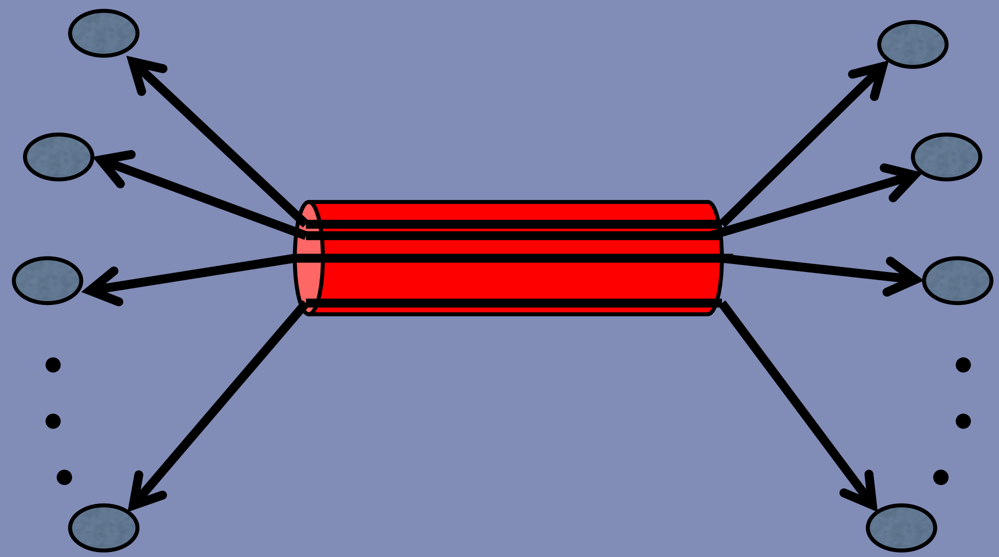
Multiplexing

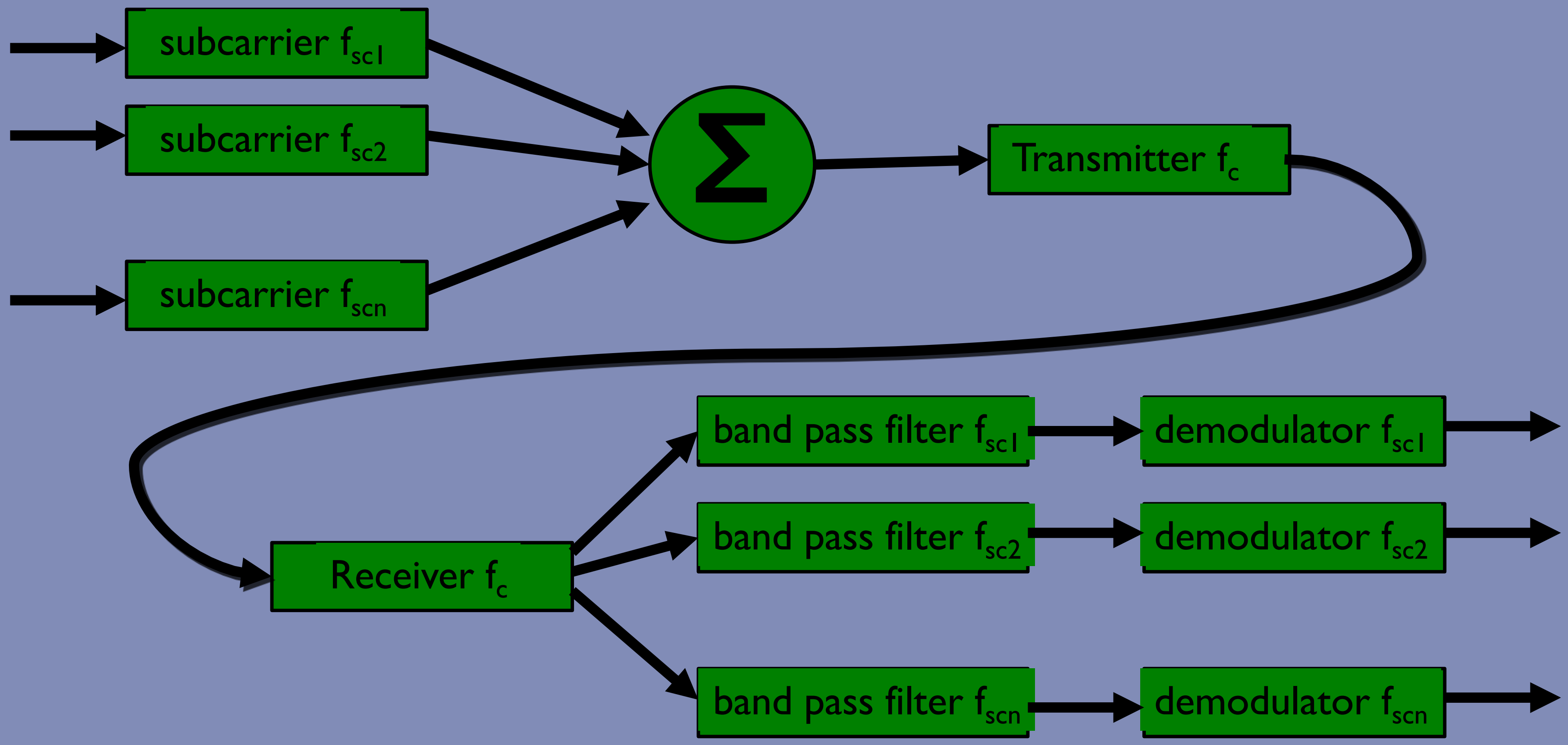
"From one channel to multiple channels"

How to share one medium while facilitating multiple channels of communication:



Frequency Division and Time Division Multiplexing

Frequency Division Multiplexing (FDM alla FSK)



Standards

# voice channel	bandwidth	spectrum	US/AT&T	ITU_T
12	48 kHz	60-108 kHz	Group	Group
60	240 kHz	312-552 kHz	Super Group	Super Group
300	1,23 MHz	812-2044 kHz	Super Group	Master Group
600	2,52 MHz	564-3084 kHz	Master Group	Master Group
900	3,87 MHz	8,52-12.39 MHz	Master Group	Super Master Group
3600	16,98 MHz	0.56-17,55 MHz	Jumbo Group	Jumbo Group
10800	57,44 MHz	3,12-60,57 MHz	Jumbo Group Multiplexed	Jumbo Group Multiplexed

Example: ADSL

ADSL Asymmetric Digital Subscriber Line

Originally for Video-on-Demand: less control going up – lots of image going down

➔ Very similar to internet usage !!!!!!!

