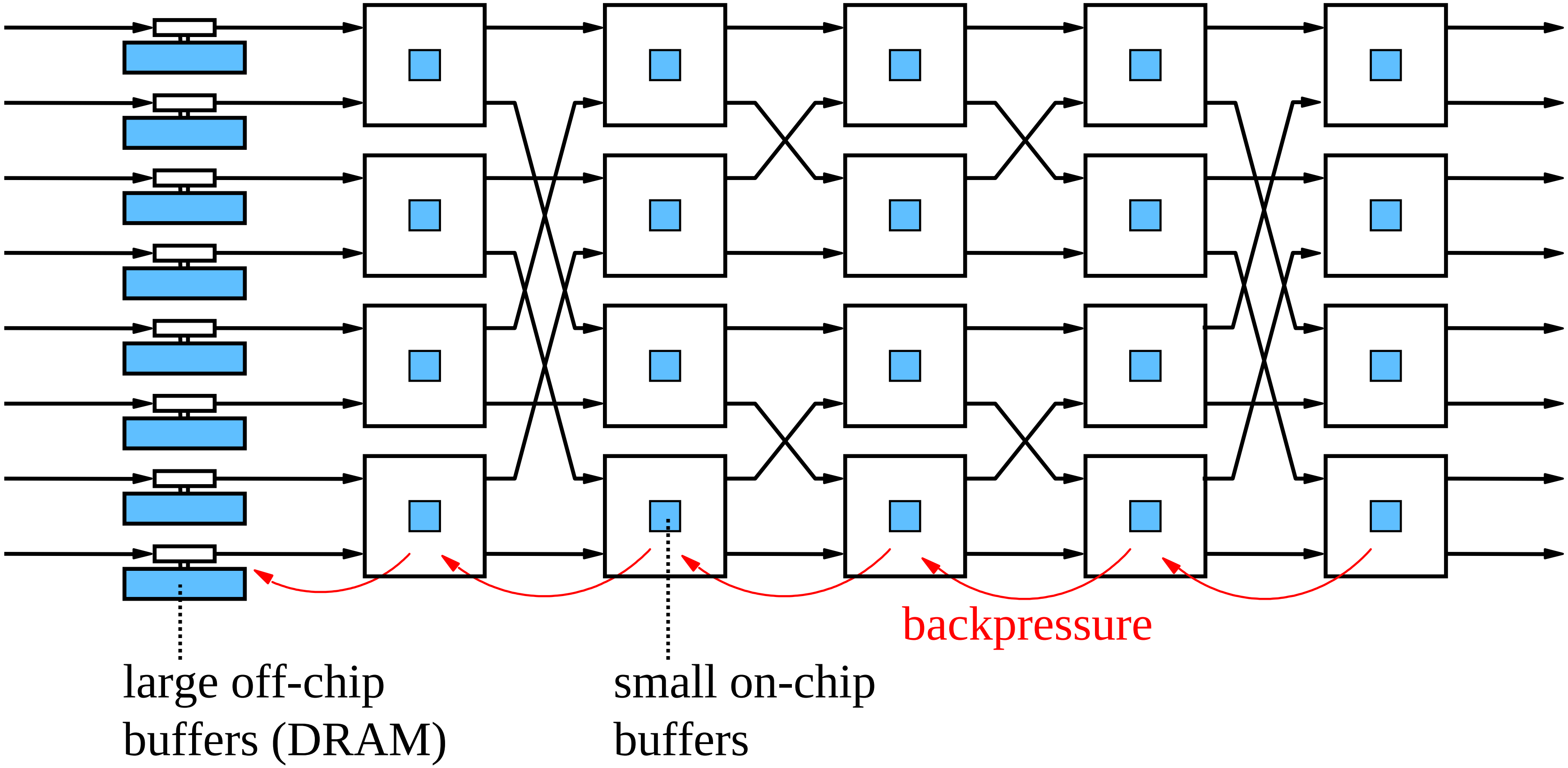
6.3 Buffer Space vesrus Number of Flows

- What to do when the number of flows is so large that it becomes impractical to allocate a separate flow-control “window” for each one of them
  - Per-destination flow merging: Sapountzis and Katevenis, IEEE Communications Magazine, Jan. 2005, pp. 88-94.
  - Dynamically sharing the buffer space among the flows: the ATLAS I and the QFC flow control protocol, and its evaluation
  - Regional Explicit Congestion Notification (RECN)
  - Request-Grant protocols: N. Chrysos, 2005
  - End-to-end congestion control via request-grant: N. Chrysos, 2006
  - Other buffer sharing protocols of the mid-90’s
  - Buffer memory cost versus transmission throughput cost in 1995

Buffered Switching Fabrics with Internal Backpressure

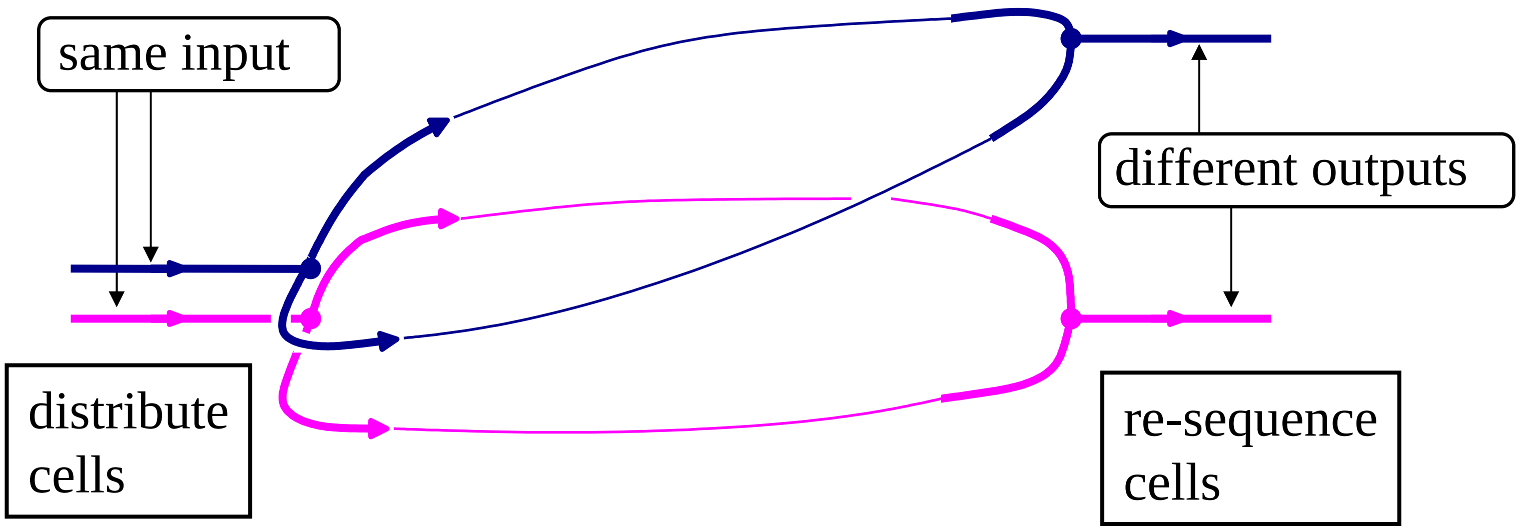


- Performance of OQ at the cost of IQ,
- Requires per-flow backpressure.

