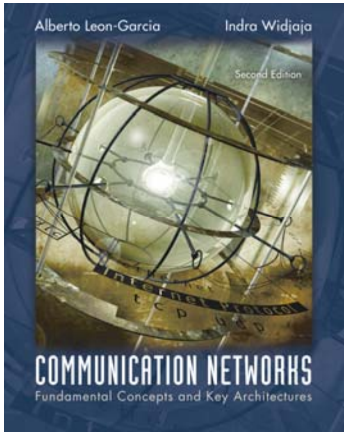
Chapter 4 Circuit-Switching Networks



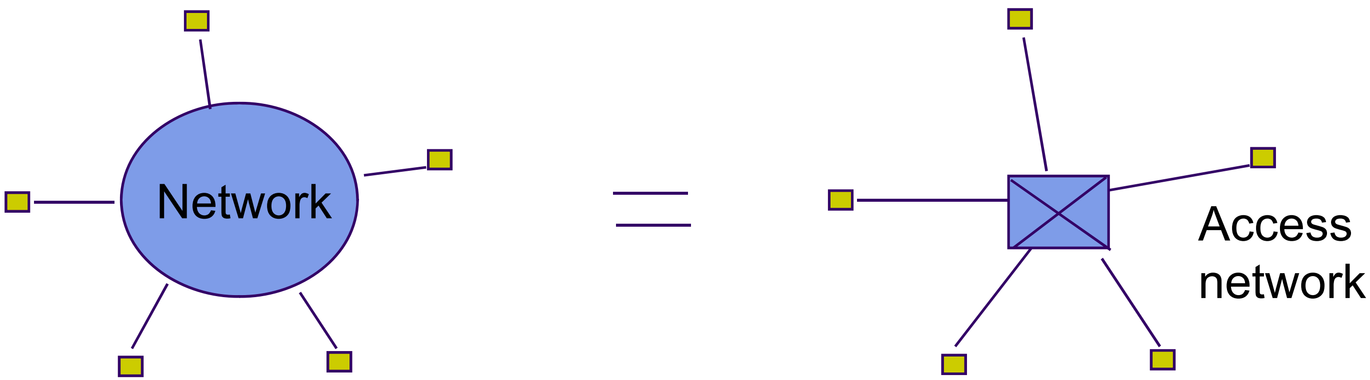
Multiplexing
SONET
Transport Networks
Circuit Switches
The Telephone Network
Signaling
Traffic and Overload Control in Telephone Networks
Cellular Telephone Networks

Circuit Switching Networks

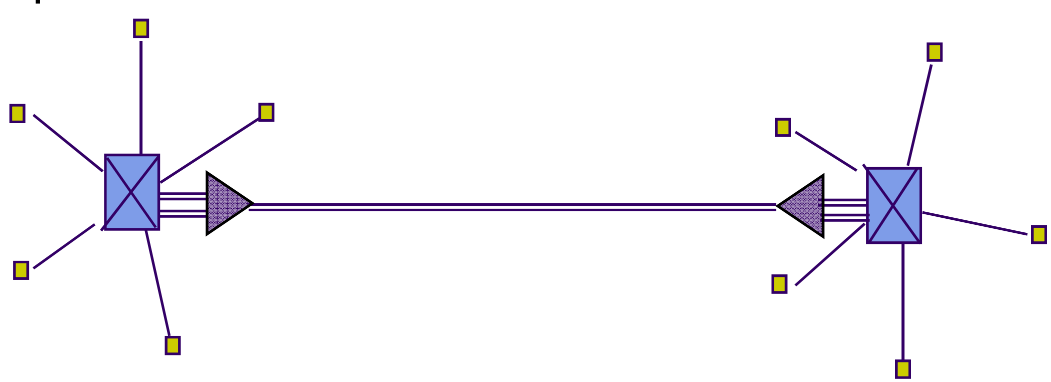
- End-to-end dedicated circuits between clients
  - Client can be a person or equipment (router or switch)
- Circuit can take different forms
  - Dedicated path for the transfer of electrical current
  - Dedicated time slots for transfer of voice samples
  - Dedicated frames for transfer of Nx51.84 Mbps signals
  - Dedicated wavelengths for transfer of optical signals
- Circuit switching networks require:
  - Multiplexing & switching of circuits
  - Signaling & control for establishing circuits
- These are the subjects covered in this chapter

How a network grows

(a) A switch provides the network to a cluster of users, e.g. a telephone switch connects a local community



