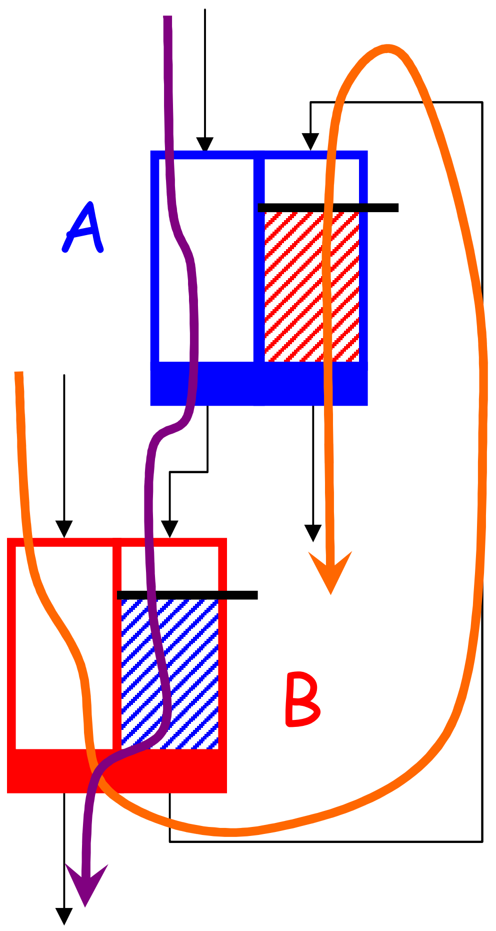
The Mechanism of LL-FC-induced Deadlocks



- When incorrectly implemented, LL-FC-based flow control can cause hogging and deadlocks

- LL-FC-deadlocking in shared-memory switches:
  - Switches A and B are both full (within the granularity of an MTU or Jumbo) => LL-FC thresholds exceeded
    - All traffic from A is destined to B and viceversa
  - Neither can send, waiting on each other indefinitely: Deadlock.
  - Note: Traffic from A never takes the path from B back to A and vice versa
    - Due to shortest path routing