Multiple "regular" phone connections at the same time on which QAM (Quadratic Amplitude Modulation) is implemented

- Reserve lowest 25 kHz for Voice (POTS, Plain Old Telephone Service) 25 instead of 5 to prevent cross talk between voice&data
- Facilitate two bands: small upstream / big downstream
- Use FDM within upstream and downstream band

ADSL 4 kHz channels

Frequency plan for ADSL Annex A. Red area is the frequency range used by normal voice telephony (PSTN), the green (upstream) and blue (downstream) areas are used for ADSL.

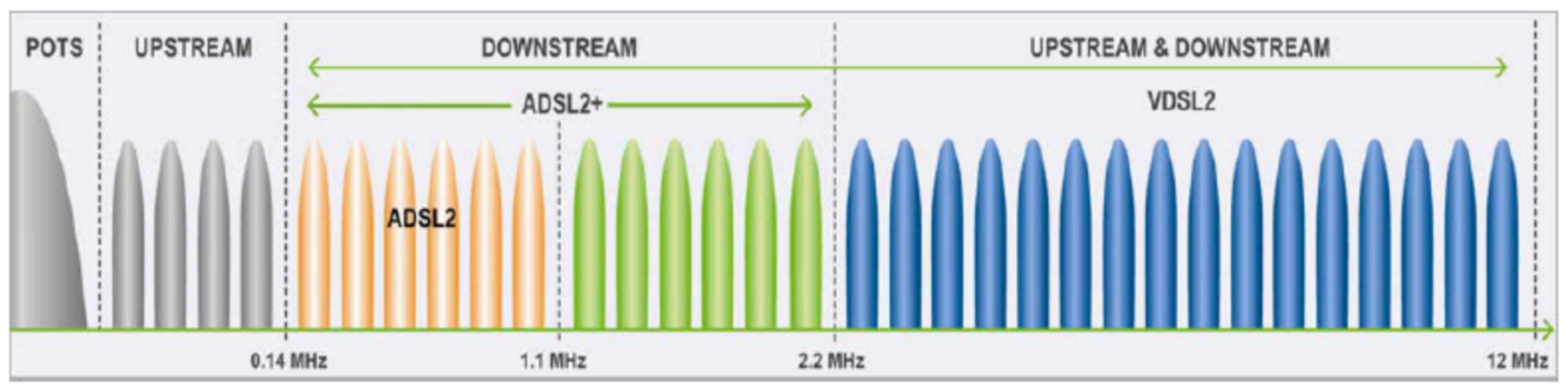
ADSL standards

Version	Standard name	Common name	Downstream rate	Upstream rate	Approved in
ADSL	ANSI T1.413-1998 Issue 2	ADSL	8.0 Mbit/s	1.0 Mbit/s	1998
ADSL	ITU G.992.1	ADSL (G.DMT)	12.0 Mbit/s	1.3 Mbit/s	1999-07
ADSL	ITU G.992.1 Annex A	ADSL over POTS	12.0 Mbit/s	1.3 Mbit/s	2001
ADSL	ITU G.992.1 Annex B	ADSL over ISDN	12.0 Mbit/s	1.8 Mbit/s	2005
ADSL	ITU G.992.2	ADSL Lite (G.Lite)	1.5 Mbit/s	0.5 Mbit/s	1999-07
ADSL2	ITU G.992.3	ADSL2	12.0 Mbit/s	1.3 Mbit/s	2002-07
ADSL2	ITU G.992.3 Annex J	ADSL2	12.0 Mbit/s	3.5 Mbit/s	
ADSL2	ITU G.992.3 Annex L	RE-ADSL2	5.0 Mbit/s	0.8 Mbit/s	
ADSL2	ITU G.992.4	splitterless ADSL2	1.5 Mbit/s	0.5 Mbit/s	2002-07
ADSL2+	ITU G.992.5	ADSL2+	24.0 Mbit/s	1.1 Mbit/s	2003-05
ADSL2+	ITU G.992.5 Annex M	ADSL2+M	24.0 Mbit/s	3.3 Mbit/s	2008

VDSL

- ADSL has been succeeded over the last years by **Very High Bit Rate Digital Subscriber Line** (VDSL), and **Very High Bit Rate Digital Subscriber Line 2** (VDSL2)

- Main difference: up to 12 MHz FDM instead of 1 MHz and use "noise cancellation techniques"



Version	Standard name	Common name	Downstream rate	Upstream rate	Approved on
VDSL	ITU G.993.1	VDSL	55 Mbit/s	3 Mbit/s	2001-11-29
VDSL2	ITU G.993.2	VDSL2	100 Mbit/s	100 Mbit/s	2006-02-17
VDSL2-Vplus	ITU G.993.2 Amendment 1 (11/15)	VDSL2 Annex Q VPlus/35b	300 Mbit/s	100 Mbit/s	2015-11-06

DOCSIS

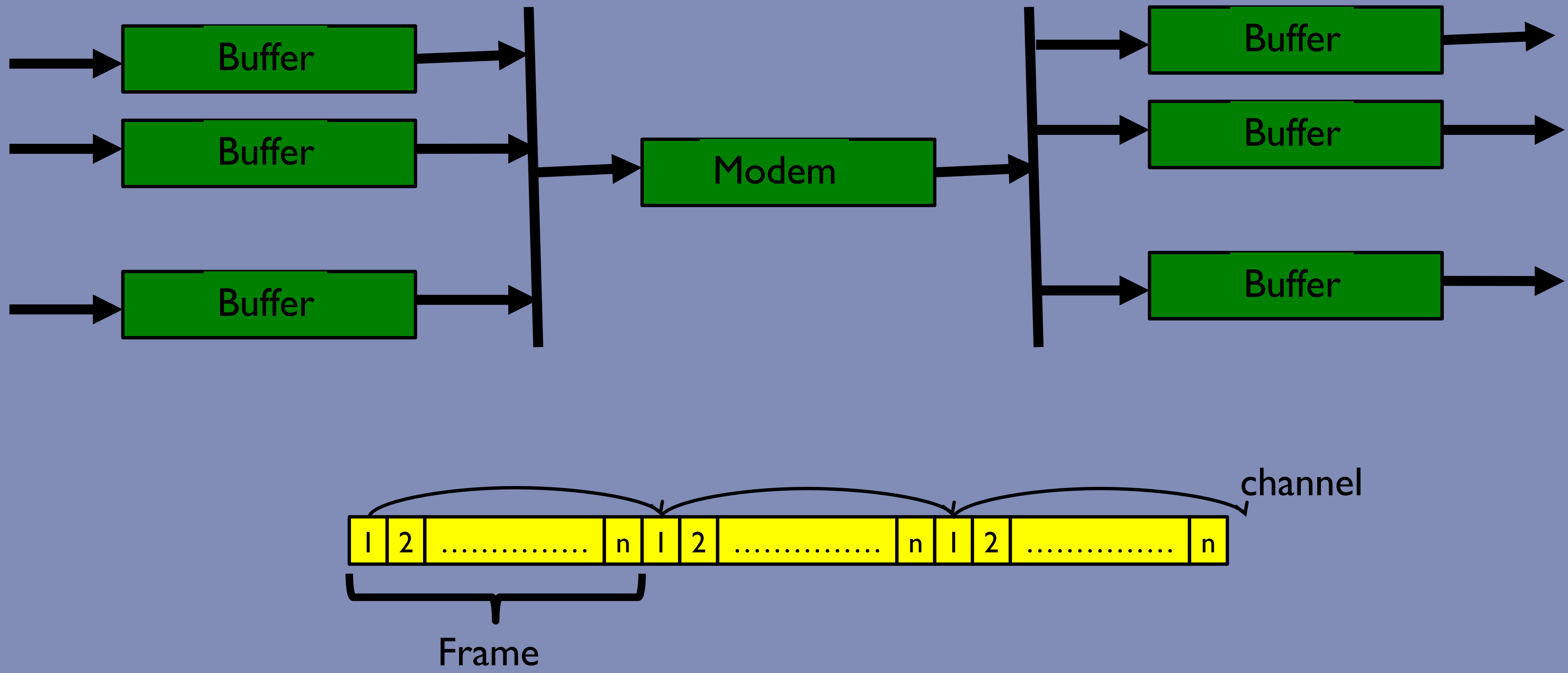
In the meantime we also have a Cable alternative for home usage:

