Lecture 1:

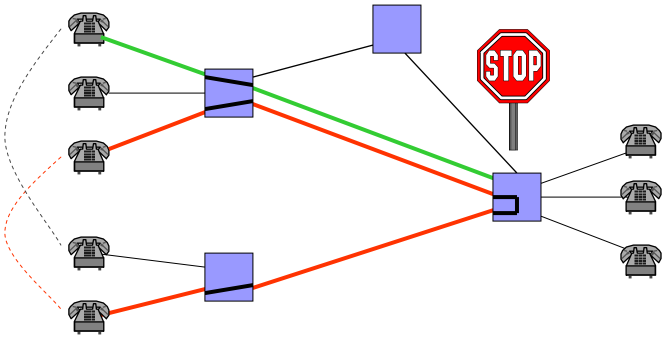
Basic switching concepts

circuit switching
message switching
packet switching

Switching

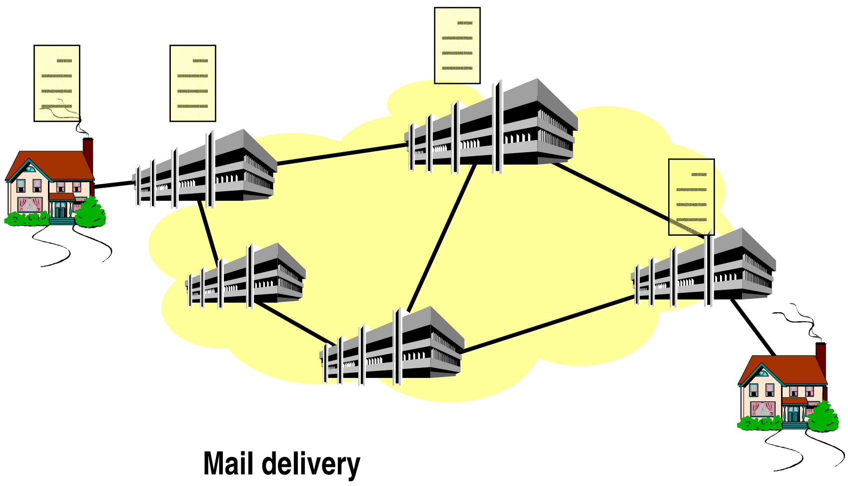
- **Circuit Switching**
  - Fixed and mobile telephone network
    - Frequency Division Multiplexing (FDM)
    - Time Division Multiplexing (TDM)
  - Optical rings (SDH)
- **Message Switching**
  - Not in core technology
  - Some application (e.g. SMTP)
- **Packet Switching**
  - Internet
  - Some core networking technologies (e.g. ATM)