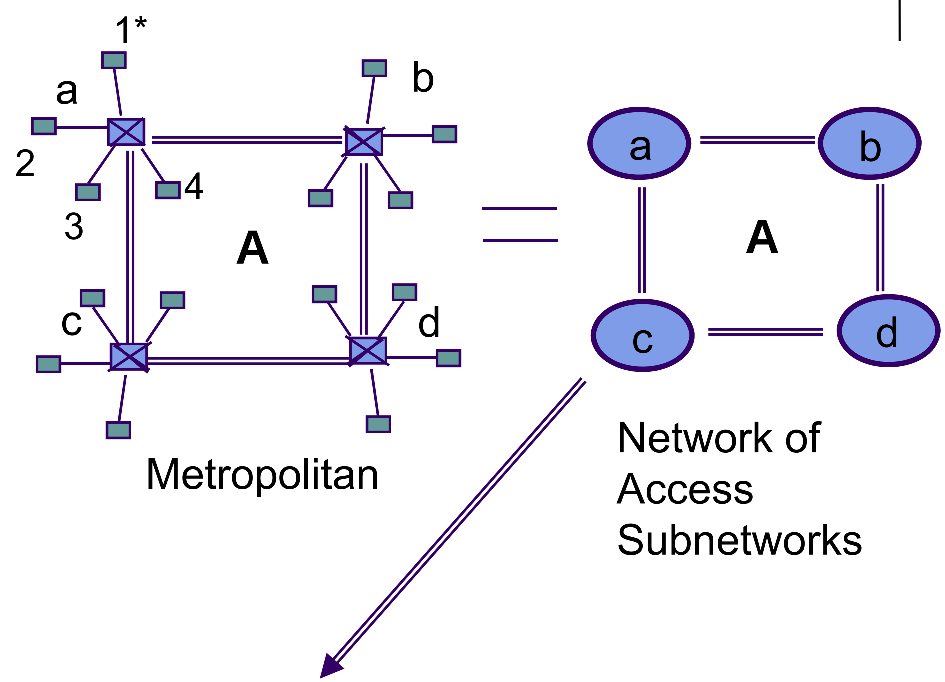
(b) A multiplexer connects two access networks, e.g. a high speed line connects two switches



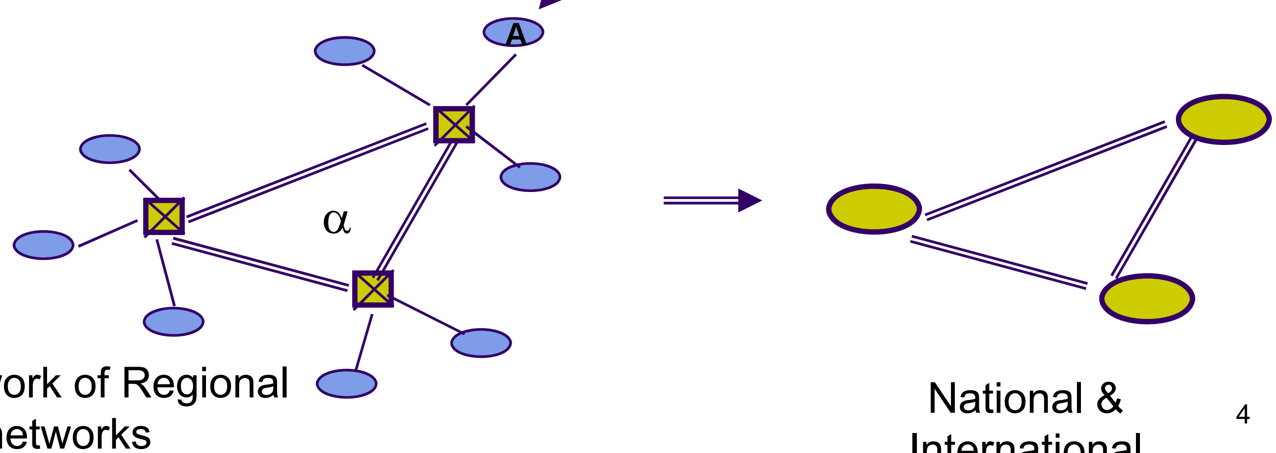
A Network Keeps Growing

(a) Metropolitan network **A** viewed as Network **A** of Access Subnetworks

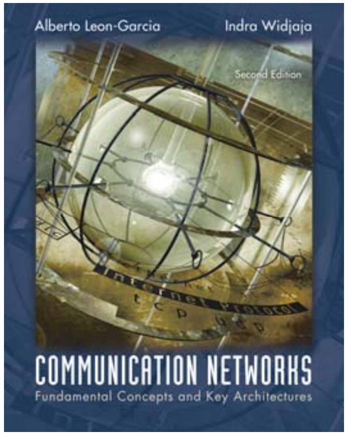
(b) National network viewed as Network of Regional Subnetworks (including **A)**