Data Over Cable Service Interface Specification

which relies on 256-QAM modulation for downstream and 64-QAM for upstream (DOCSIS 3.0), and 4096-QAM modulation for OFDM/OFDMA (DOCSIS 3.1). OFDM is Orthogonal FDM also used in VDSL. OFDMA is OFD Multiple Access.

DOCSIS version[13]	Production date	Maximum downstream capacity	Maximum upstream capacity	Features
1.0	1997	40 Mbit/s	10 Mbit/s	Initial release
1.1	2001	40 Mbit/s	10 Mbit/s	Added VOIP capabilities, standardized the DOCSIS 1.0 QoS mechanisms
2.0	2002	40 Mbit/s	30 Mbit/s	Enhanced upstream data rates
3.0	2006	1.2 Gbit/s	200 Mbit/s	Significantly increased downstream/upstream data rates, introduced support for IPv6, introduced channel bonding
3.1	2013	10 Gbit/s	1–2 Gbit/s	Significantly increased downstream/upstream data rates, restructured channel specifications
3.1 Full Duplex	2017	10 Gbit/s	10 Gbit/s	Introduces support for fully symmetrical speeds

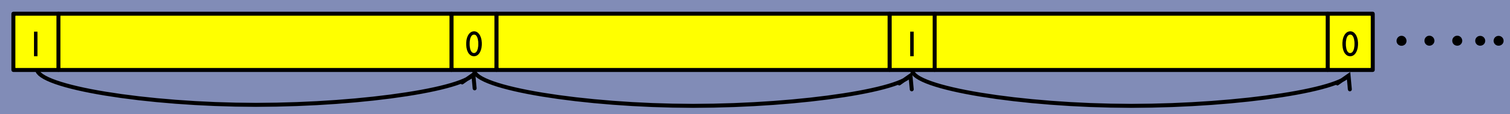
Time Division Multiplexing(TDM)



Synchronous TDM: not synchronous but frames are fixed and slots are always filled

How is framing implemented

Added digit framing



Pulse Stuffing

Frequency > Σ (freq. of the sources)

additional bits are added at fixed position in the frame

Relationship with data link framing

$F_1F_2A_1F_2C_1A_2d_1C_2d_2$................

for

$F_1f_1f_1d_1d_1d_1C_1A_1F_1$ in characters

flag
FCS
information
control
address

Example: ISDN (Integrated Services Digital Network)

DS-1 transmission format

Voice → PCM (8000 samples per second, 8-bit)

TDM-frame = 24 (channels) x 8 bits +1 (frame bit)

= 193 bits

Data rate: 8000 x 193 = **1.544 Mbps**

DATA only 23 out of 24 channels used,

24th channel has special SYNC BYTE

per channel 1 bit for user/system data

→ 7 x 23 x 8000 = 56 x 23 kbps = **56 kbps** p. channel

Standards Telephony

US/JAPAN			ITU-T		
	# channels	Mbps	Level	#channels	Mbps
DS-1	24	1.544	1	30	2.048
DS-1C	48	3.152	2	120	8.448
DS-2	96	6.312	3	480	34.368
DS-3	672	44.736	4	1920	139.264
DS-4	4032	274.176	5	7680	565.148

Currently being phased out!!

- Initially used heavily by the broadcasting industry. Also introduced for home usage. For instance, 25 million installments in Germany in 2003
- Became obsolete due to ADSL (in 2018 it will be phase out in Germany)
- ***I**t **S**till **D**oes **N**othing, **I**nnovations **S**ubscribers **D**on't **N**eed*