Circuit Switching



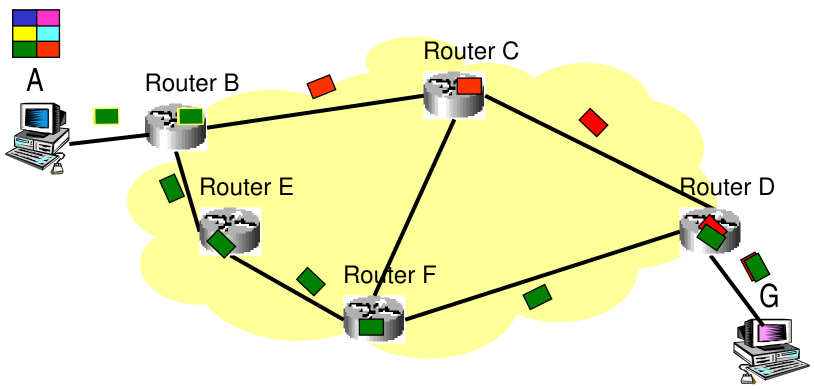
Phone Call routing

Message Switching



Mail delivery

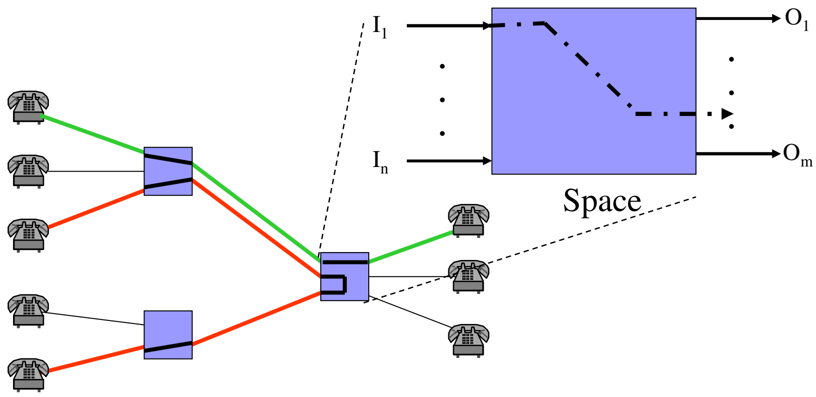
Packet Switching



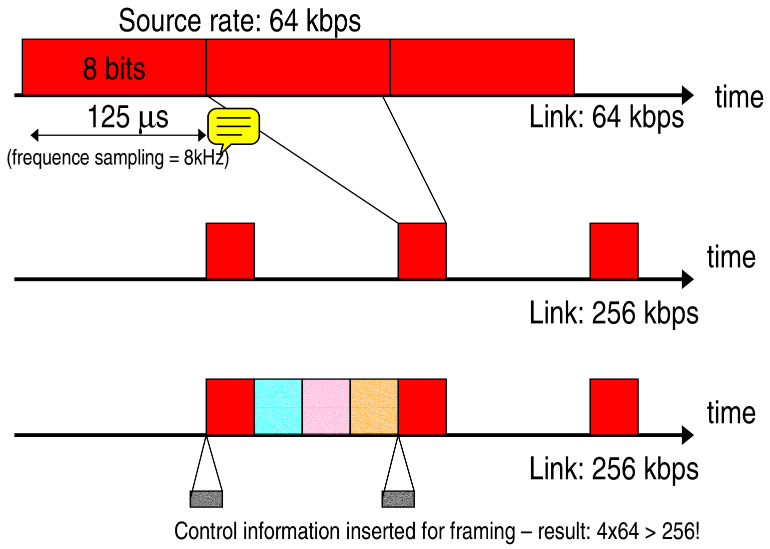
Internet routing

Space Division Switching
(for Circuit Switching)

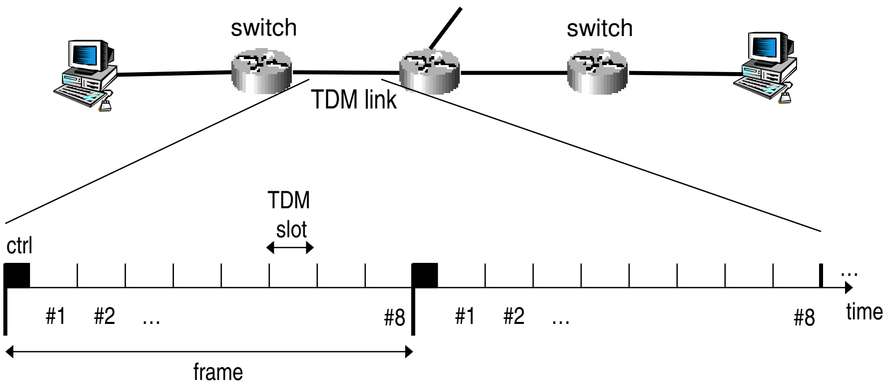
➔ **Spatial mapping of inputs and outputs**
- ⇨ Used primarily in analog switching systems



Time Division Multiplexing

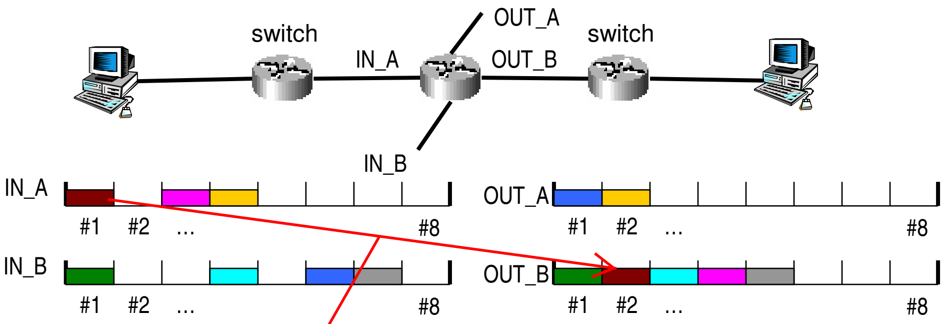


Circuit Switching (i)