Very high-speed lines



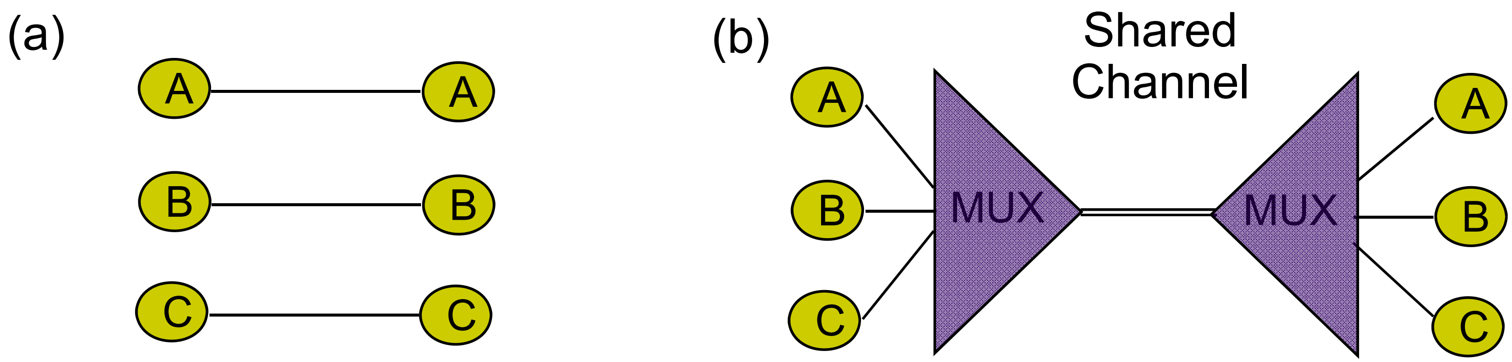
Chapter 4
Circuit-Switching Networks



Multiplexing

Multiplexing

- Multiplexing involves the sharing of a transmission channel (resource) by several connections or information flows
  - Channel = 1 wire, 1 optical fiber, or 1 frequency band
- Significant economies of scale can be achieved by combining many signals into one
  - Fewer wires/pole; fiber replaces thousands of cables
- Implicit or explicit information is required to demultiplex the information flows.