Cell Distribution Methods

- Aggregate traffic distribution:
  - Randomized routing (no backpressure)
  - Adaptive routing (indiscriminate backpressure)

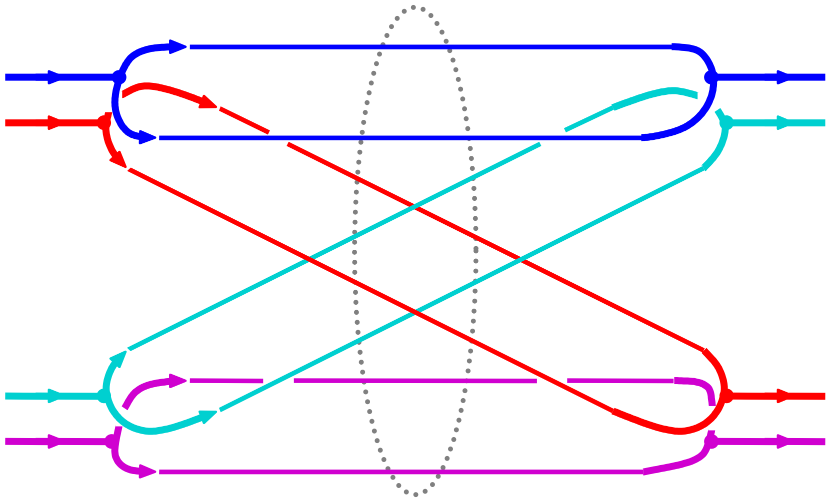
  ⇒ load balancing on the long-term only



- Per-flow traffic distribution:
  - Per-flow round-robin (PerFlowRR)
  - Per-flow imbalance up to 1 cell (PerFlowIC)

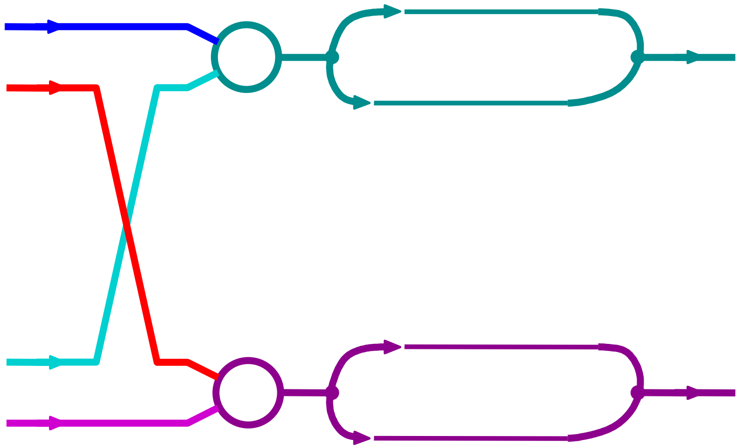
  ⇒ accurate load balancing, on a shorter-term basis

Too many Flows



- N^2 per chip in the middle stage

Per-output Flow Merging



- Retains the benefits of per-flow backpressure
- N flows per link, everywhere

  – Re-sequencing needs to consider flows as they were before merging

  – Freedom from deadlock

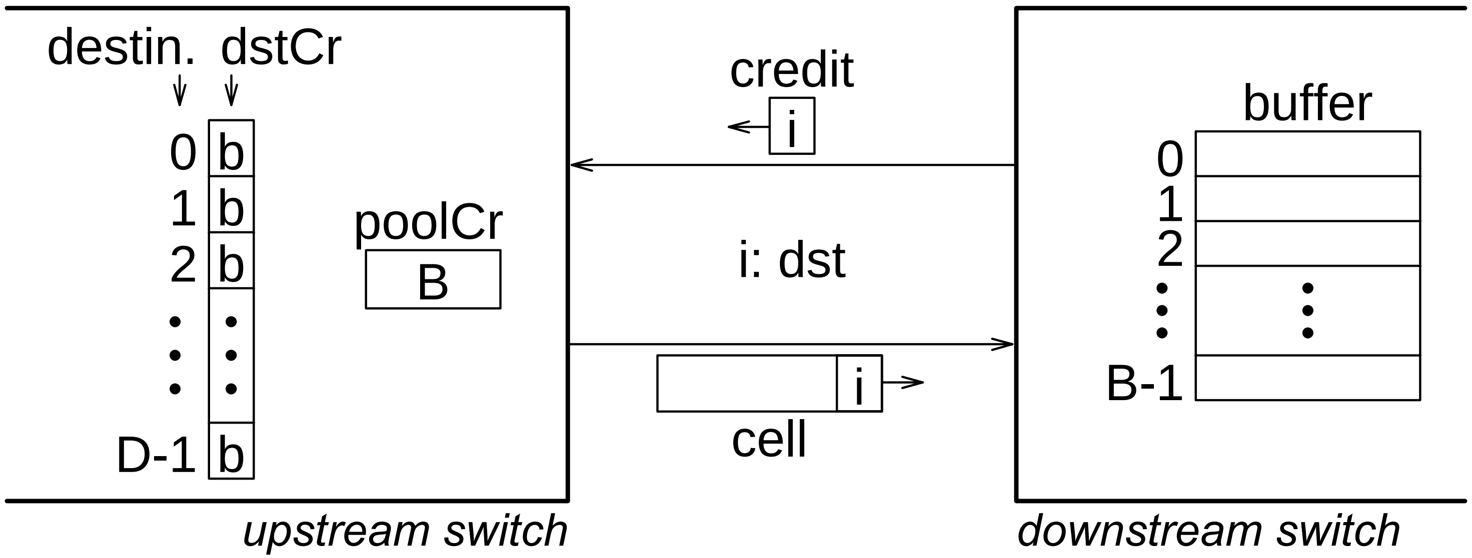
The “ATLAS I” Credit Flow-Control Protocol

- M. Katevenis, D. Serpanos, E. Spyridakis: “Credit-Flow-Controlled ATM for MP Interconnection: the ATLAS I Single-Chip ATM Switch”, Proc. IEEE HPCA-4 (High Perf. Comp. Arch.), Las Vegas, USA, Feb. 1998, pp. 47-56; http://archvlsi.ics.forth.gr/atlasI/atlasI_hpca98.ps.gz
- Features:
  - identically destined traffic is confined to a single “lane”
  - each “lane” can be shared by cells belonging to multiple packets
- As opposed to Wormhole Routing, where:
  - a “virtual circuit” (VC) is allocated to a packet and dedicated to it for its entire duration, i.e. until all “flits” (cells) of that packet go through
  - identically destined packets are allowed to occupy distinct VC’s

QFC-like Credit Protocol

⇒ Quantum Flow Control (QFC) Alliance: proposed standard for credit-based flow control over WAN ATM links

⇒ ATLAS I: similar protocol, adapted to
- short links
- hardware implem.