Time Division Multiplexing

Circuit Switching (ii)



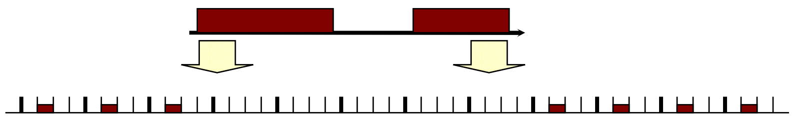
SWITCHING TABLE

IN	OUT
A,1	B,2
A,3	B,4
A,4	A,2
B,1	B,1
B,4	B,3
B,6	A,1
B,7	B,5

Table setup: upon signalling

Circuit Switching Pros & Cons

- ➔ **Advantages**
  - ⇨ Limited overhead
  - ⇨ Very efficient switching fabrics
    - → Highly parallelized
- ➔ **Disadvantages**
  - ⇨ Requires signalling for switching tables set-up
  - ⇨ Underutilization of resources in the presence of bursty traffic and variable rate traffic



Bandwidth waste

Example of bursty traffic (ON/OFF voice flows)

VOICE SOURCE MODEL for conversation (Brady):
average ON duration (talkspurt): 1 second
average OFF duration (silence): 1.35 seconds

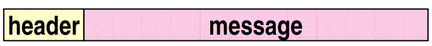
$$activity = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{1}{1+1.35} = 42.55\% \quad \text{(before packetization)}$$

Efficiency = utilization % = source activity

Message vs Packet Switching

➔Message Switching

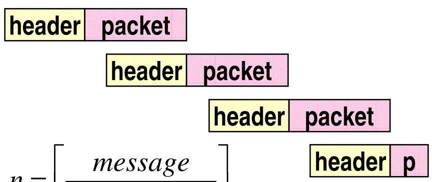
- ⇨ One single datagram



$$overhead = \frac{header}{header + message}$$

➔Packet Switching

- ⇨ Message chopped in small packets
- ⇨ Each packet includes header
  - ➔like postal letters! Each must have a specified destination data



$$n = \left\lceil \frac{message}{packet\_size} \right\rceil$$

$$overhead = \frac{n \cdot header}{n \cdot header + message}$$

Message switching overhead lower than packet switching

Message vs Packet Switching

➔ **Message Switching**

- ➪ One single datagram
  - →either received or lost
  - →One single network path

➔ **Packet Switching**

- ➪ Many packets generated by a same node and belonging to a same destination
  - → may take different paths (and packets received out of order – need sequence)
  - →May lose/corrupt a subset (what happens on the message consistency?)

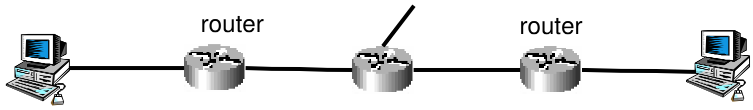
Message switching: higher reliability, lower complexity

header	message

header	packet
header	packet
header	packet
header	p

But sometimes message switching not possible (e.g. for real time sources such as voice)

Message/packet Switching vs circuit switching



header	mesg/pack

Router:

- reads header (destination address)
- selects output path

➔ **Advantages**

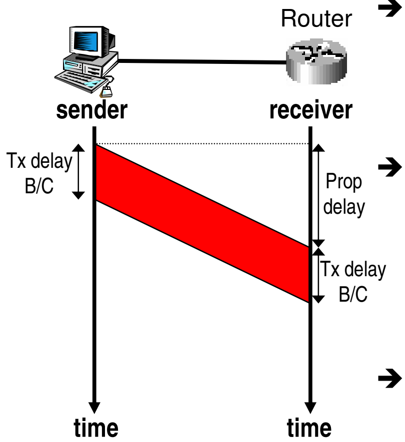
- ➪ Transmission resources used only when needed (data available)
- ➪ No signalling needed