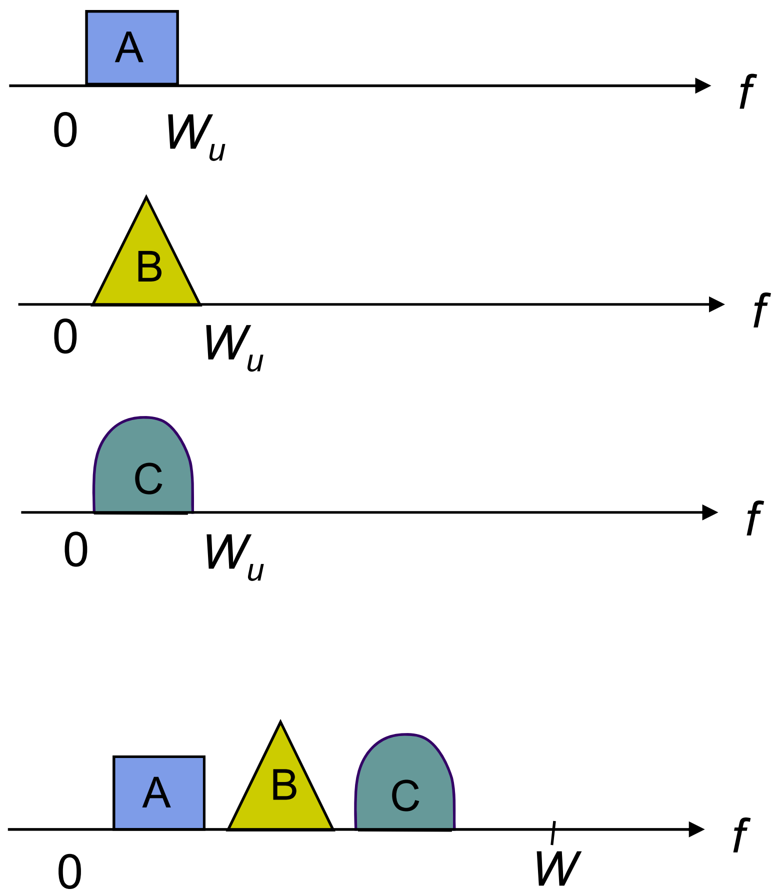


Frequency-Division Multiplexing

- Channel divided into frequency slots

(a) Individual signals occupy W_u Hz

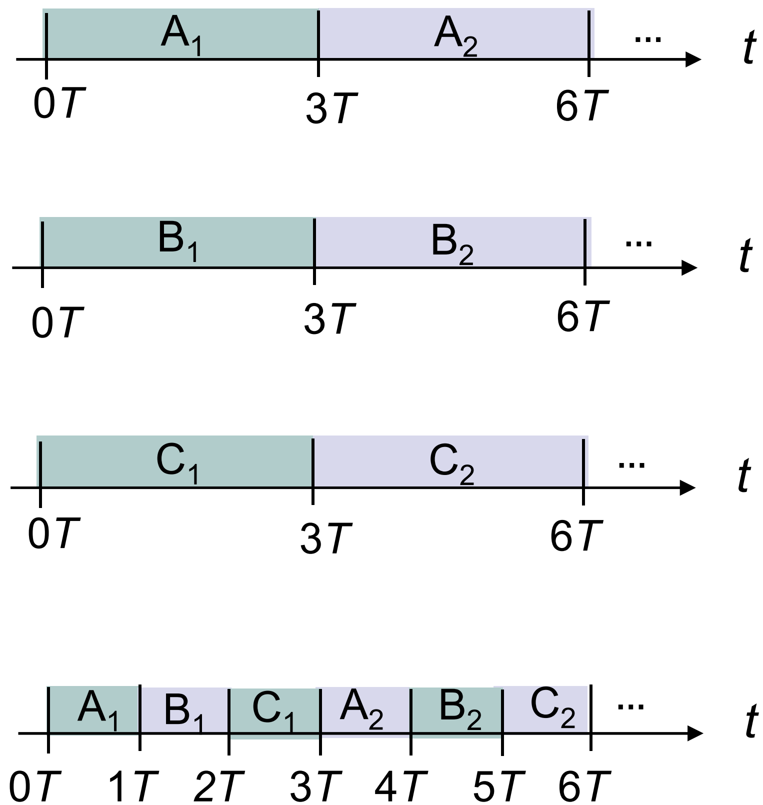
(b) Combined signal fits into channel bandwidth



- Guard bands required
- AM or FM radio stations
- TV stations in air or cable
- Analog telephone systems

Time-Division Multiplexing

- High-speed digital channel divided into time slots



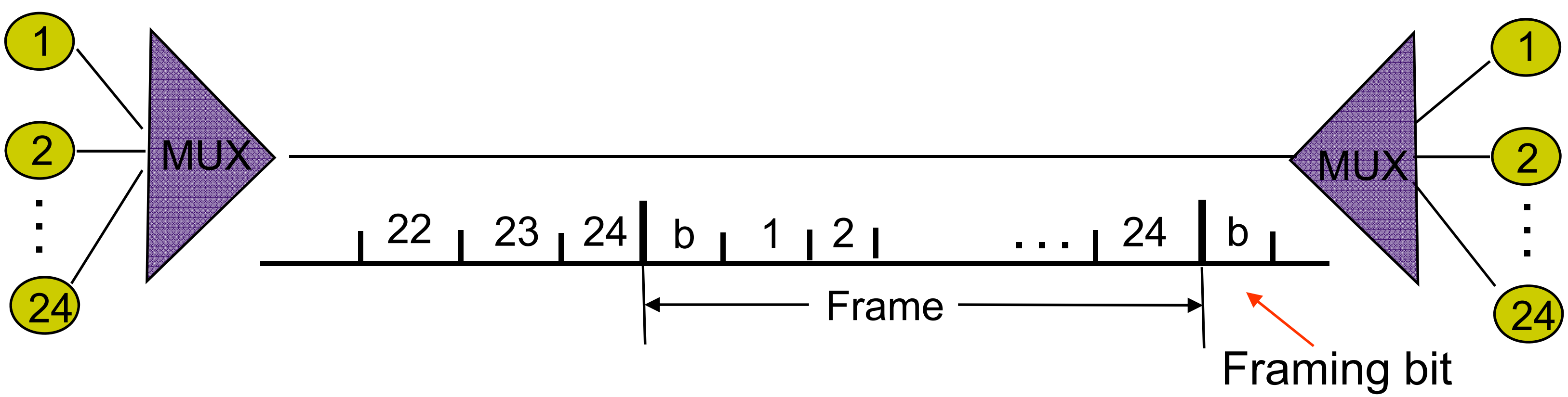
(a) Each signal transmits 1 unit every $3T$ seconds