Solution to Defeat this Deadlock: Partitioning

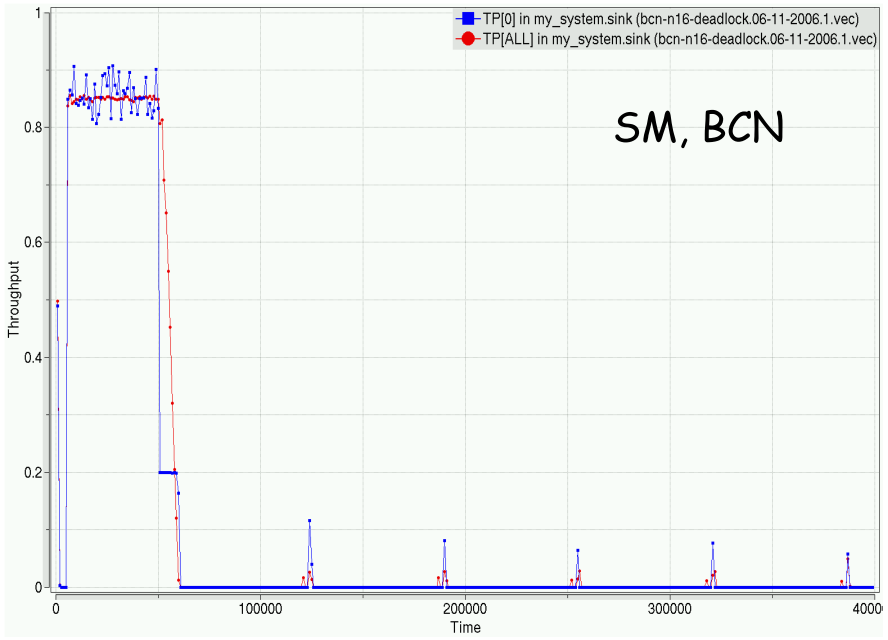


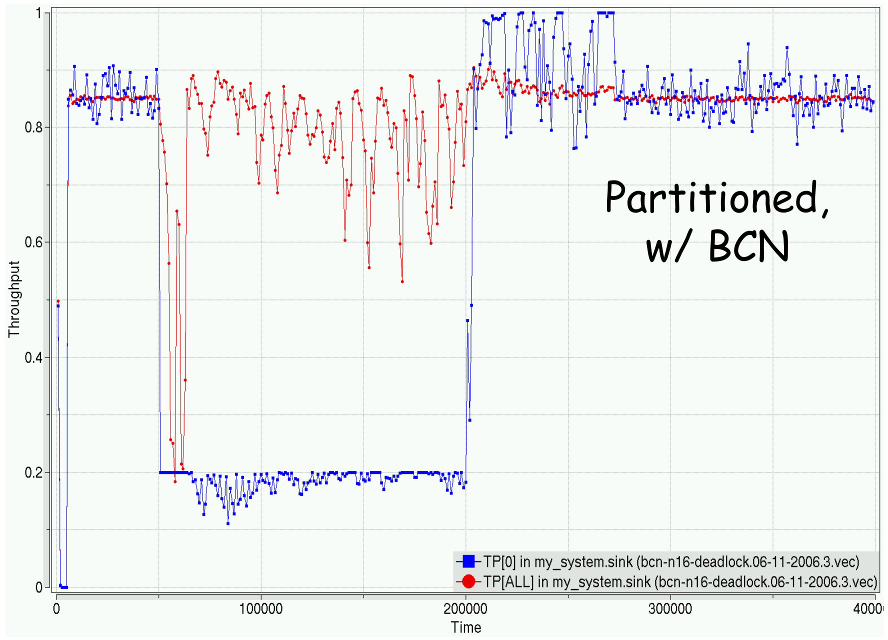
- Architectural: Assert LL-FC on a per-input basis
  - No input is allowed to consume more than 1/Nth of the shared memory
  - All traffic in B's input buffer for A is guaranteed to be destined to a different port than the one leading back to A (and vice versa)
  - Hence, the circular dependence has been broken!

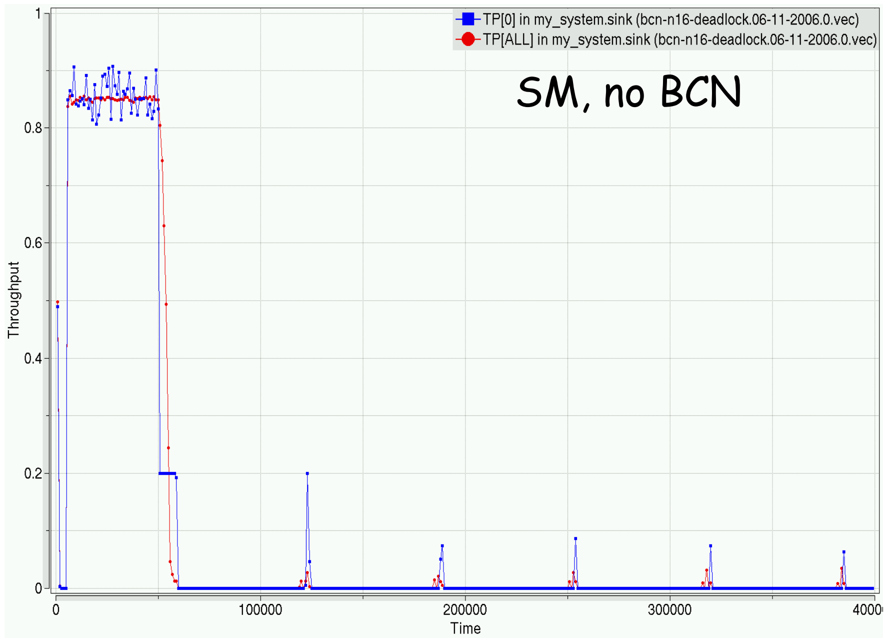
- Confirmed by simulations
  - Assert LL-FC on input i:
    - $occ_{mem} >= T_h$ *or* $occ[i] >= T_h/N$
  - Deassert LL-FC on input i:
    - $occ_{mem} < T_h$ *and* $occ[i] < T_l/N$
  - $Q_{eq} = M / (2N)$

