## Lecture 1:

## Basic switching concepts

*circuit switching*
*message switching*
*packet switching*

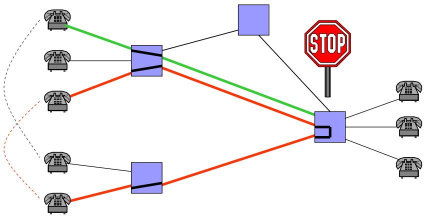


## Switching

- **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)

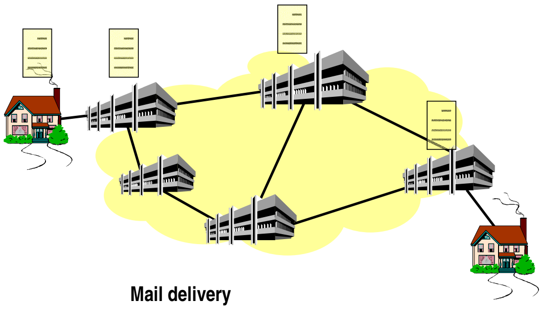


## Circuit Switching




Phone Call routing

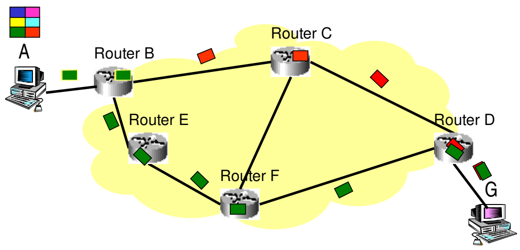
## Message Switching



Mail delivery



## Packet Switching

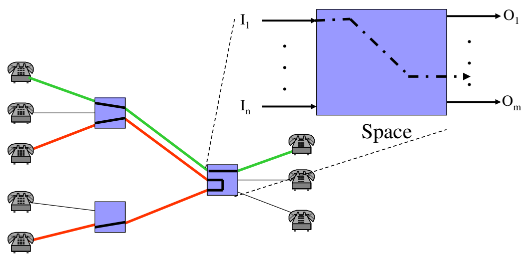



Internet routing

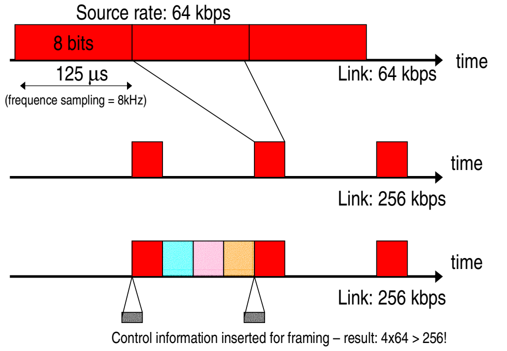


## Space Division Switching
**(for Circuit Switching)**

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



# Time Division Multiplexing

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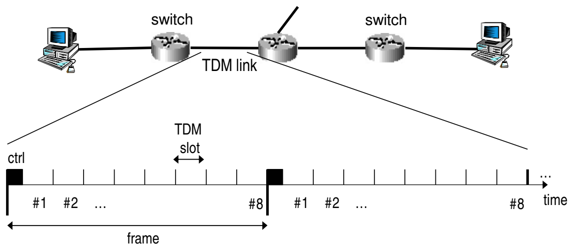
# Circuit Switching (i)




Time Division Multiplexing

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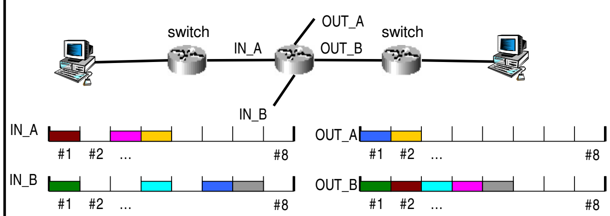
# Circuit Switching (ii)




SWITCHING TABLE

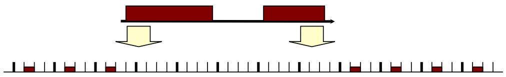
| IN | OUT |
|---|---|
| A,1 | B,2 |
| A,3 | B,4 |
| A,4 | A,2 |
| B,1 | B,1 |
| B,4 | B,3 |
| B,6 | A,1 |
| B,7 | B,5 |