(b) Combined signal transmits 1 unit every T seconds

- Framing required
- Telephone digital transmission
- Digital transmission in backbone network

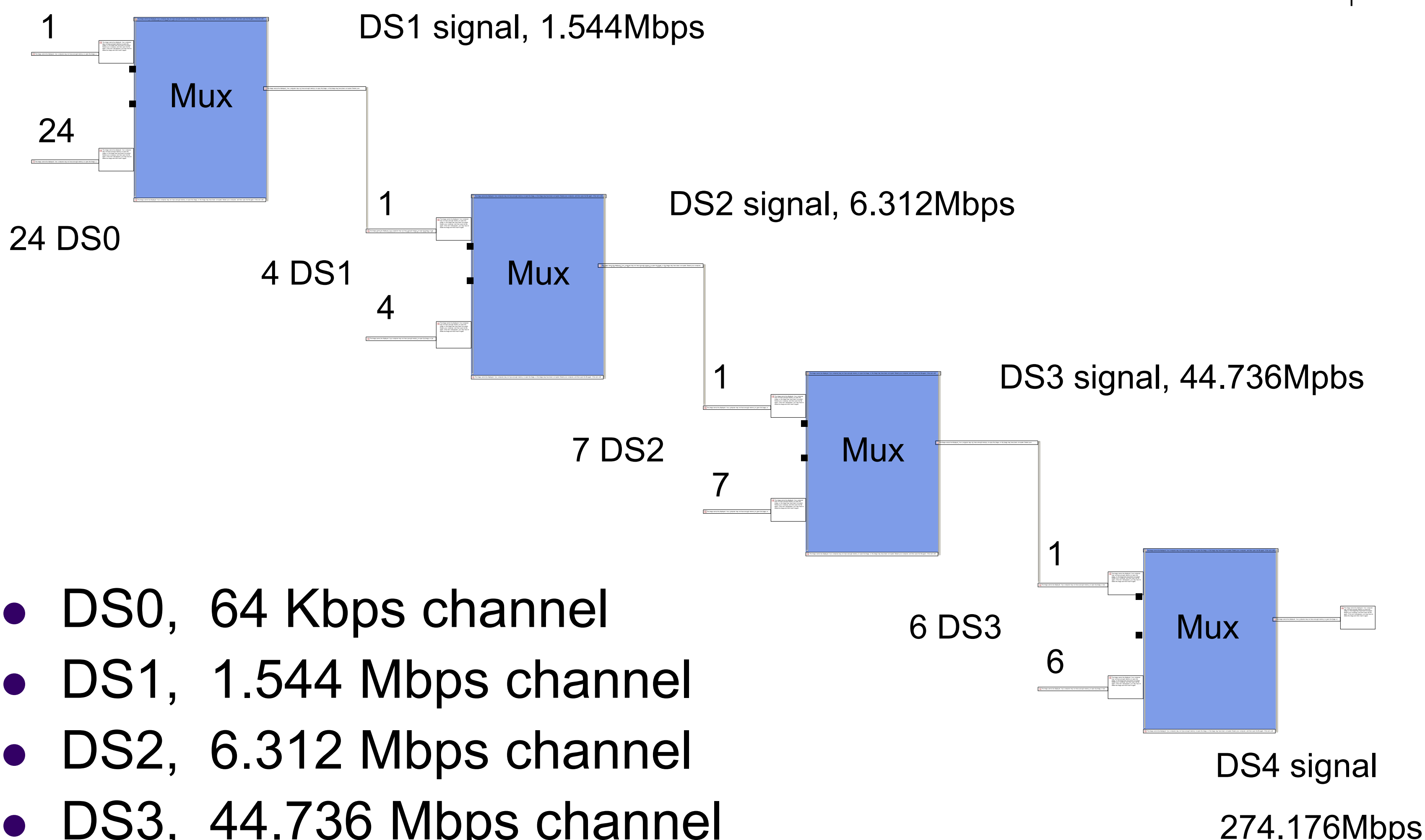
T-Carrier System

- Digital telephone system uses TDM.
- PCM voice channel is basic unit for TDM
  - 1 channel = 8 bits/sample x 8000 samples/sec. = 64 kbps
- T-1 carrier carries Digital Signal 1 (DS-1) that combines 24 voice channels into a digital stream:



Bit Rate = 8000 frames/sec. x (1 + 8 x 24) bits/frame
= 1.544 Mbps

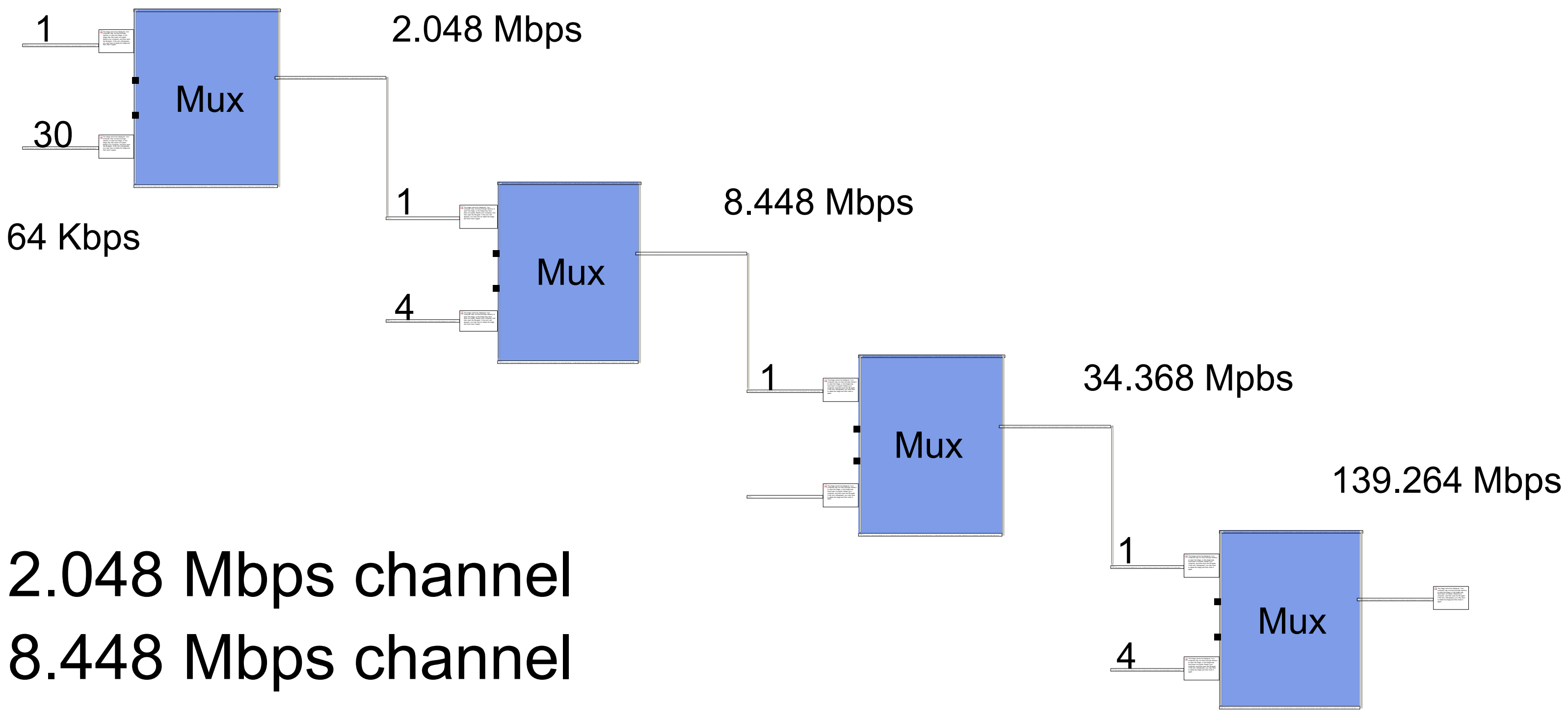
North American Digital Multiplexing Hierarchy



- DS0, 64 Kbps channel
- DS1, 1.544 Mbps channel
- DS2, 6.312 Mbps channel
- DS3, 44.736 Mbps channel
- DS4, 274.176 Mbps channel