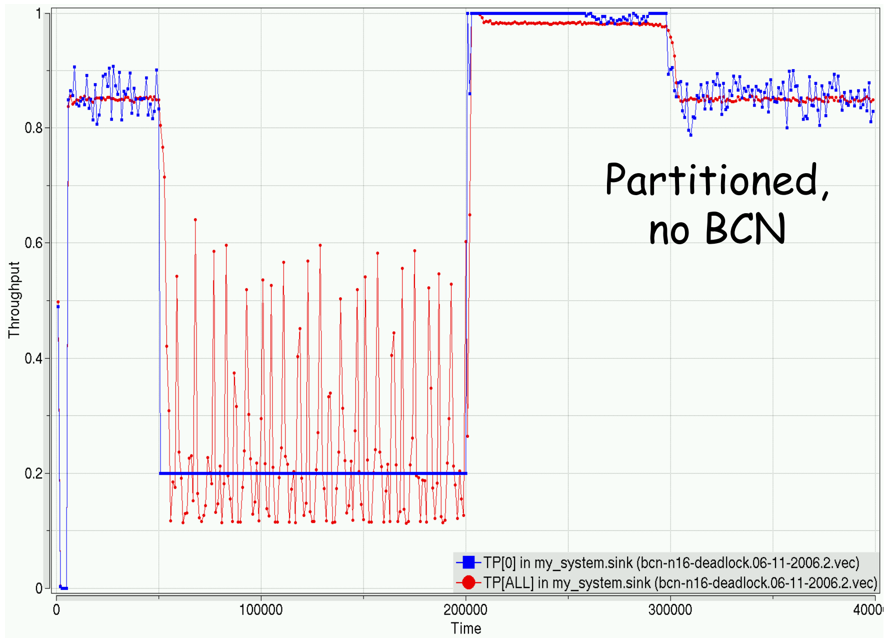
... this deadlock is solved!

LL-FC-caused Deadlocks in BCN Simulations 16-node 5-stage fabric Bernoulli traffic