Table setup: upon signalling

G. Bianchi, G. Neglia

## 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

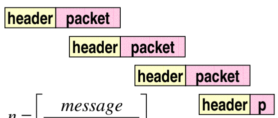


## Message vs Packet Switching

- **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***

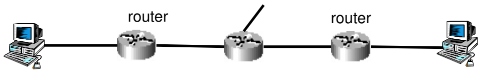
header | message

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

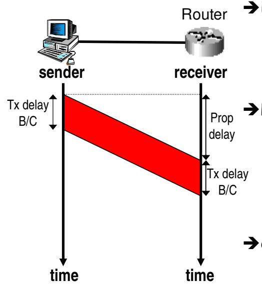
Router:
- reads header (destination address)
- selects output path

- **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



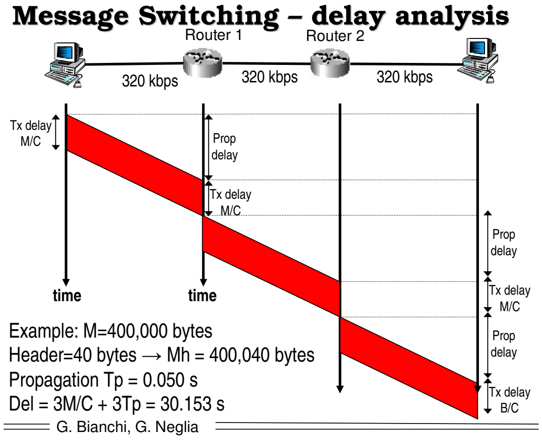
## Link delay computation

- **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

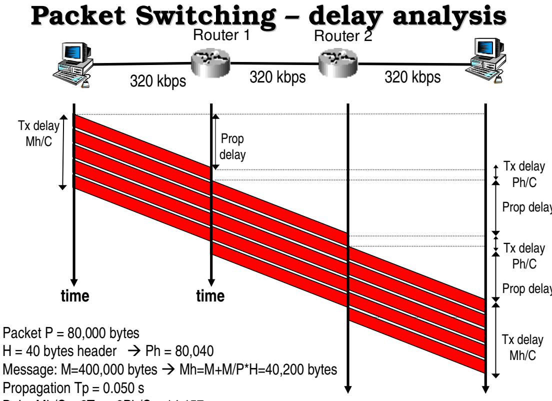
## Message Switching – delay analysis




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



## Packet Switching – delay analysis

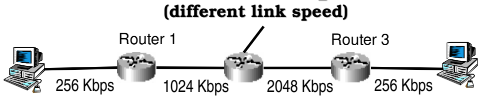



Packet P = 80,000 bytes
H = 40 bytes header → Ph = 80,040
Message: M=400,000 bytes → Mh=M+M/P*H=40,200 bytes
Propagation Tp = 0.050 s
Del = Mh/C + 3Tp + 2Ph/C = 14.157 s

**But if packet size = 40 bytes, Del = 20,154s!**



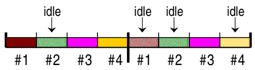
## Other example
### (different link speed)




- **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 = 0.06 + 33.67 =33.73s
- **Key advantage: pipelining reduces end to end delay versus message switching!**

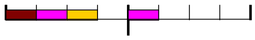
# Statistical Multiplexing
## the advantage of packet switching

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
in 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%):**

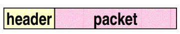
Assumptions: neglect last packet effect

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

$$(\text{versus } 64000 \text{ nominal rate} = 55.85\%)$$

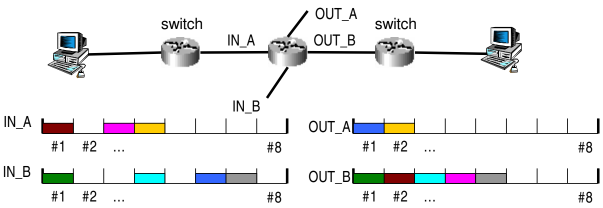


# Packet switching overhead




- ➔ **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)