CCITT Digital Hierarchy

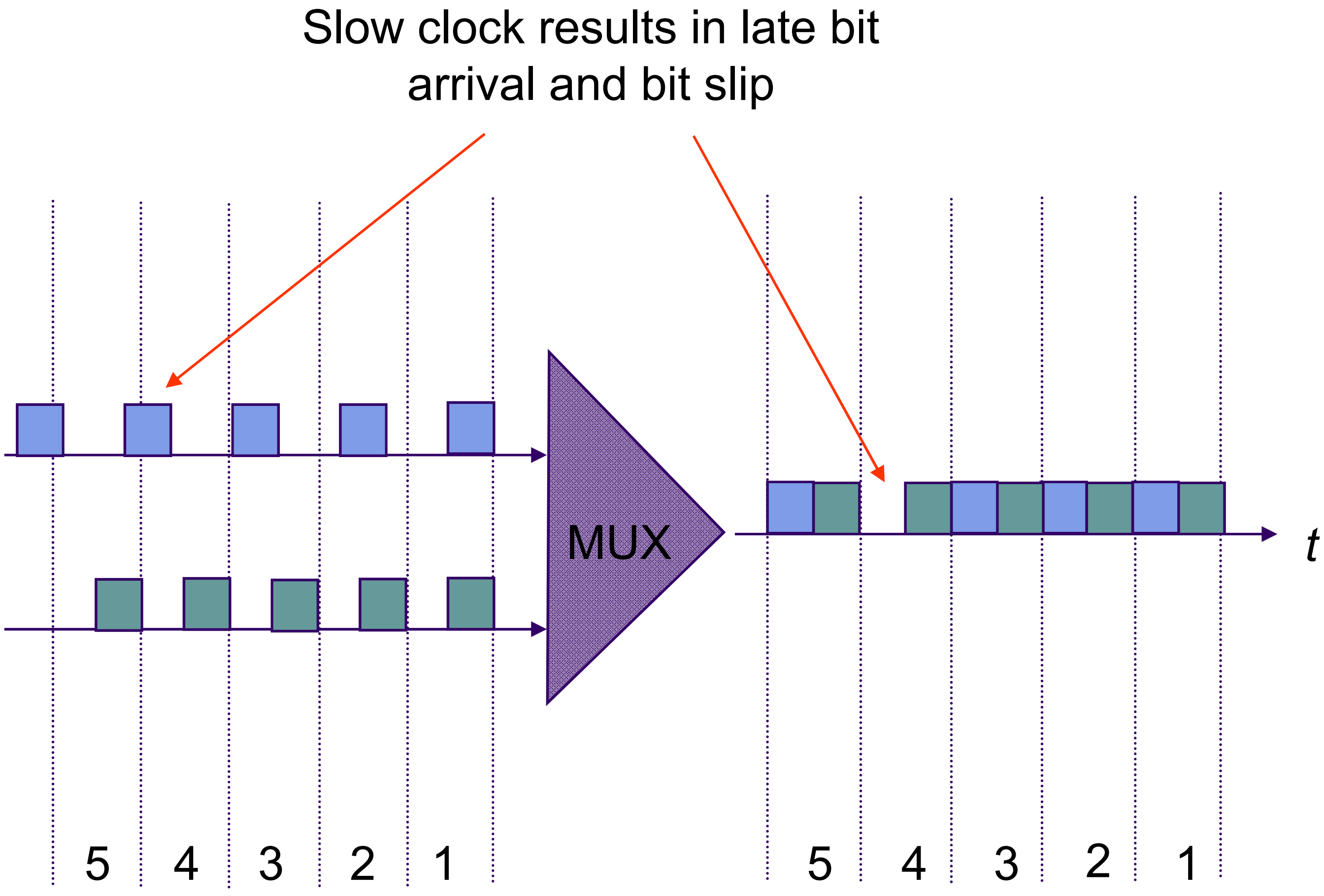
- CCITT digital hierarchy based on 30 PCM channels



- E1, 2.048 Mbps channel
- E2, 8.448 Mbps channel
- E3, 34.368 Mbps channel
- E4, 139.264 Mbps channel