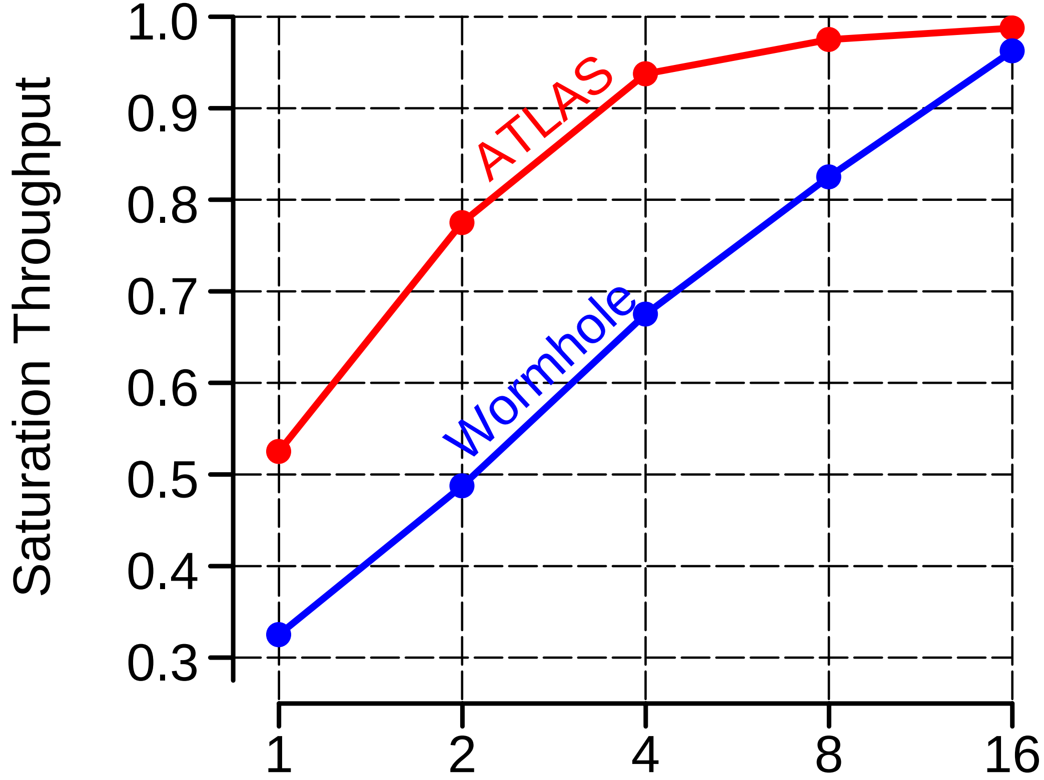
both kinds of credit are needed for a cell to depart

Number of Lanes $L = \frac{B}{b}$

(in ATLAS I: b=1)

Saturation Throughput

64x64 fabric: 6-stage banyan using 2x2 eleme
20-cell or 20-flit bursts, uniformly destined

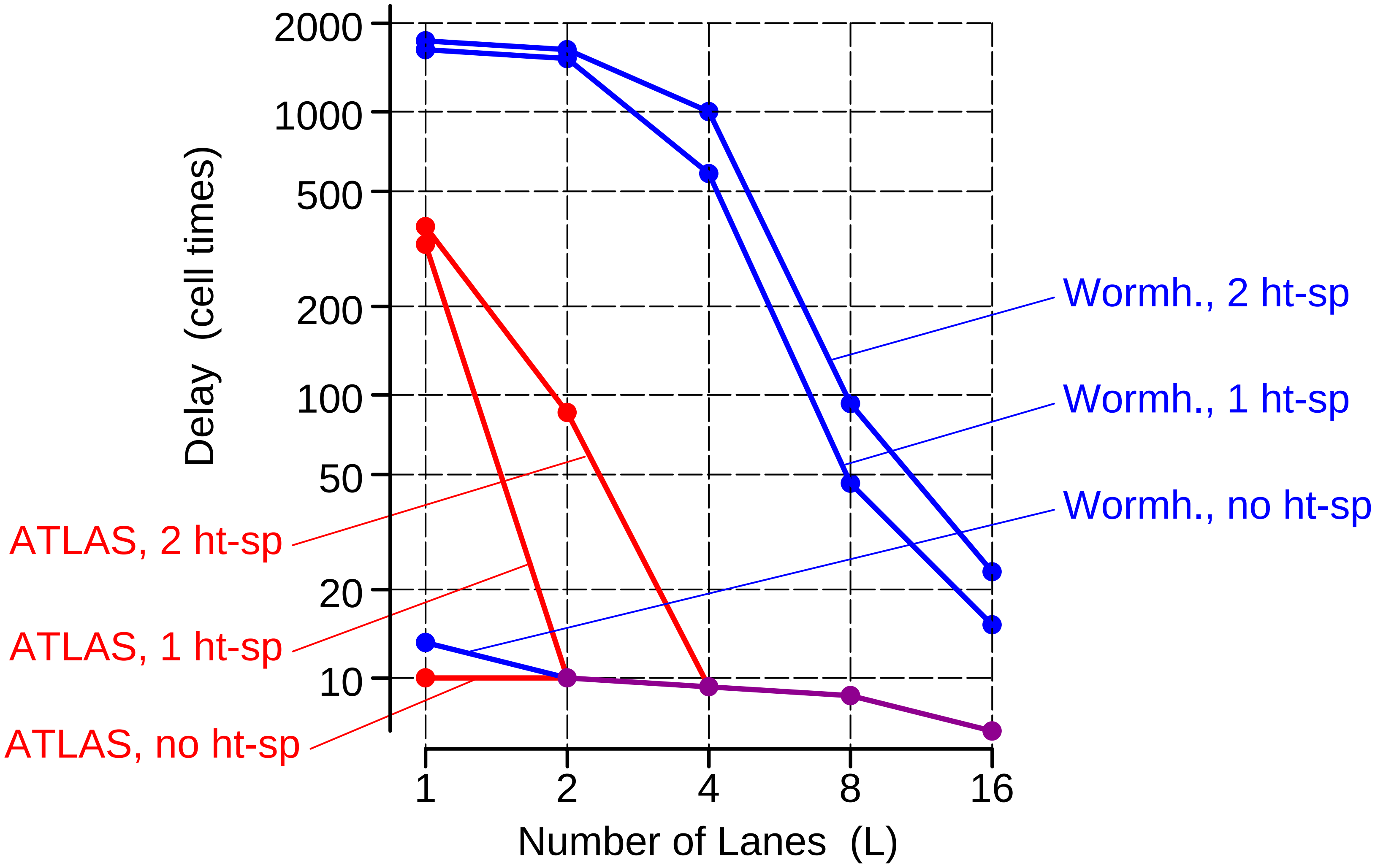


Buffer Space (=Lanes) per Link
cells or flits

(B=L, with b=1)