➔ **Disadvantages**

- ➪ Overhead
- ➪ Inefficient routing fabrics (needs to select output per each packet)
- ➪ Processing time at routers (routing table lookup)
- ➪ Queueing at routers

Link delay computation

- ➔ **Delay components:**
  - →Processing delay
  - →Transmission delay
  - →Queueing delay
  - →Propagation delay



- ➔Transmission delay:
  - ➔C [bit/s] = link rate
  - ➔B [bit] = packet size
  - ➔transmission delay = B/C [sec]
- ➔Example:
  - ➔512 bytes packet
  - ➔64 kbps link
  - ➔transmission delay = 512*8/64000 = 64ms
- ➔Propagation delay - constant depending on
  - ➔Link length
  - ➔Electromagnetig waves propagation speed in considered media
    - ➔200 km/s for copper links
    - ➔300 km/s in air
- ➔other delays neglected
  - ➔Queueing delay
  - ➔Processing delay

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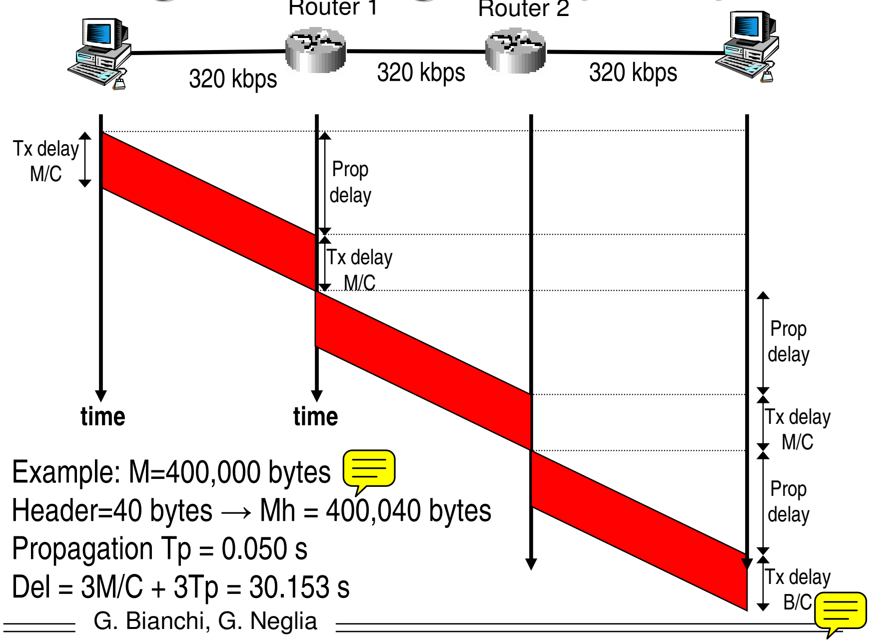
Message Switching – delay analysis



Example: M=400,000 bytes
Header=40 bytes → Mh = 400,040 bytes
Propagation Tp = 0.050 s
Del = 3M/C + 3Tp = 30.153 s

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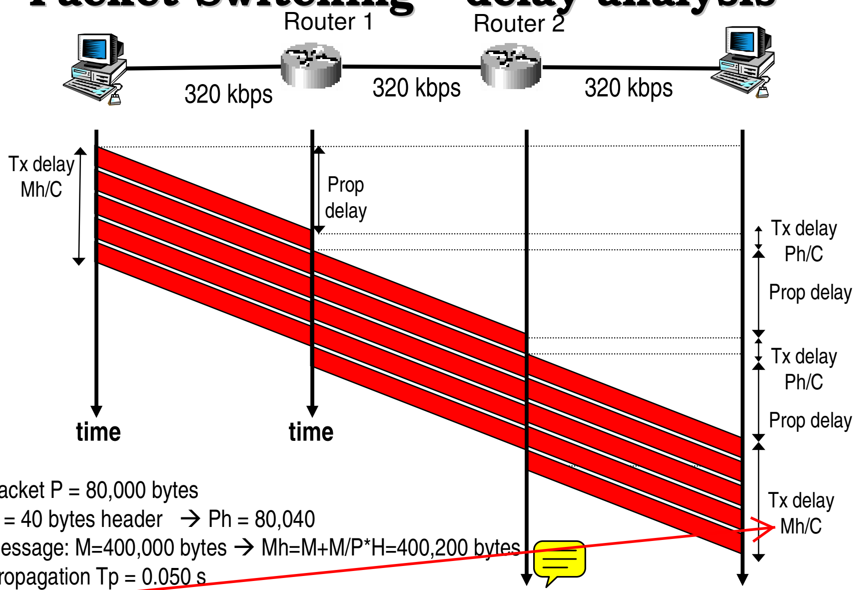
Packet Switching – delay analysis