SWITCHING TABLE

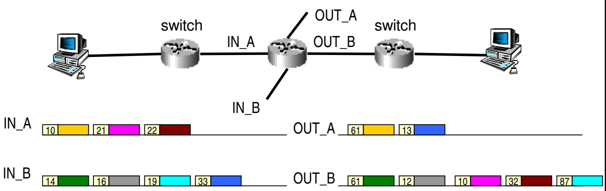
| IN | OUT |
|---|---|
| A,1 | B,2 |
| A,3 | B,4 |
| A,4 | A,2 |
| B,1 | B,1 |
| B,4 | B,3 |
| B,6 | A,1 |
| B,7 | B,5 |

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 |

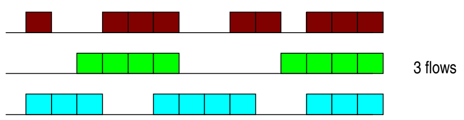
Condition: labels unique @ input

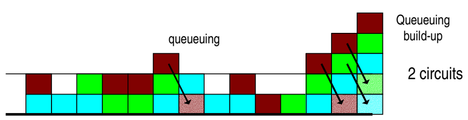
Advantage: labels very small!!
(ATM technology overhead:
only 5 bytes for all info!)

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



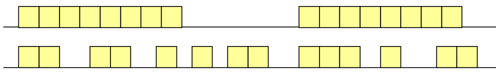
# Statistical mux efficiency
## (for simplicity, fixed-size packets)



## 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**



## 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

| number of active sources | probability |
|---|---|
| 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…



## 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 | loss |
|---|---|---|---|---|
| 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

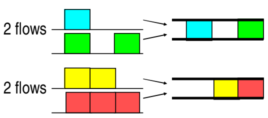
| k (or C) | binom | p(k) | k * p(k) | overflow | loss |
|---|---|---|---|---|---|
| 0 | 1 | 1,2E-03 | 0,0E+00 | 9,99E-01 | 1,00E+00 |
| 1 | 30 | 9,3E-03 | 9,3E-03 | 9,89E-01 | 8,34E-01 |
| 2 | 435 | 3,4E-02 | 6,7E-02 | 9,56E-01 | 6,69E-01 |
| 3 | 4060 | 7,9E-02 | 2,4E-01 | 8,77E-01 | 5,09E-01 |
| 4 | 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.

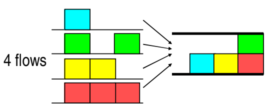


# Statistical Mux Gain (i)




Average load = 4 $\rho$
C = 2

$$Ploss_1 = \frac{1\times1\times\rho^2}{2\rho} = \frac{\rho}{2}$$



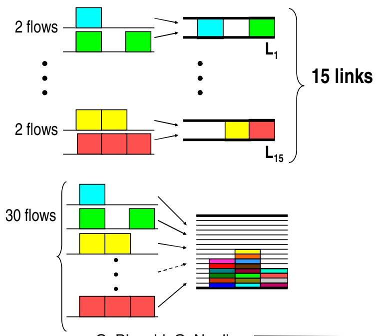

Average load = 4 $\rho$
C = 2

$$Ploss_2 = \frac{1\times4\times\rho^3(1-\rho)+2\times1\times\rho^4}{4\rho}$$

$$= \frac{\rho^2(2-\rho)}{2} < Ploss_1$$

**A sample-path argument is faster!**

## Statistical Mux Gain (ii)

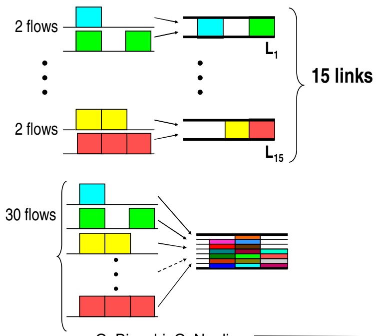



$\rho$ = 20%
Average load = 6
C = 15
$Ploss_1 = 0.1$

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



## Statistical Mux Gain (iii)




$\rho$ = 20%
Average load = 6
C = 15
$Ploss_1 = 0.1$

$\rho$ = 20%
Average load = 6
**C = 7**
$Ploss_2 = 0.0781$

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