Non-Hot-Spot Delay, in the Presence of Hot-Spot Destinations

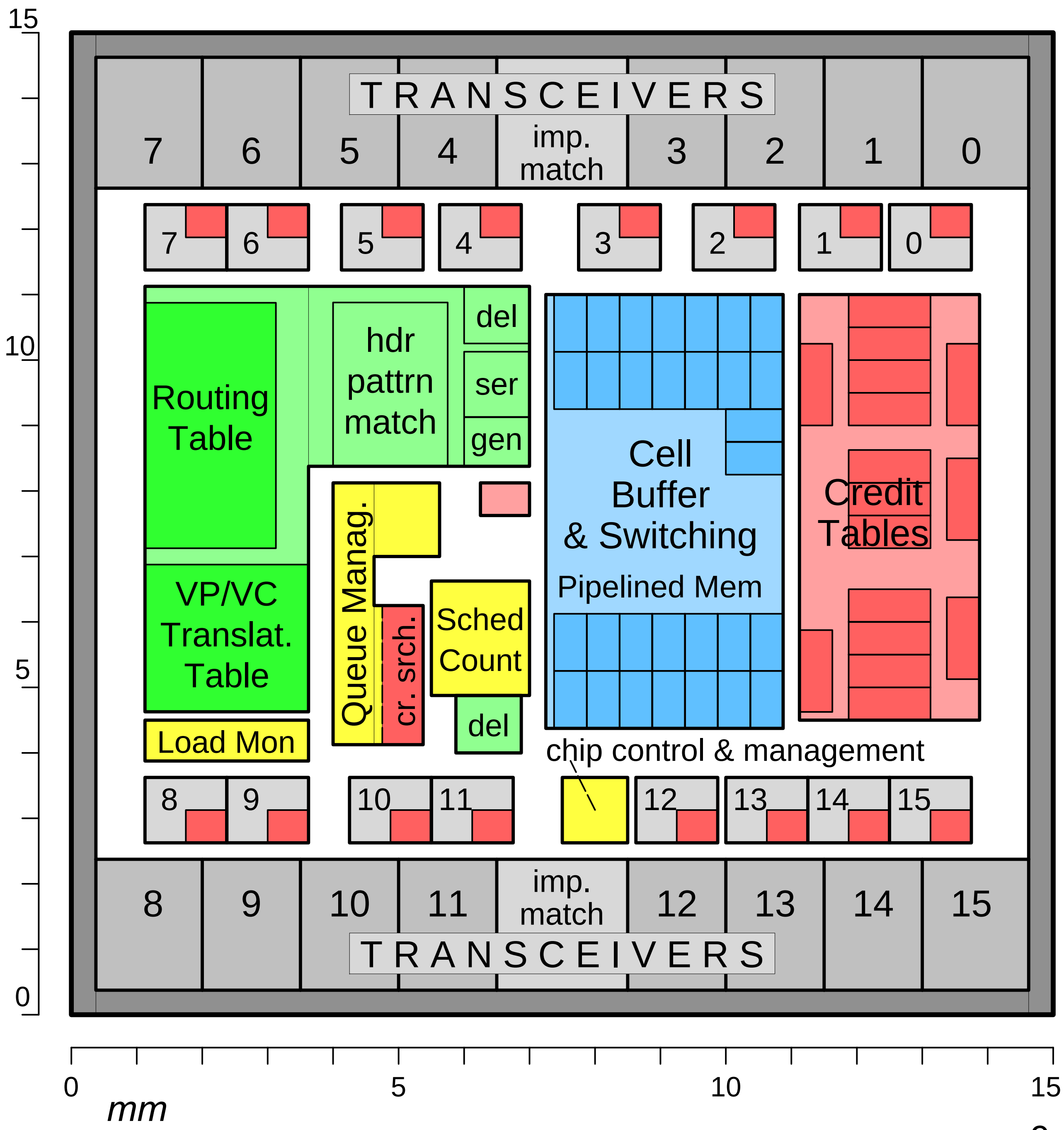
non-hot-spot load = 0.2; 20-cell/flit bursts; 64x64 fabric: 6-stg banyan w. 2x2 el.