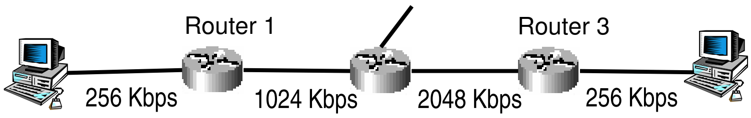


Packet P = 80,000 bytes
H = 40 bytes header → Ph = 80,040
Message: M=400,000 bytes → Mh=M+M/P*H=400,200 bytes
Propagation Tp = 0.050 s
Del = Mh/C + 3Tp + 2Ph/C = 14.157 s

But if packet size = 40 bytes, Del = 20.154s!

Other example

(different link speed)

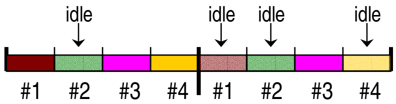


- **Time to transmit 1 MB file**
- **Message switching (assume 40 bytes header)**
  - 1MB = 1024*1024 bytes = 1,048,576 bytes = 8,388,608 bits
  - Including 40 bytes (320 bits) header: 8,388,928
  - Neglecting processing, propagation & queueing delays:
    - →D = 32.76 + 8.19 + 4.10 + 32.77 = 77.83s
- **Packet switching (40 bytes header, 1460 bytes packet)**
  - 718.2 → 719 packets
  - total message size including overhead = 8,618,688 bits
  - Just considering transmission delays (slowest link = last – try with intermediate, too)
    - →D = + 33.67 =33.73s
- **Key advantage: pipelining reduces end to end delay versus message switching!**

Statistical Multiplexing

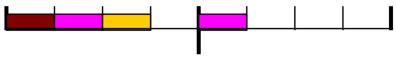
the advantage of packet switching

Circuit switching:
Each slot uniquely
Assigned to a flow



Full capacity does not imply full utilization!!

Packet switching:
Each packet grabs
The first slot available



More flows than nominal capacity may be admitted!!

Packet Switching overhead vs burstiness

Overhead for voice sources at 64 kbps

Source rate: 64 kbps
during 16 ms 128 voice samples = 1024 bit every 16 ms ⟷ 62.5 packets/s
Assumption: 40 bytes header

$$\text{emission rate} = 62.5 \cdot (1024 + 40 \cdot 8) = 84000$$

$$(\text{versus } 64000 \text{ nominal rate} = 31.25\% \text{ overhead})$$

PACKETIZATION for voice sources (Brady model, activity=42.55%):

Assumptions: neglect last packet effect

$$\text{average emission rate} = 62.5 \cdot (1024 + 40 \cdot 8) \cdot 0.4255 = 35745$$

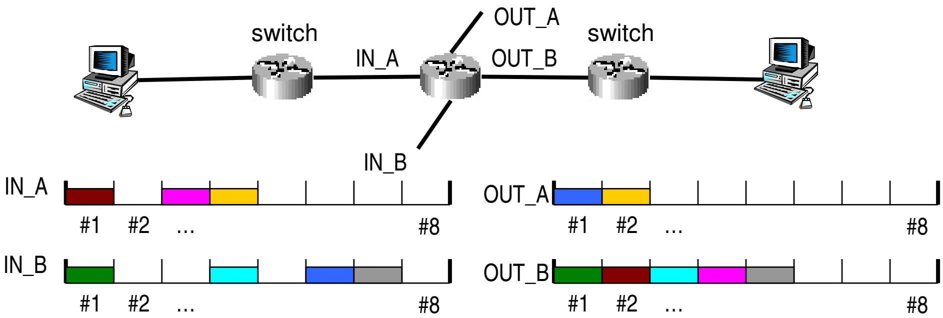
$$(\text{versus } 64000 \text{ nominal rate} = 55.85\%)$$ Overhead > lower than data rate