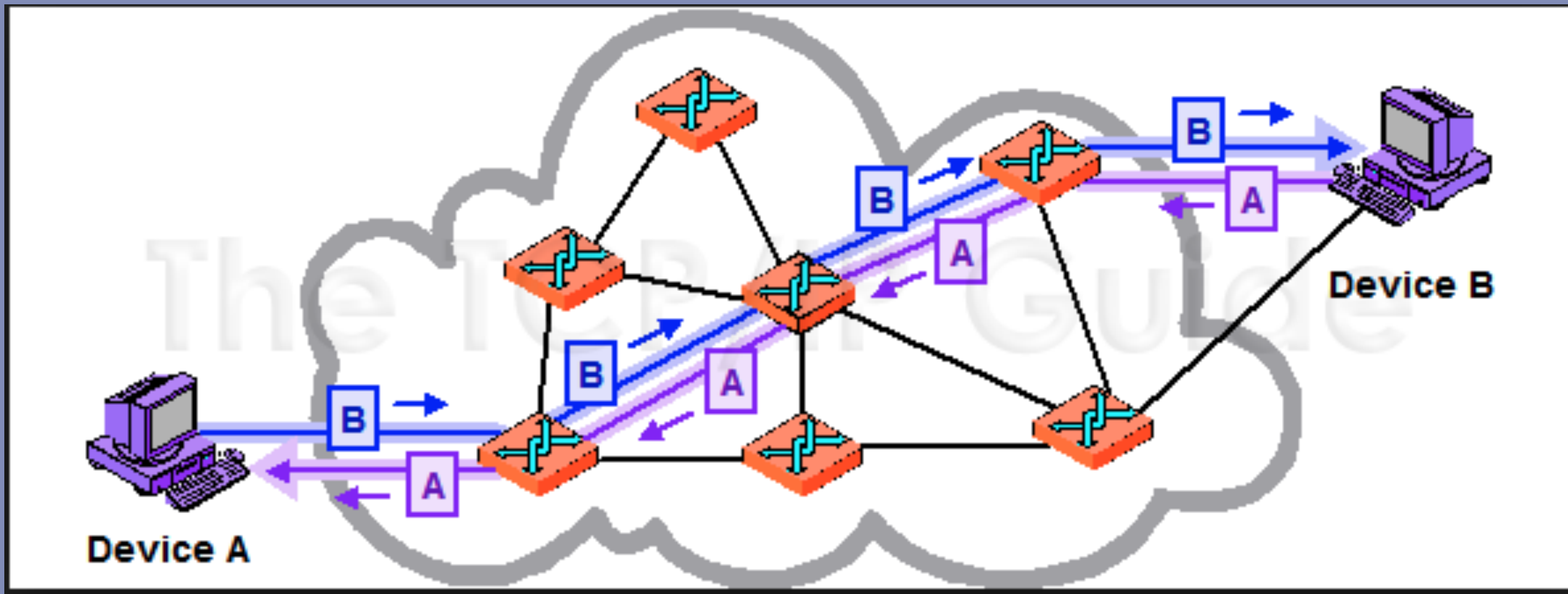
Network **SWITCHING**

Next to multiplexing: **switching** is required to realize multi to multi connections

Especially needed in Wide Area Networks (WAN)

Also present in Local Area Networks (LAN) or in multi processors architectures.

Circuit Switching



1. A dedicated path between two end stations is realized or channel (TDM/FDM)
2. Data is being transmitted (Switches don't inspect data)
3. Path is broken up

Circuit switching

IMPORTANT CHARACTERISTIC:

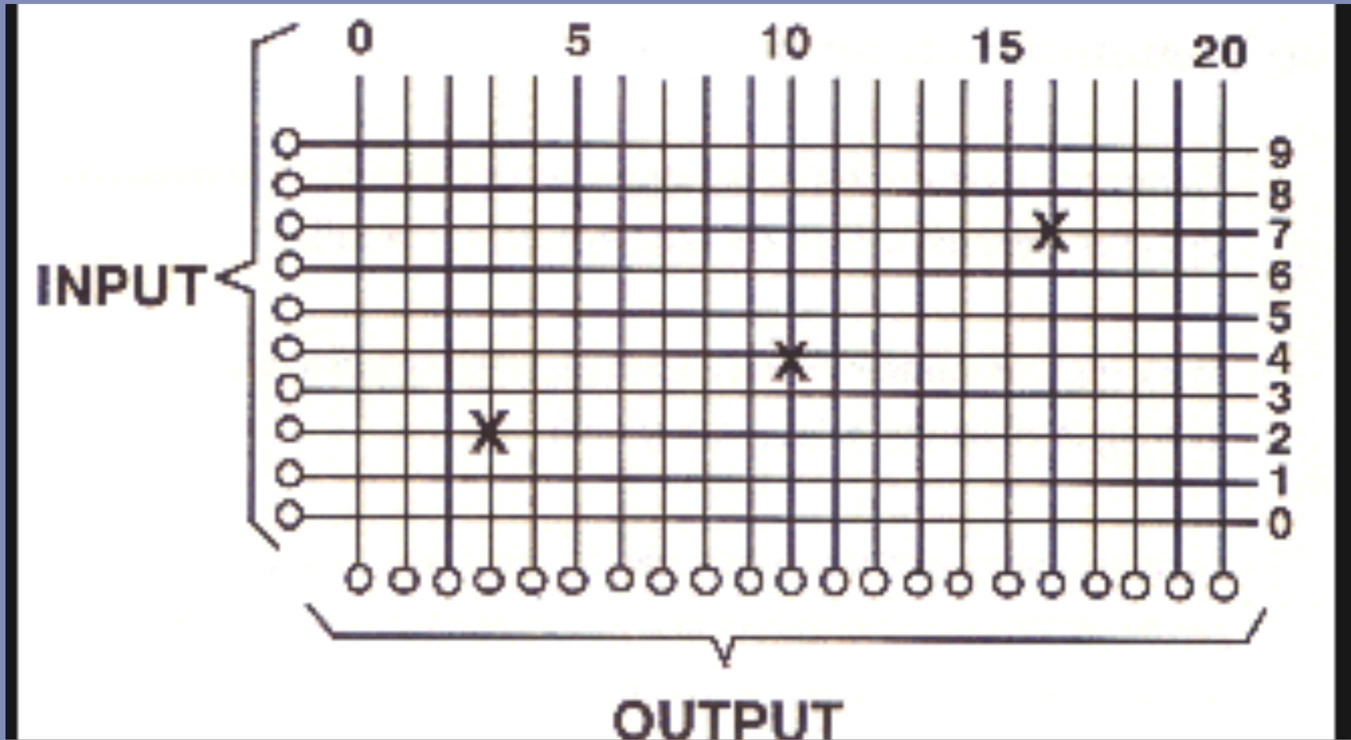
BLOCKING VS NON-BLOCKING

Connection cannot be realized because all paths are occupied

Connection can always be realized and at any time

Space Division Switching:

non-blocking **Crossbar Switch**

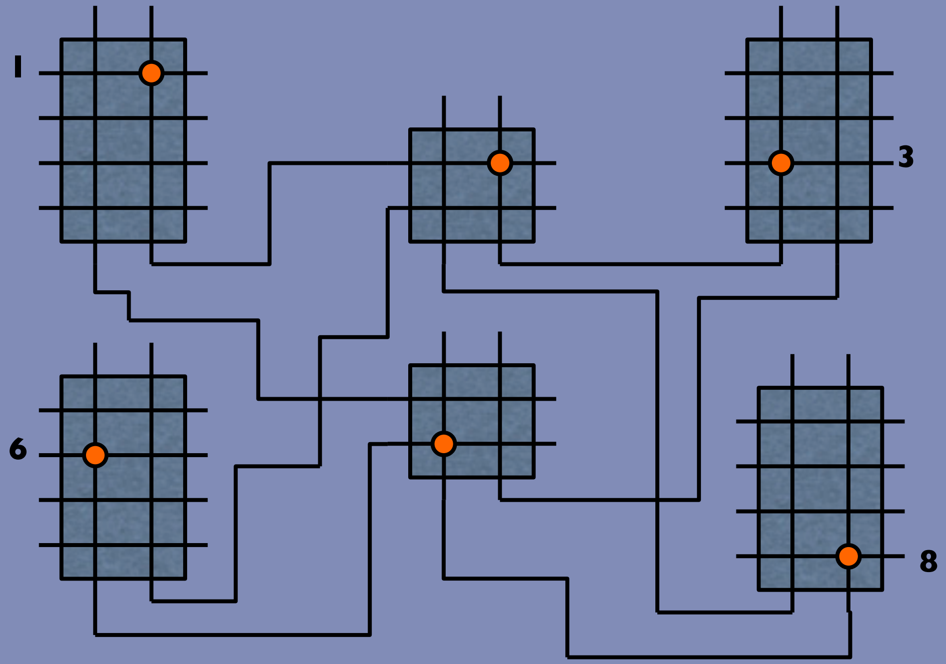


Very costly: N^2 switches

Multistage Networks

Use many small crossbar switches and connect them wisely.