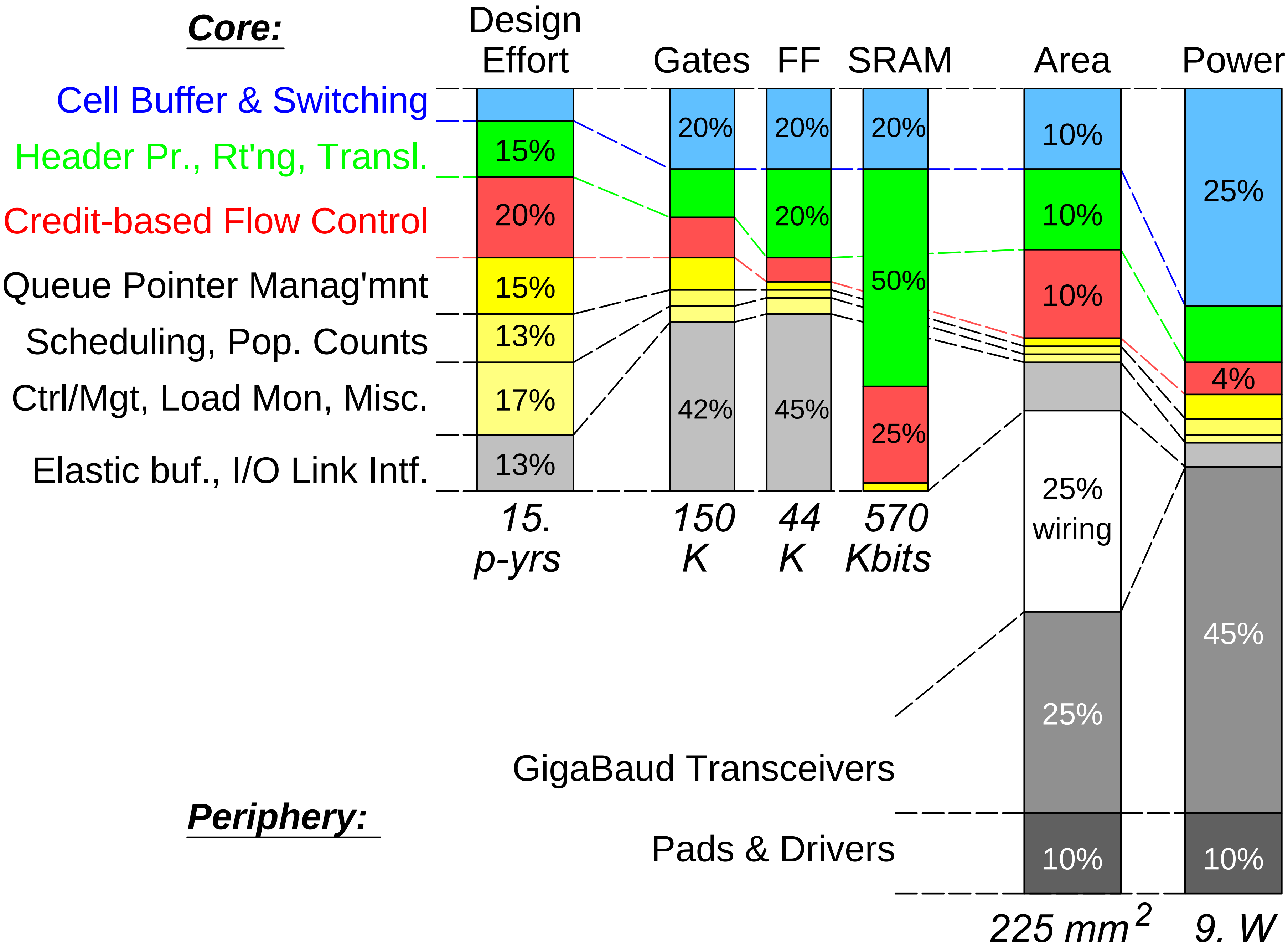


(with buffer space B=16 cells or flits per link)

ATLAS I

- Single-chip ATM Switch with Multilane Backpressure
- 10 Gbit/s = 16×16 @ 622 Mb/s/port
- Shared Buffer
- 0.35 µm CMOS
- 1996-98, FORTH-ICS, Crete, GR




Core:
Design Effort
Gates
FF
SRAM
Area
Power
Cell Buffer & Switching
Header Pr., Rt'ng, Transl.
Credit-based Flow Control
Queue Pointer Manag'mnt
Scheduling, Pop. Counts
Ctrl/Mgt, Load Mon, Misc.
Elastic buf., I/O Link Intf.
15%
20%
15%
13%
17%
13%
20%
20%
20%
20%
50%
25%
42%
45%
10%
10%
10%
25% wiring
25%
10%
25%
4%
45%
10%
15. p-yrs
150 K
44 K
570 Kbits
225 mm 2
9. W
GigaBaud Transceivers
Periphery:
Pads & Drivers

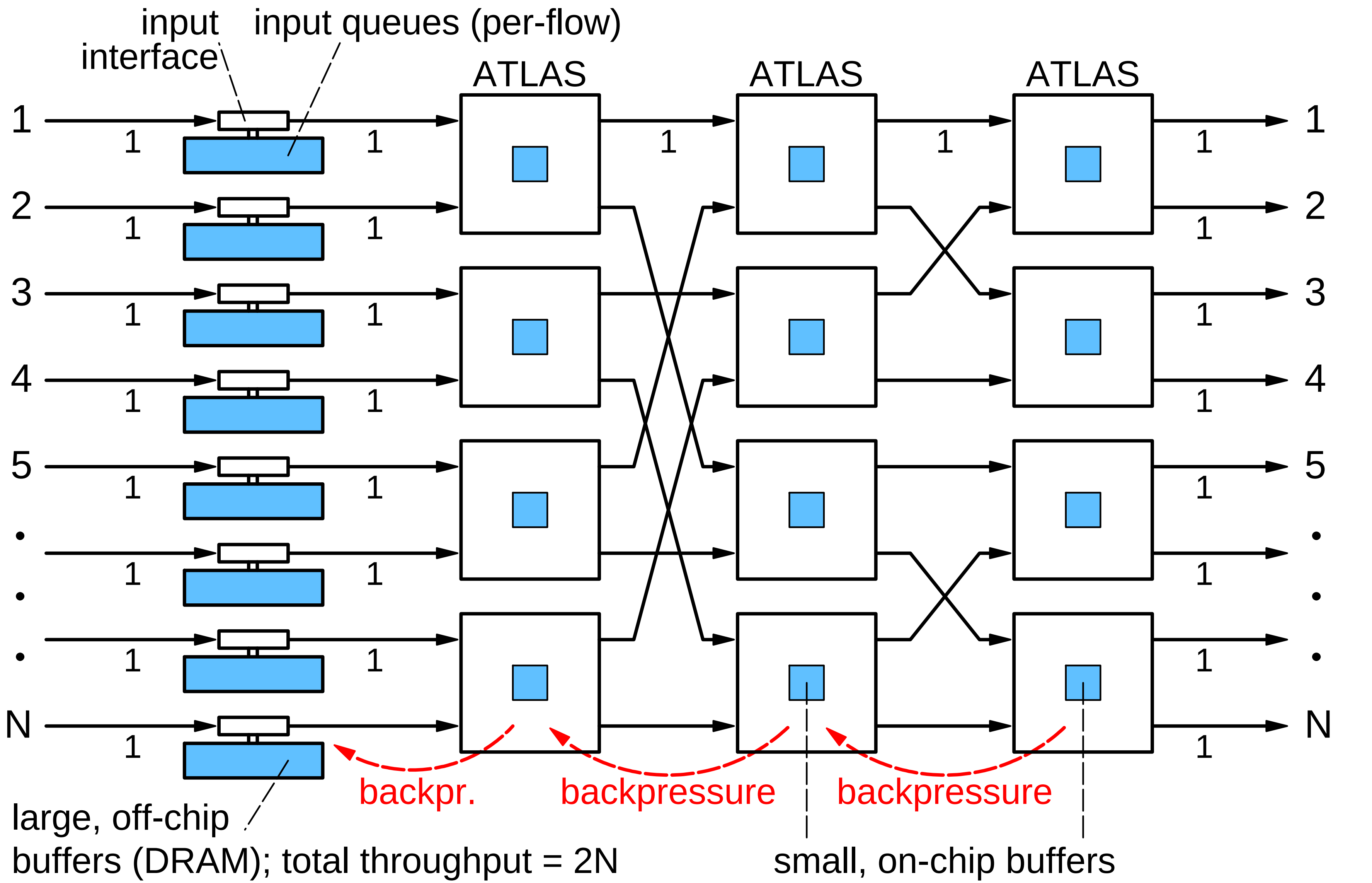
Backpressure Cost Evaluation, versus Alternatives

- Measure the cost of credit flow control in ATLAS & compare to:
- Alternatives, without internal backpressure in the fabric:
  - large buffers (off-chip DRAM) in all switches throughout the fabric, or
  - internal speedup in the fabric and output buffers