Packet switching overhead

header	packet

- ➔ **Header: contains lots of information**
  - ⇨ Routing, protocol-specific info, etc
  - ⇨ Minimum: 28 bytes; in practice much more than 40 bytes
    - → Overhead for every considered protocol: (for voice: 20 bytes IP, 8 bytes UDP, 12 bytes RTP)
- ➔ **Question: how to minimize header while maintaining packet switching?**
- ➔ **Solution: label switching (virtual circuit)**
  - ⇨ ATM
  - ⇨ MPLS

Circuit Switching (again)



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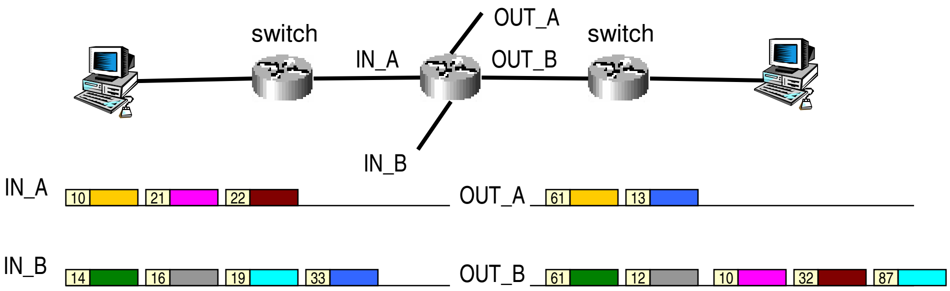
B,6	A,1
B,7	B,5

Switching table: route packet coming from Input A, position 1 to output B position 2

A1, B2 = physical slots, can be used only by THAT source.
Let them be "virtual" (labels on packet!)

Label Switching (virtual circuit)



LABEL SWITCHING TABLE

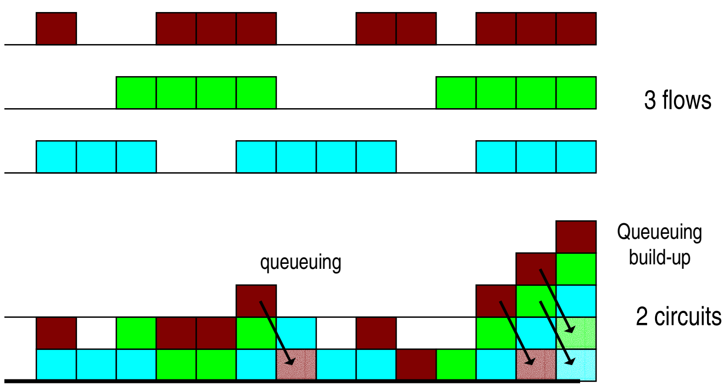
Label-IN	OUT	Label-OUT
10	A	61
14	B	61
16	B	12
19	B	87
21	B	10
22	B	32
33	A	13

Condition: labels unique @ input

Advantage: labels very small!!
(ATM technology overhead:
only 5 bytes for all info!)

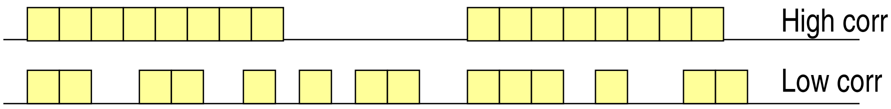
KEY advantage: no reserved phy slots!
(asynchronous transfer mode vs synchronous)

Statistical mux efficiency
(for simplicity, fixed-size packets)



Statistical mux analysis

- **➔Very complex, when queueing considered**
  - ⇨Involves queueing theory
  - ⇨Involves traffic time correlation statistics



- **➔Very easy, in the (worst case = conservative) assumption of unbuffered system**
  - ⇨In practice, burst size long with respect to buffer size
- **➔Depends only on activity factor ρ**

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(SKIP from now)

Statistical mux analysis (i)
unbuffered model

N traffic sources; Homogeneous, same activity factor ρ
Source rate = 1; Link capacity = C
TDM: N <u>must</u> be <= C Packet: N may be > C

$$\text{Prob}(\text{k sources simultaneously active}) = \binom{N}{k} \rho^k (1-\rho)^{N-k}$$