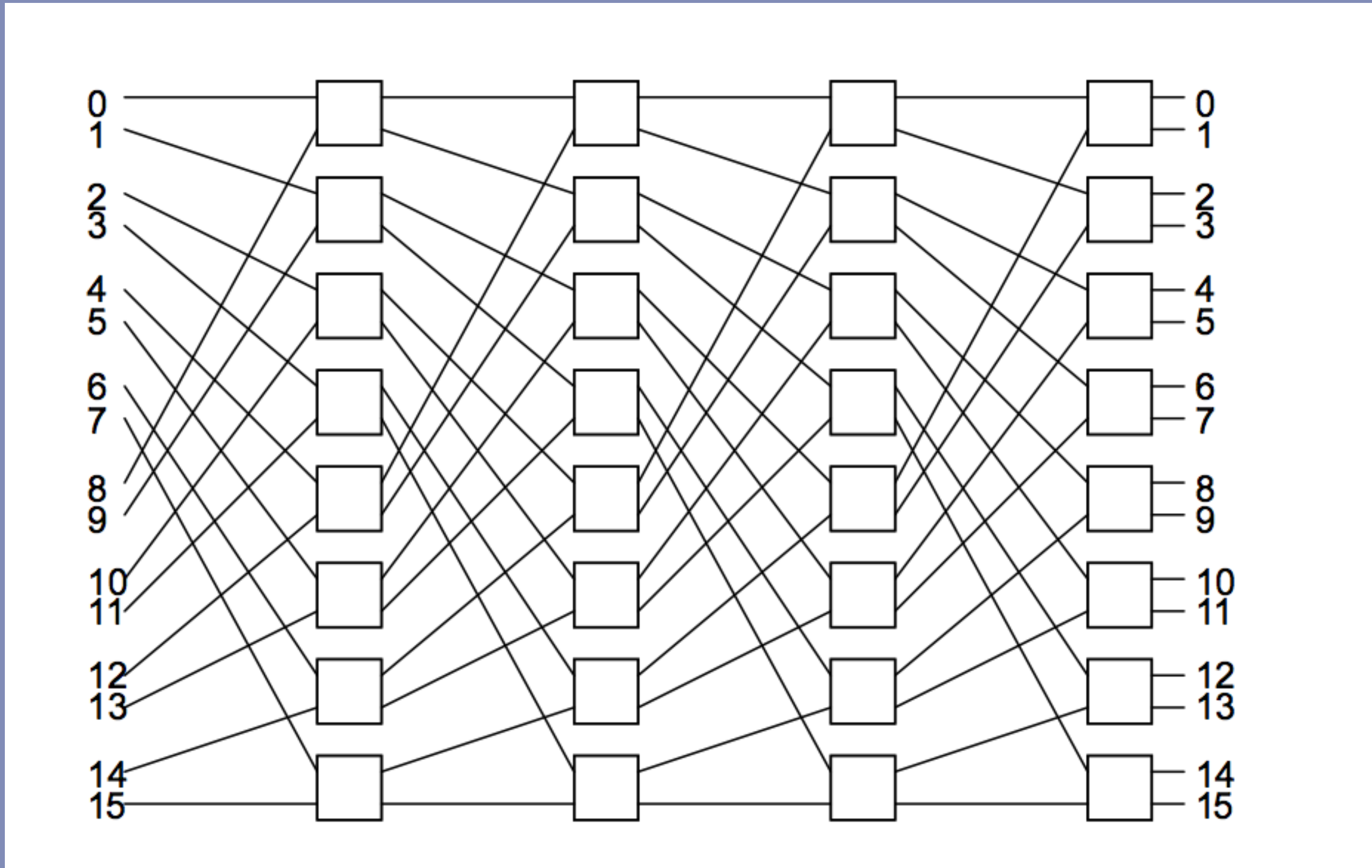
Blocking can occur!!!!!