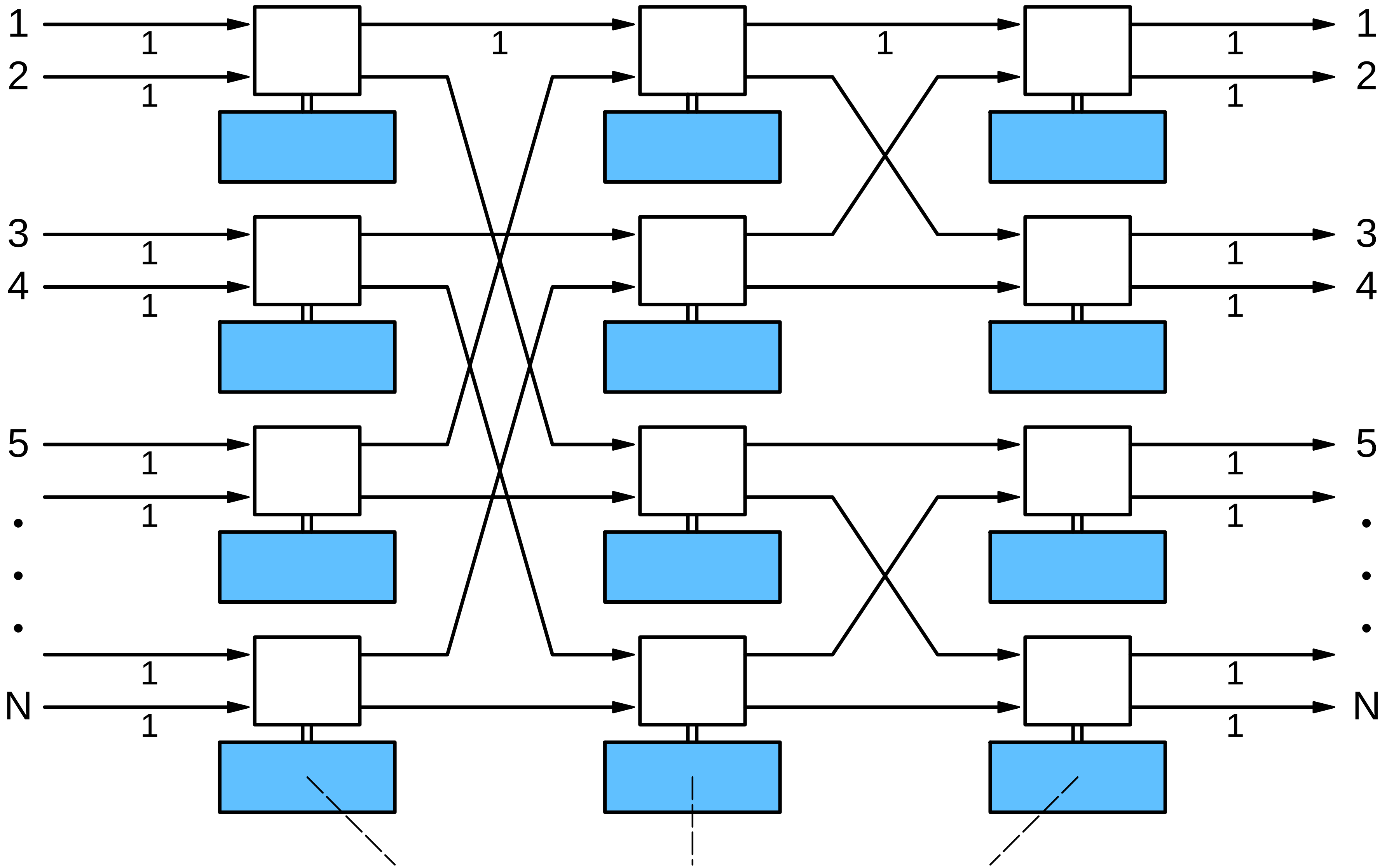
- Kornaros, Pnevmatikatos, Vatsolaki, Kalokerinos, Xanthaki, D. Mavroidis, Serpanos, Katevenis: “ATLAS I: Implementing a Single-Chip ATM Switch with Backpressure”, IEEE Micro Magazine, Jan/Feb. 1999, http://archvlsi.ics.forth.gr/atlasI/hoti98/

Making Large ATM Switches:

Switching Fabrics with Internal Backpressure

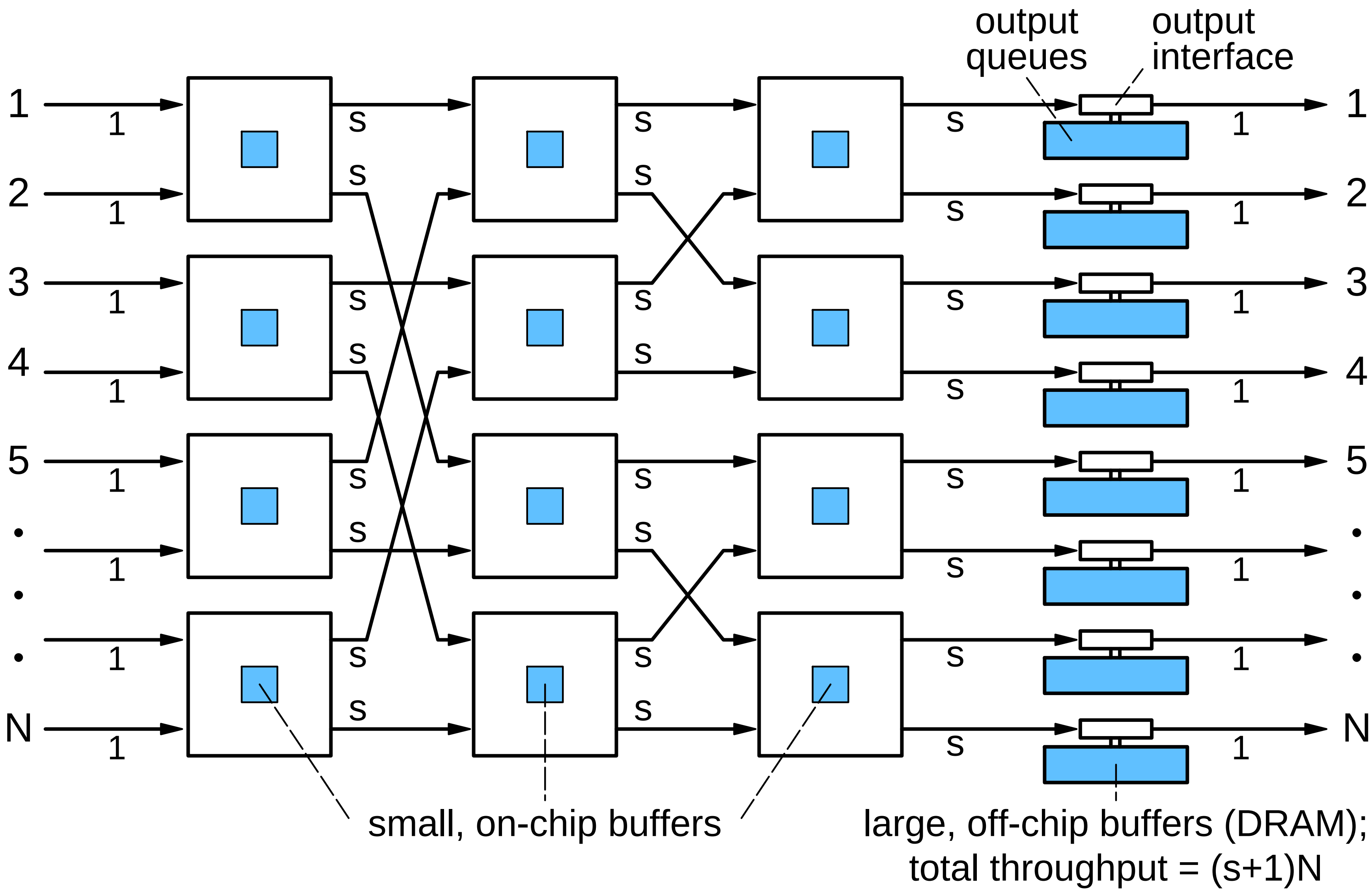


Switching Fabrics without Backpressure 1: Large Buffers



large, off-chip buffers (DRAM); total throughput = 2 N logN

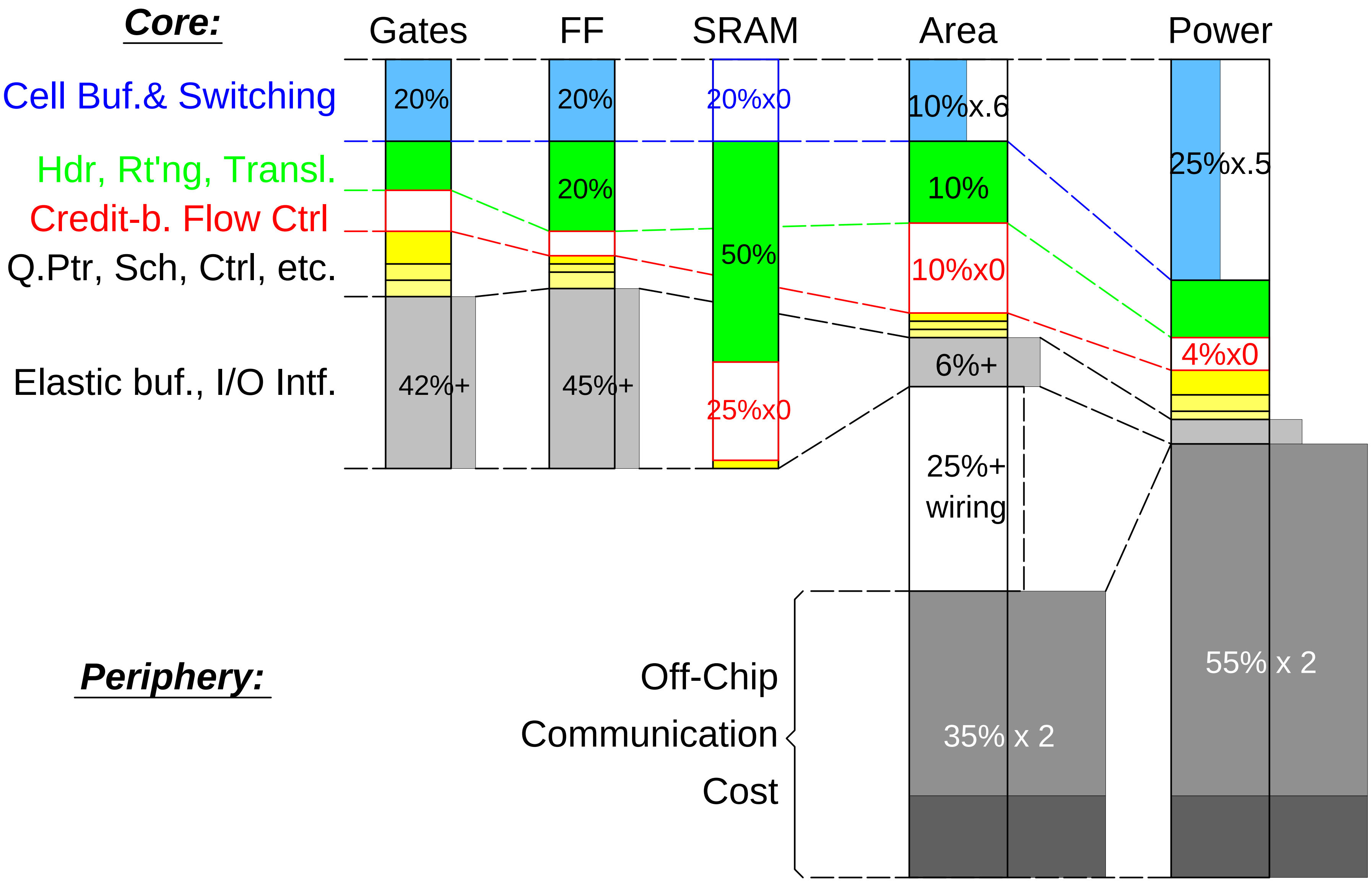
Switching Fabrics without Backpressure 2: Internal Speedup



speedup s>1; under bursty or non-uniform traffic: s>>1...

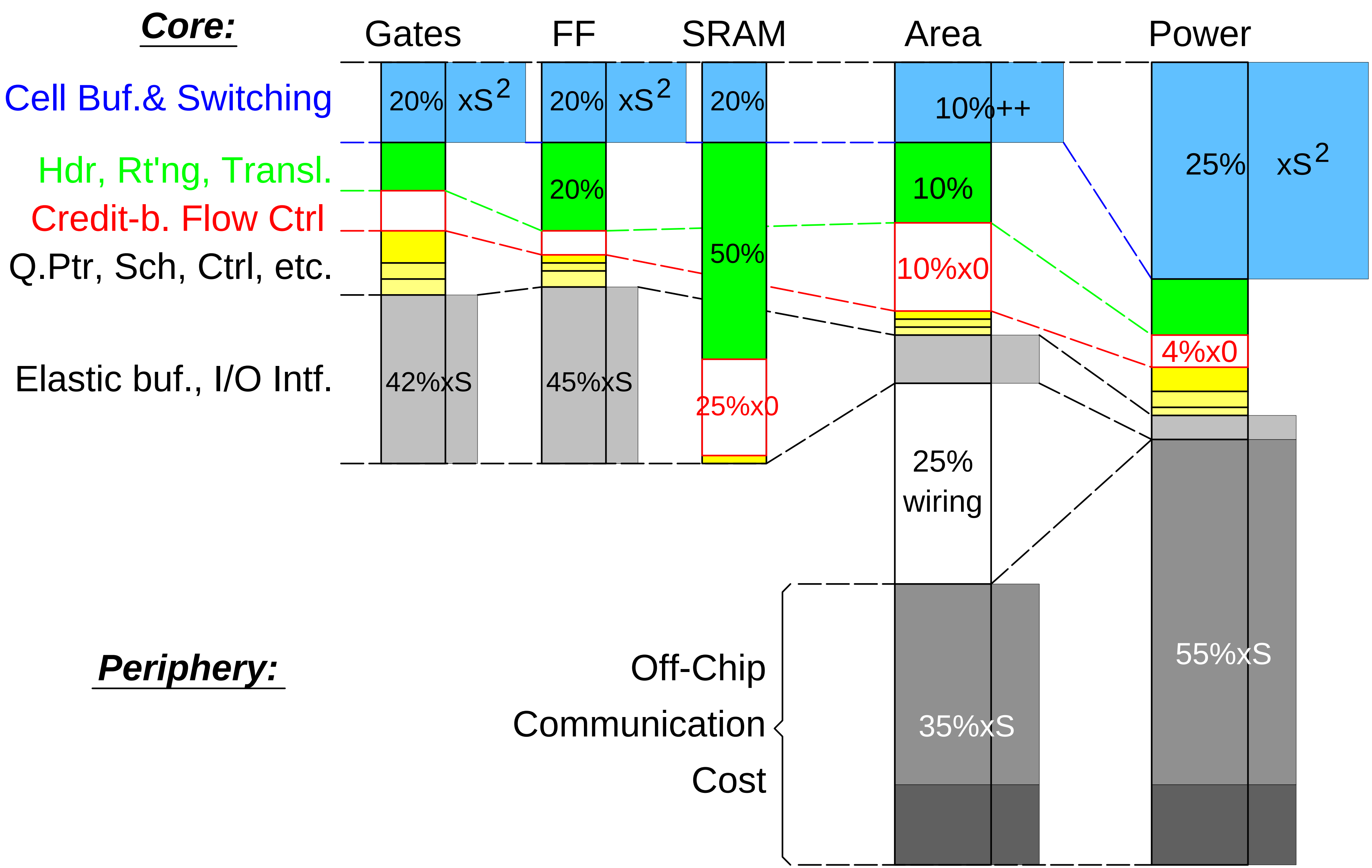
Backpressure Cost/Benefit 1:

No Backpressure, Large Off-Chip Buffers



Backpressure Cost/Benefit 2:

No Backpressure, Internal Speedup, Output Queues



Regional Explicit Congestion Notification (RECN)

- Generalization & evolution of the ATLAS/QFC protocol
- Source-routing header describes path through fabric
- Intermediate or final link congestion sends back-notification
- All packets to congested link confined to a single lane
  - intermediate links identified via path component in header

    ⇒ entire trees of destinations in single lane (improvement over QFC)
  - equivalent of lane here called *“Set-Aside Queue”* (SAQ)
- VOQ’s replaced by Single (!) Input Queue + SAQ’s
  - dynamically create/delete SAQ’s
  - CAM assumed to match incoming pck header versus current SAQ’s
- Duato, Johnson, Flich, Naven, Garcia, Nachiondo: “A New Scalable and Cost-Effective Congestion Management Strategy for Lossless Multistage Interconnection Networks”, HPCA-11, San Francisco, USA, Feb. 2005.

Request-Grant Protocols

- Consider a buffer feeding an output link, and receiving traffic from multiple sources:
- If credits are pre-allocated to each source, the buffer needs to be as large as one RTT-window per source;
- If credits are “held” at buffer and only allocated to requesting source(s) when these have something to transmit, then a single RTT-window suffices for all sources!

  $\Rightarrow$ economize on buffer space at the cost of longer latency

- N. Chrysos, M. Katevenis: “Scheduling in Switches with Small Internal Buffers”, IEEE Globecom 2005, St. Louis, USA, Nov. 2005;

  N. Chrysos, M. Katevenis: “Scheduling in Non-Blocking Buffered Three-Stage Switching Fabrics”, IEEE Infocom 2006, Barcelona, Spain, Apr. 2006; http://archvlsi.ics.forth.gr/bpbenes/

Buffer Space for Bounded Peak-to-Average Rate Ratio

- Assume $R_{peak}(i) / R_{average}(i) \leq PAR$ for all flows *i* on a link
  - $R(i)$ is the rate (throughput) of flow *i*
  - *PAR* is a constant: peak-to-average ratio bound
  - interpretation: rate fluctuation is bounded by *PAR*
- Each flow *i* needs a credit window of $RTT \cdot R_{peak}(i)$
- Buffer space for all flows is $\sum (RTT \cdot R_{peak}(i)) =$

$$= RTT \cdot \sum(R_{peak}(i)) \leq RTT \cdot \sum(PAR \cdot R_{average}(i)) =$$

$$= PAR \cdot RTT \cdot \sum(R_{average}(i)) \leq PAR \cdot (RTT \cdot R_{link})$$

$\Rightarrow$ Allocate buffer space = *PAR* number of "windows"
When individual flow rates change, rearrange the allocation of buffer space between flows –but must wait for the buffer of one flow to drain before rallocating it (not obvious how to)

- H.T. Kung, T. Blackwell, A. Chapman: "Credit-Based Flow Control for ATM Networks: Credit Update Protocol, Adaptive Credit Allocation, and Statistical Multiplexing", SIGCOMM '94, pp. 101-114.

Dynamically Sharing the Buffer Space among Flows

- In order to depart, a packet must acquire both:
  - a per-flow credit (to guard against “buffer hogging”), and
  - a per-link credit (to ensure that the shared buffer does not overflow)
- Properly manage (increase or decrease) the per-flow window allocation based on traffic circumstances:
  - ATLAS and QFC protocols never change the per-flow window
  - H.T.Kung protocol moves allocations between flows (unclear how)
  - other idea: use two window sizes –a “full” one and a “small” one; use full-size windows when total buffer occupancy is below a threshold, use small-size windows (for all flows) above that point (flows that had already filled more than a small window will lose their allocation on packet departure) – C. Ozveren, R. Simcoe, G. Varghese: “Reliable and Efficient Hop-by-Hop Flow Control”, IEEE JSAC, May 1995.
- Draining Rate Theorem: M. Katevenis: “Buffer Requirements of Credit-Based Flow Control when a Minimum Draining Rate is Guaranteed”, HPCS'97; ftp://ftp.ics.forth.gr/tech-reports/1997/1997.HPCS97.drain_cr_buf.ps.gz

Communication Cost versus Buffer/Logic Cost

- On-Chip: millions of transistors - hundreds of pins
- Off-Chip: data from Hot Interconnects '95 keynote speech, by A. Fraser, VP, AT&T Bell Labs:

speed of transmission line	45	Mb/s
cost of long distance xmission	45	$/mile/month
speed of signal propagation	7	microsec/mile
round-trip window size	79	bytes/mile
cost of 16 MByte DRAM	1000	$
cost of window size memory	0.5	cents/mile
investment write-down period	36	months
cost of queue mem. per month	0.014	cents/mile/month

ratio: transmission/memory cost 330,000 to 1

Per-Connection Queueing & FC:

How many ``Windows'' of Buffer Space?

- windowSize(VCi) = RTT * peakThroughput(VCi)

  ⇒ windowSize(VCi) < or << windowL := RTT * throughput(Link)
- cost(Link) ~= 330,000 * cost(windowL)
- lossy flow control usually operates the network with goodput reaching up to 70 - 80 % of link throughput
- lossless flow control operates up to 98 - 100 % link utilization
- the 20-30 % extra utilization with lossless FC is worth approx. 10 to 100 thousand windowL's worth of extra buffer memory

⇒ if lossless flow control can yield its link utilization advantage with less than a few tens of thousands of windowL's of extra buffer memory, then lossless flow control is a clear win

- indeed, lossless FC can do that, even with quite less buffer space...