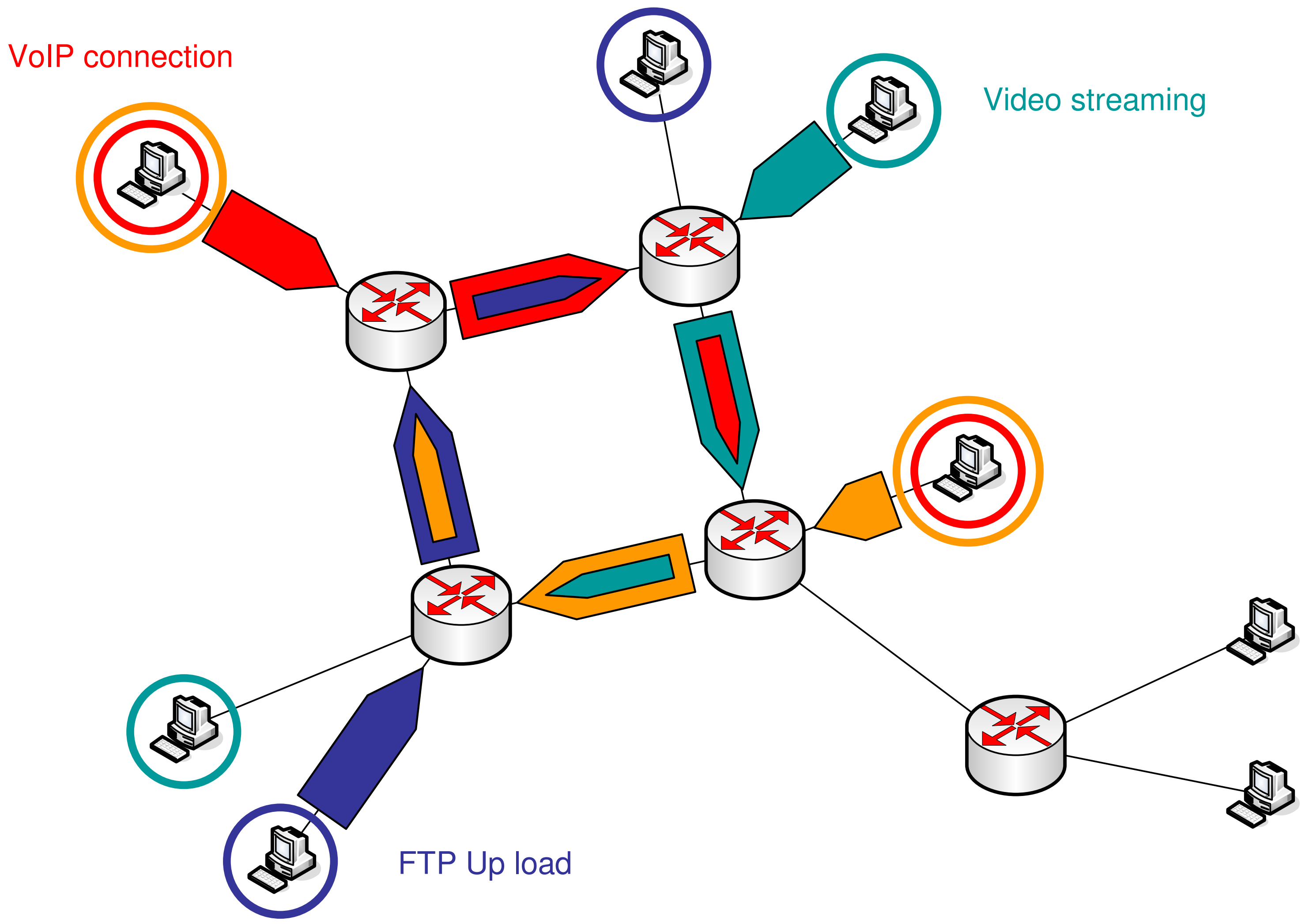


BKUP

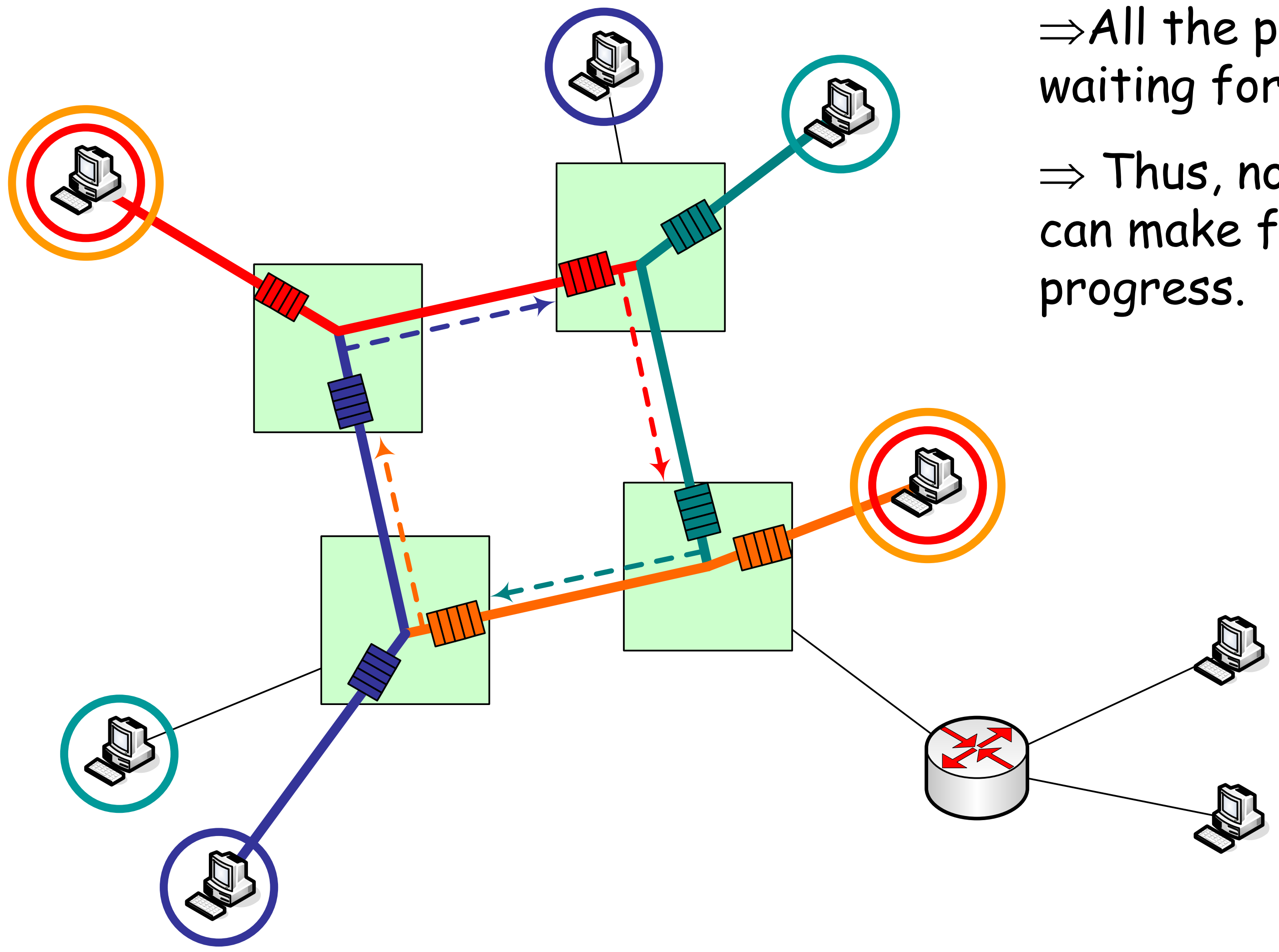
Routing Deadlocks

Routing Deadlock Scenario

Def.: Cyclic dependency relationship between two or more resources that are waiting on each other to free resources, but without freeing their own. Resources: physical (hardware) or logical (software)