5 cannot be connected to 2

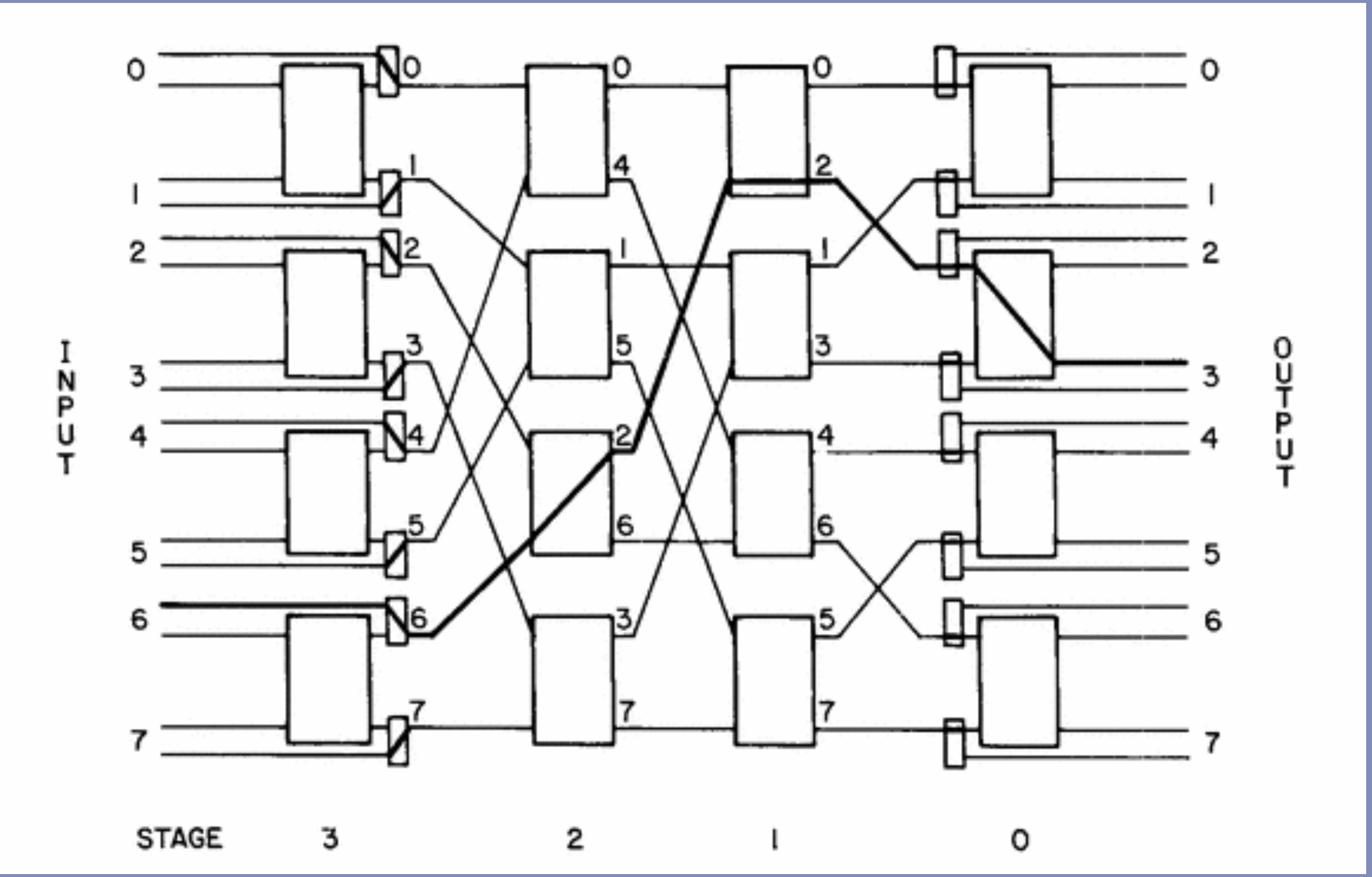
Omega Networks

(based on Perfect Shuffles)

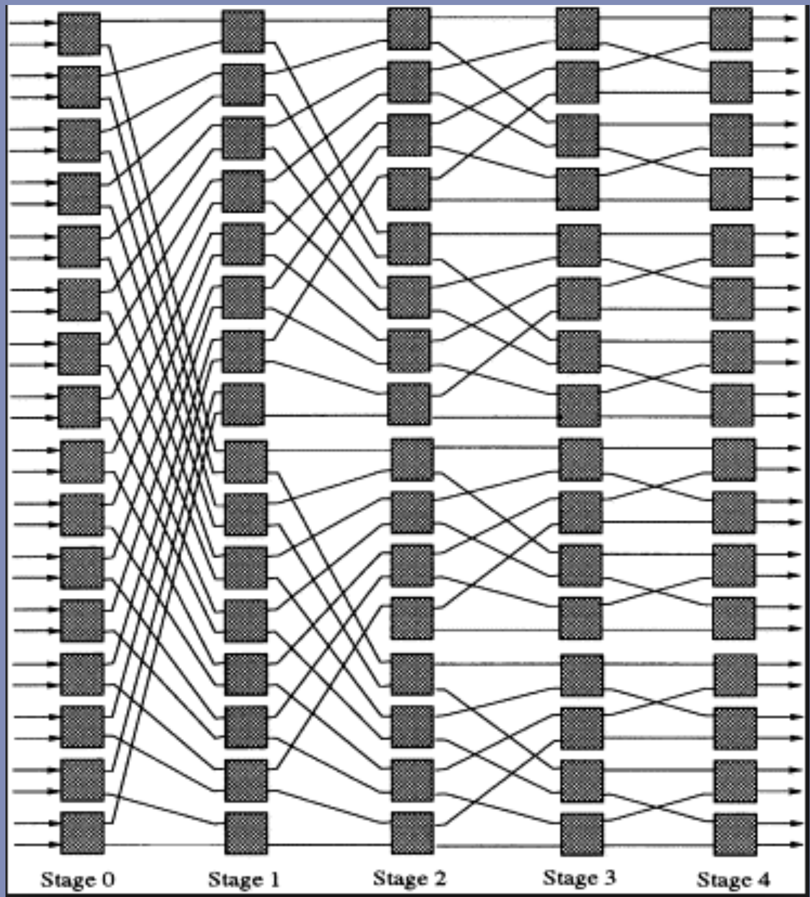


2logN + 1 stages: non blocking with O(NlogN switches)