Example: N=5; each having 20% activity

0	32.77%
1	40.96%
2	20.48%
3	5.12%
4	0.64%
5	0.03%

Average load = 5*0.2 = 1
But C=1 appears insufficient…

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Statistical mux analysis (ii)
unbuffered model

- **Overflow probability**
  - Probability that, at a given instant of time (random), the link load is greater than the link capacity
  - Implies packet loss if buffer=0

$$overflow\_prob = \sum_{k=C+1}^{N} \binom{N}{k} \rho^k (1-\rho)^{N-k} =$$

$$= 1 - \sum_{k=0}^{C} \binom{N}{k} \rho^k (1-\rho)^{N-k}$$

Example: N=5;
each having 20% activity;

link capacity	overflow prob
0	67.23%
1	26.27%
2	5.79%
3	0.67%
4	0.03%
5	0.00%

Statistical mux analysis (iii)
unbuffered model

- **Packet loss probability**
  - Number of lost packets over number of offered packets
- **Offered packets**
  - N * average number of offered packets per source = N * ρ
- **Lost packets:**
  - If k <= C active sources, no packet loss
  - If k > C, k-C lost packets
- **hence**

Example: N=5; each having 20% activity;
N ρ = 1

k or C	p(k)	k*p(k)	overflow(C)	**loss(C)**
0	32.77%	0	*67.23%*	**100.00%**
1	40.96%	0.4096	*26.27%*	**32.77%**
2	20.48%	0.4096	*5.79%*	**6.50%**
3	5.12%	0.1536	*0.67%*	**0.70%**
4	0.64%	0.0256	*0.03%*	**0.03%**
5	0.03%	0.0016	*0.00%*	**0.00%**

$$Ploss = \frac{\sum_{k=C+1}^{N} (k-C) \binom{N}{k} \rho^k (1-\rho)^{N-k}}{N\rho} =$$

$$= \frac{1}{N\rho} \sum_{k=C+1}^{N} k \binom{N}{k} \rho^k (1-\rho)^{N-k} - \frac{C}{N\rho} P(overflow)$$

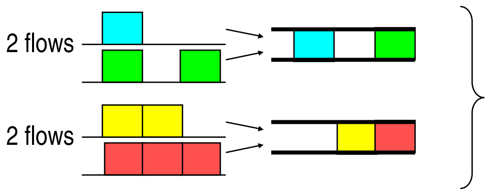
Loss vs overflow

k or C	binom	p(k)	k * p(k)	overflow(C)	loss(C)
0	1	1,2E-03	0,0E+00	9,99E-01	1,00E+00
1	30	9,3E-03	9,3E-03	9,89E-01	8,34E-01
2	435	3,4E-02	6,7E-02	9,56E-01	6,69E-01
3	4060	7,9E-02	2,4E-01	8,77E-01	5,09E-01
4	27405	1,3E-01	5,3E-01	7,45E-01	3,63E-01
5	142506	1,7E-01	8,6E-01	5,72E-01	2,39E-01
6	593775	1,8E-01	1,1E+00	3,93E-01	1,44E-01
7	2035800	1,5E-01	1,1E+00	2,39E-01	7,81E-02
8	5852925	1,1E-01	8,8E-01	1,29E-01	3,82E-02
9	14307150	6,8E-02	6,1E-01	6,11E-02	1,68E-02
10	30045015	3,5E-02	3,5E-01	2,56E-02	6,57E-03
11	54627300	1,6E-02	1,8E-01	9,49E-03	2,30E-03
12	86493225	6,4E-03	7,7E-02	3,11E-03	7,18E-04
13	119759850	2,2E-03	2,9E-02	9,02E-04	2,00E-04
14	145422675	6,7E-04	9,4E-03	2,31E-04	4,94E-05
15	155117520	1,8E-04	2,7E-03	5,24E-05	1,08E-05
16	145422675	4,2E-05	6,7E-04	1,05E-05	2,11E-06
17	119759850	8,6E-06	1,5E-04	1,84E-06	3,62E-07
18	86493225	1,6E-06	2,8E-05	2,84E-07	5,46E-08
19	54627300	2,5E-07	4,7E-06	3,83E-08	7,21E-09
20	30045015	3,4E-08	6,8E-07	4,48E-09	8,28E-10
21	14307150	4,0E-09	8,5E-08	4,50E-10	8,20E-11
22	5852925	4,1E-10	9,1E-09	3,86E-11	6,92E-12
23	2035800	3,6E-11	8,2E-10	2,78E-12	4,91E-13
24	593775	2,6E-12	6,3E-11	1,65E-13	2,88E-14
25	142506	1,6E-13	3,9E-12	7,82E-15	1,35E-15
26	27405	7,5E-15	2,0E-13	2,87E-16	4,91E-17
27	4060	2,8E-16	7,5E-15	7,60E-18	1,29E-18
28	435	7,5E-18	2,1E-16	1,30E-19	2,18E-20
29	30	1,3E-19	3,7E-18	1,07E-21	1,79E-22
30	1	1,1E-21	3,2E-20	0,00E+00	0,00E+00