Deadlocked Buffers: Dependency Loop in the Routing Graph

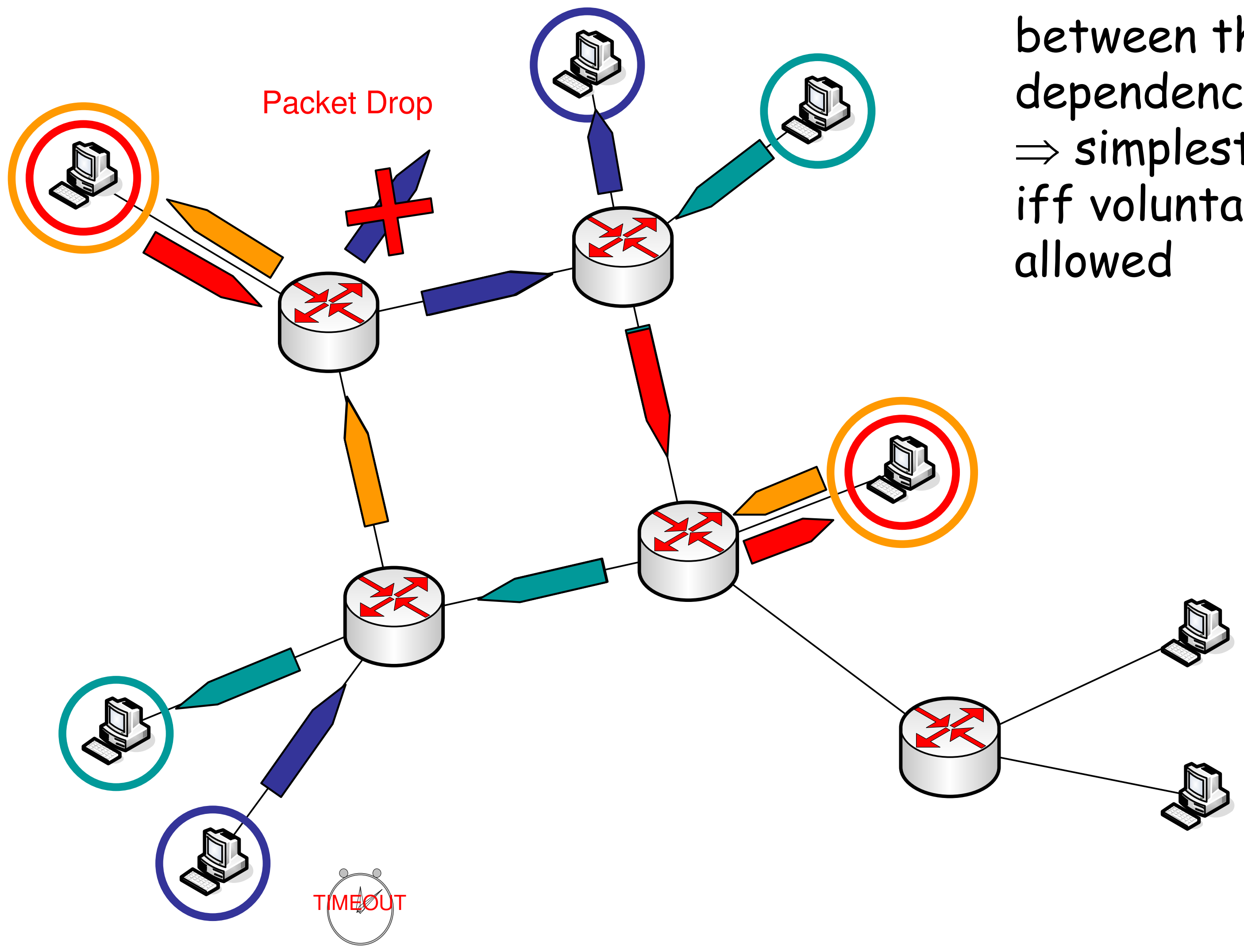


All buffers in this network cycle are full

⇒All the packets are waiting for each other

⇒ Thus, no message can make forward progress.