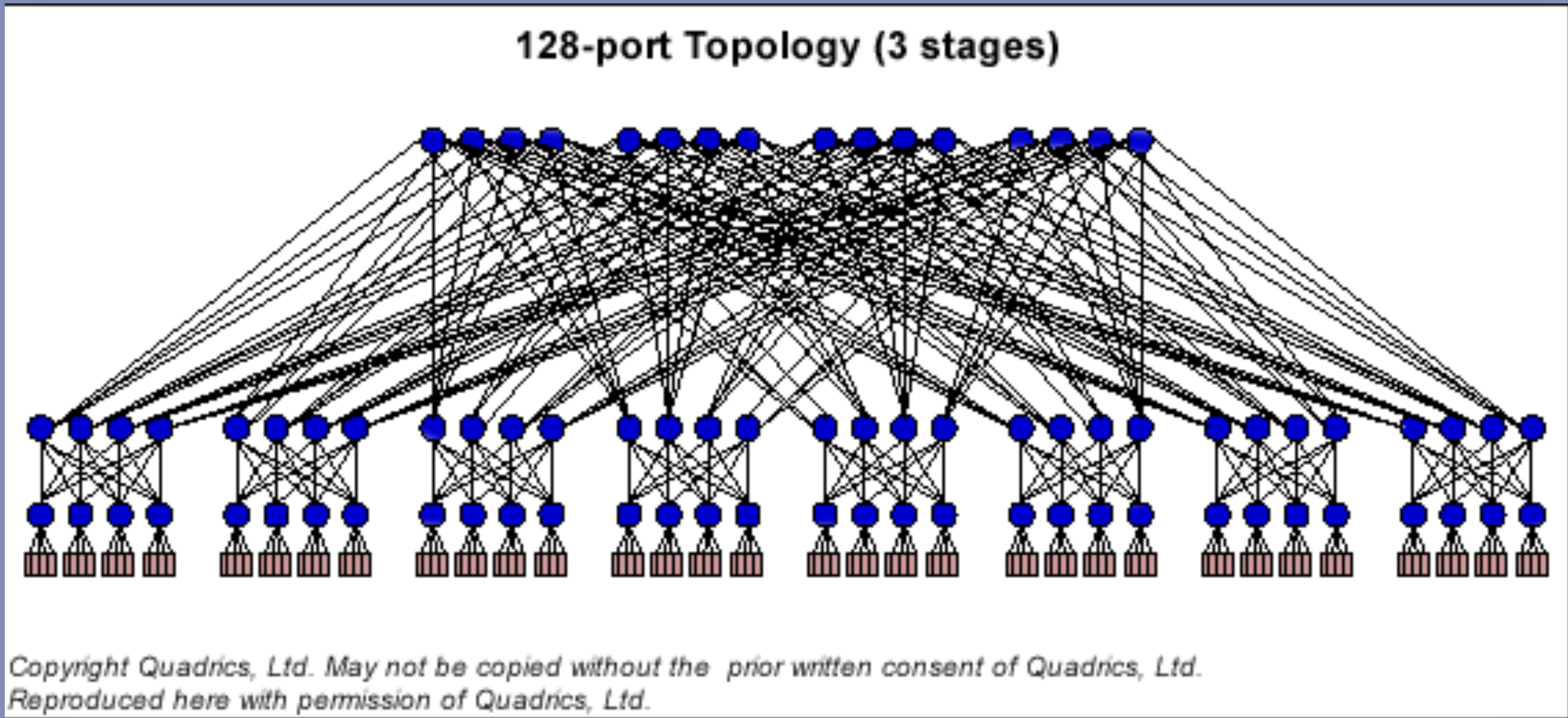
Variants of PS networks
Cube Network



Butterfly Network

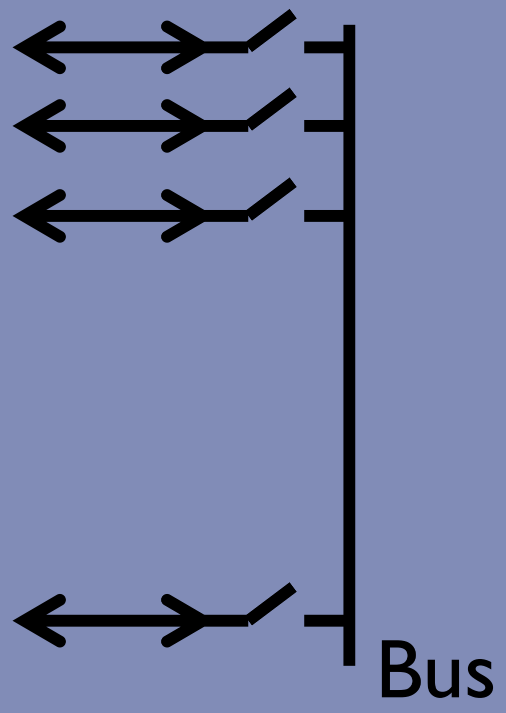


Fat Tree Network



Time Division Switching

Do not confuse with TDM !!!



Bandwidth of Bus >
Σ indiv. bandw.
Then non-blocking!

Routing in Circuit Switched Networks

- Alternate Routing
  ➔ Each switching node has its own routing table

	First Choice	Second Choice
A to B	Via switch i	Via switch j
A to C	Via switch j	Via switch k

- Fixed Alternate Routing
  Routing tables do not change
- Dynamic Alternate Routing
  Depending on time (e.g. time of the day) routing tables will change
- Adaptive Routing
  Central Controller gets status of all switches and gives routing updates to all switches

Packet Switching

Data is sent by packets (usually < 1000 octets),
Every switching nodes has buffers

- **Datagram**

  Every packet is routed independently

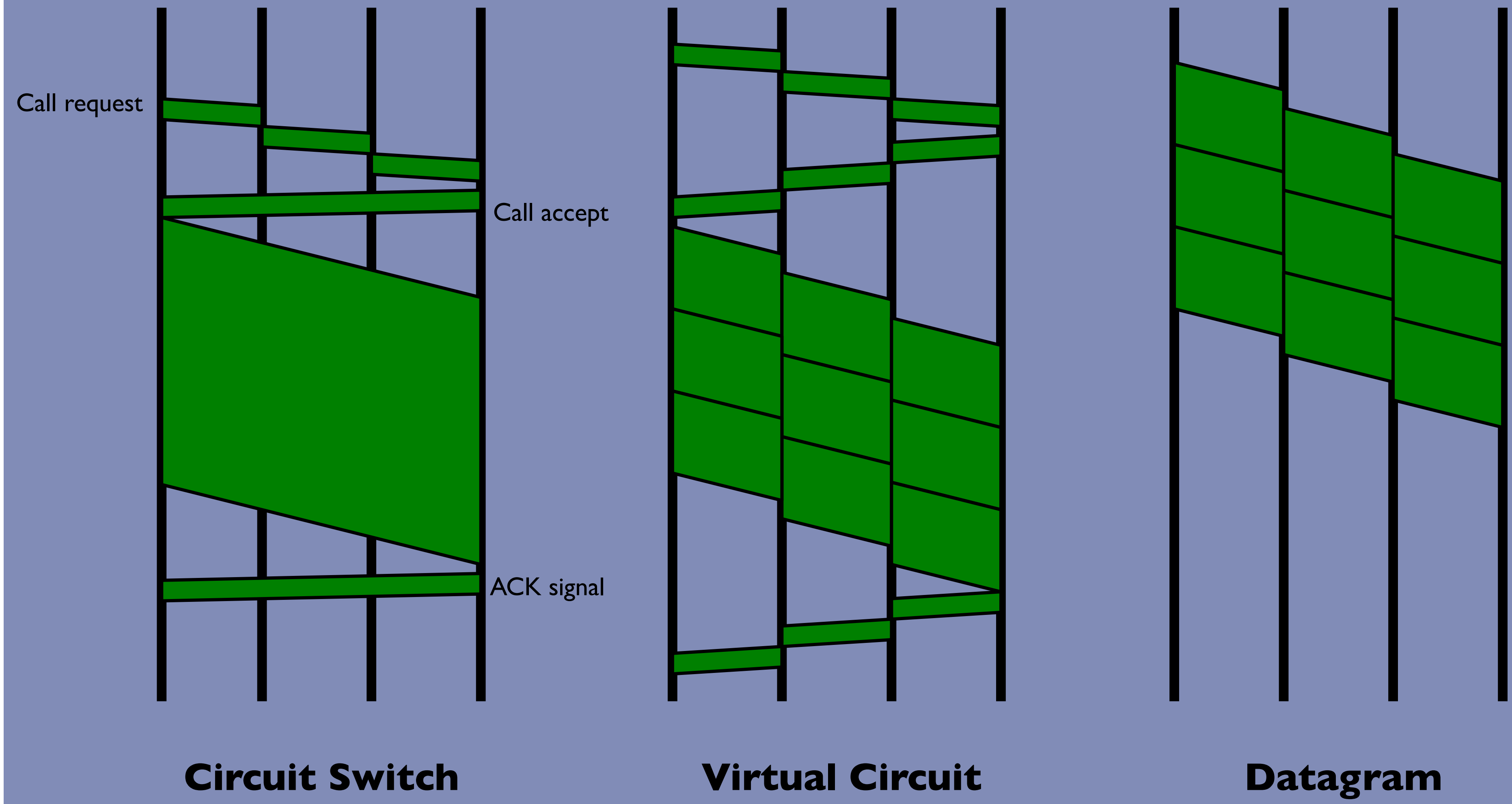
  ➔ As a consequence packets can arrive out of order

- **Virtual Circuit (Wormhole)**

  Before communication is initiated a Call-Request packet is sent on the network, which fixates a virtual path between sender and receiver.