Example: N=30;
each 20% activity;
N ρ = 6

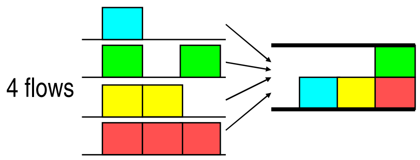
for C>>Nρ:
Overflow=good approx for loss.

Statistical Mux Gain (i)



Average load = 4 ρ
C = 2

$$Ploss_1 = \frac{1\times 1\times \rho^2}{2\rho} = \frac{\rho}{2}$$

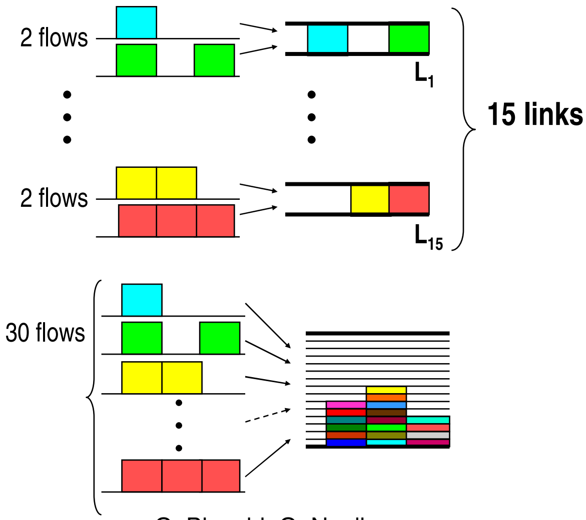


Average load = 4 ρ
C = 2

$$Ploss_2 = \frac{1\times 4\times \rho^3(1-\rho)+2\times 1\times \rho^4}{4\rho}$$
$$= \frac{\rho^2(2-\rho)}{2} < Ploss_1$$

A sample-path argument is faster!

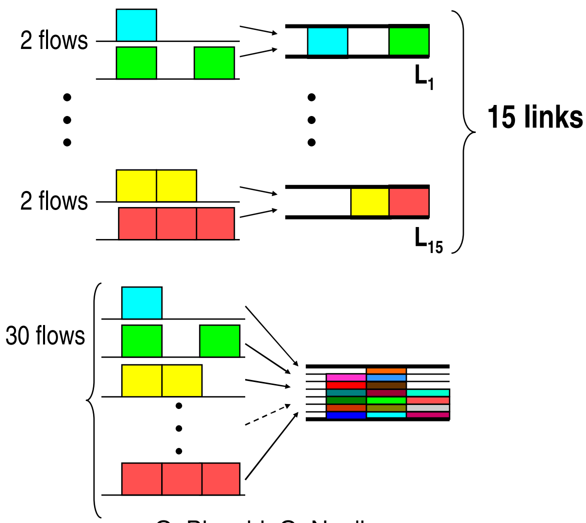
Statistical Mux Gain (ii)



ρ = 20%
Average load = 6
C = 15
$Ploss_1 = 0.1$

ρ = 20%
Average load = 6
C = 15
$Ploss_2 = 1.08 \times 10^{-5}$

Statistical Mux Gain (iii)



ρ = 20%
Average load = 6
C = 15
$Ploss_1 = 0.1$

ρ = 20%
Average load = 6
C = 7
$Ploss_2 = 0.0781$

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