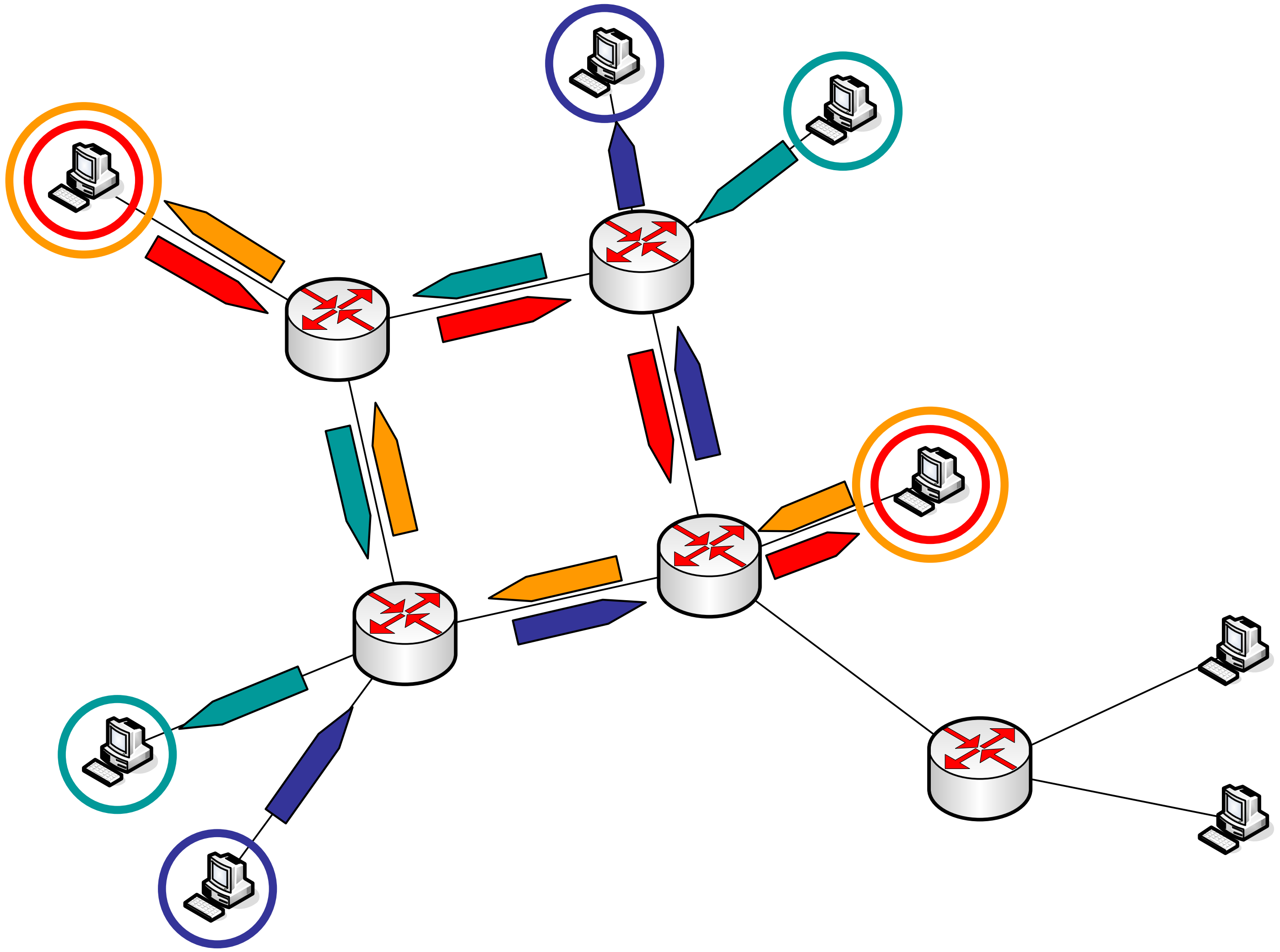
Deadlock Recovery in Lossy Networks



Packet drop
=> frees deadlocked resources
⇒ eliminates cycles between their inter-dependencies.
⇒ simplest solution, iff voluntary loss is allowed

Deadlock Avoidance by Ordering: Deadlock-free Routing

Deadlock-free algorithm => Certain turns will be forbidden in order to eliminate cycles. In figure below left-up and right-down turns are prohibited.



Deadlock Avoidance or Recovery: Virtual Channels

1. Split physical links into several VCs
2. Define the restrictions / ordering rules in the use of VCs to avoid / recover from deadlocks.

=> Enables fully or partially adaptive routing.