  ➔ Packets arrive in order, but it not as flexible as datagram

Summarizing

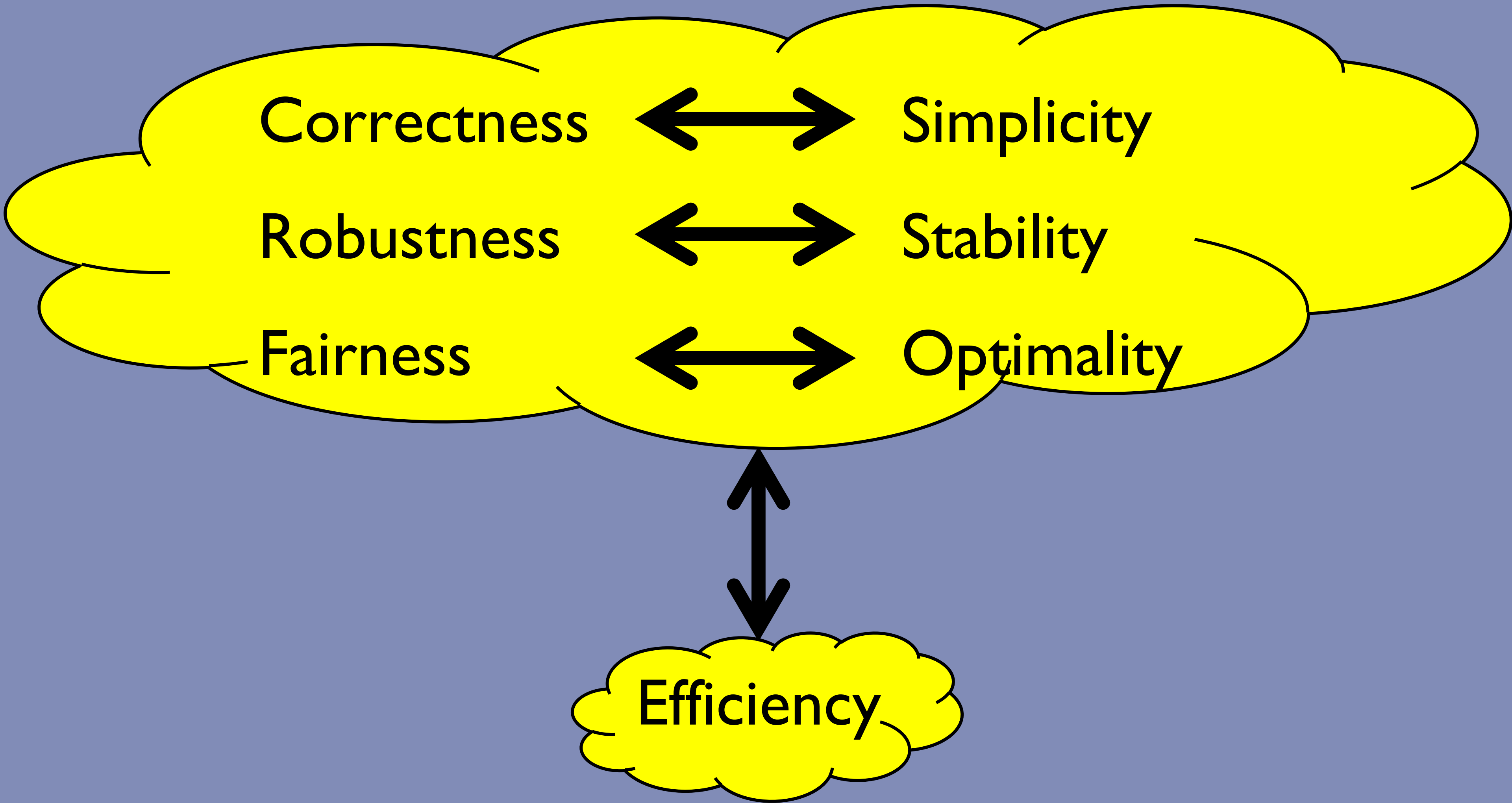


Different Combinations

- External Virtual Circuit & Internal Virtual Circuit
- External Virtual Circuit & Internal Datagram
- External Datagram & Internal Virtual Circuit
- External Datagram & Internal Datagram

Which one makes sense?

Routing Trade Offs



Routing for Packet Switched Networks

Like circuit switching can we differentiate between: Fixed Routing and Alternate Routing

→ **No difference between datagram and virtual circuit**

Random Routing

Every node chooses randomly outgoing link, based on some prob. Distribution, e.g.

$$P_i = R_i / \Sigma R_j$$

with R_i data rate possible on link i.

Flooding (very inefficient, very reliable)

Every node puts incoming packet on every outgoing link, except the incoming link

➔ Exponential growth

1. Every node logs all the packets

   If packets arrives a second time: **discard**

2. Every packet, contains counter: hop-count

   If hop-count > threshold: **discard**

Adaptive Routing (Central vs Distributed)

Every node gets network status information

- Local, e.g. queue length of the outgoing links
- Adjacent nodes
- All nodes

ARPANET

based on Adaptive Routing, Distr. & Adjacent Nodes

First Version: 1969

Based on **Bellman-Ford Algorithm**

Every node i has two vectors:

$$D_i = \begin{pmatrix} d_{i1} \\ d_{i2} \\ \vdots \\ d_{iN} \end{pmatrix} \qquad S_i = \begin{pmatrix} s_{i1} \\ s_{i2} \\ \vdots \\ s_{iN} \end{pmatrix}$$

N = #nodes
d_{ij} = estimated delay from node i to j
s_{ij} = next node on the route i to j

Every 128 ms every node exchanges delay vector with adjacent nodes.
Then every node k: $d_{kj} = \mathrm{Min}_{i \varepsilon A} [d^{new}_{ij} + d_{ki}]$ and $s_{kj} = i$,
the node i which minimizes d_{kj}. Link delays are the queue length for that link.

Disadvantages: Link delays were not accurate
Thrashing would occur

2^{de} Generation (1979)

Every node:

- Timestamp on incoming message (arrival time)
- Departure time recorded
- If pos. ACK is received: delay = (dept. time – arrival time)

Every 10 sec: every node computes the average delay per link
If delay is different: **FLOODING** is used to inform all the other nodes
Every node gets status of the whole network!!!!!!!!!
Dijkstra's shortest path algorithm is used to compute new routing table

3^{de} Generation (1987)

When load is heavy:

Observed delay under old routing ≠ delay under new routing

➔Oscillation effects

➔Instead of BEST route: a "good" route

Smoothening of link costs (delays)

Every 10 seconds:

ρ=link utilization

t = measured delay

s = service time

1. (Queuing theory) $\rho = 2(s-t)/(s-2t)$, with
2. $U(n+1) = 0.5\rho(n+1) + 0.5U(n)$, U(n) average utilization
3. New delays are computed based on U(n),

   terrestrial: 1 Hop for $U(n)<0.5$, 2 Hops for $U(n)>0.8$, and $1+(U(n)-0.5)/0.3$ Hops otherwise

   satelite: 2 Hops for $U(n)<0.8$

Otherwise the same as 2-de generation