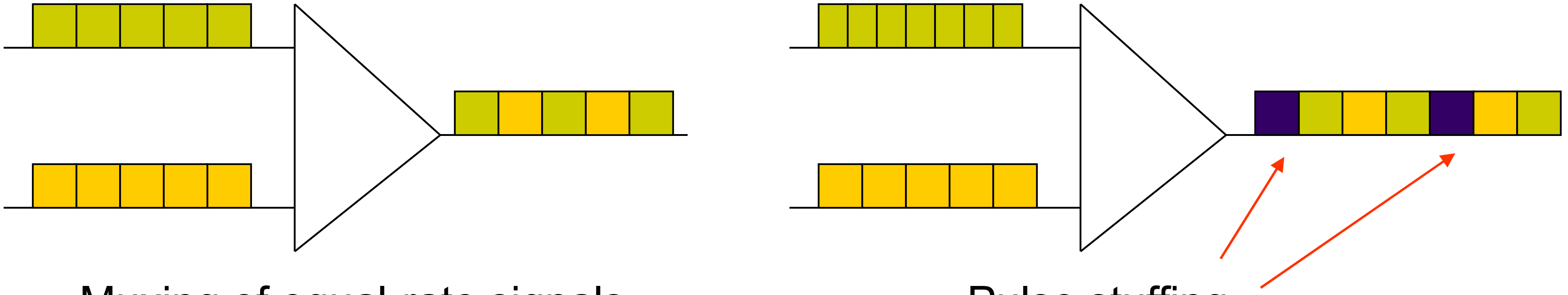
Clock Synch & Bit Slips

- Digital streams cannot be kept perfectly synchronized
- Bit slips can occur in multiplexers



Pulse Stuffing

- Pulse Stuffing: synchronization to avoid data loss due to slips
- Output rate > R1+R2
  - i.e. DS2, 6.312Mbps=4x1.544Mbps + 136 Kbps
- Pulse stuffing format
  - Fixed-length master frames with each channel allowed to stuff or not to stuff a single bit in the master frame.
  - Redundant stuffing specifications
  - signaling or specification bits (other than data bits) are distributed across a master frame.

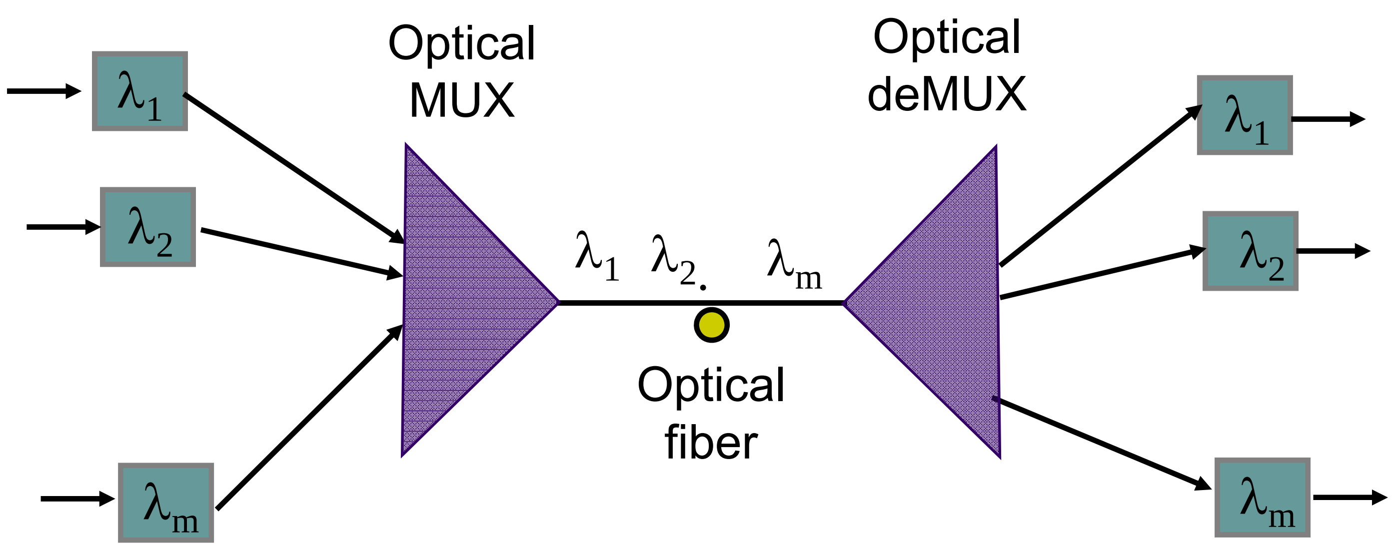


Muxing of equal-rate signals requires perfect synch

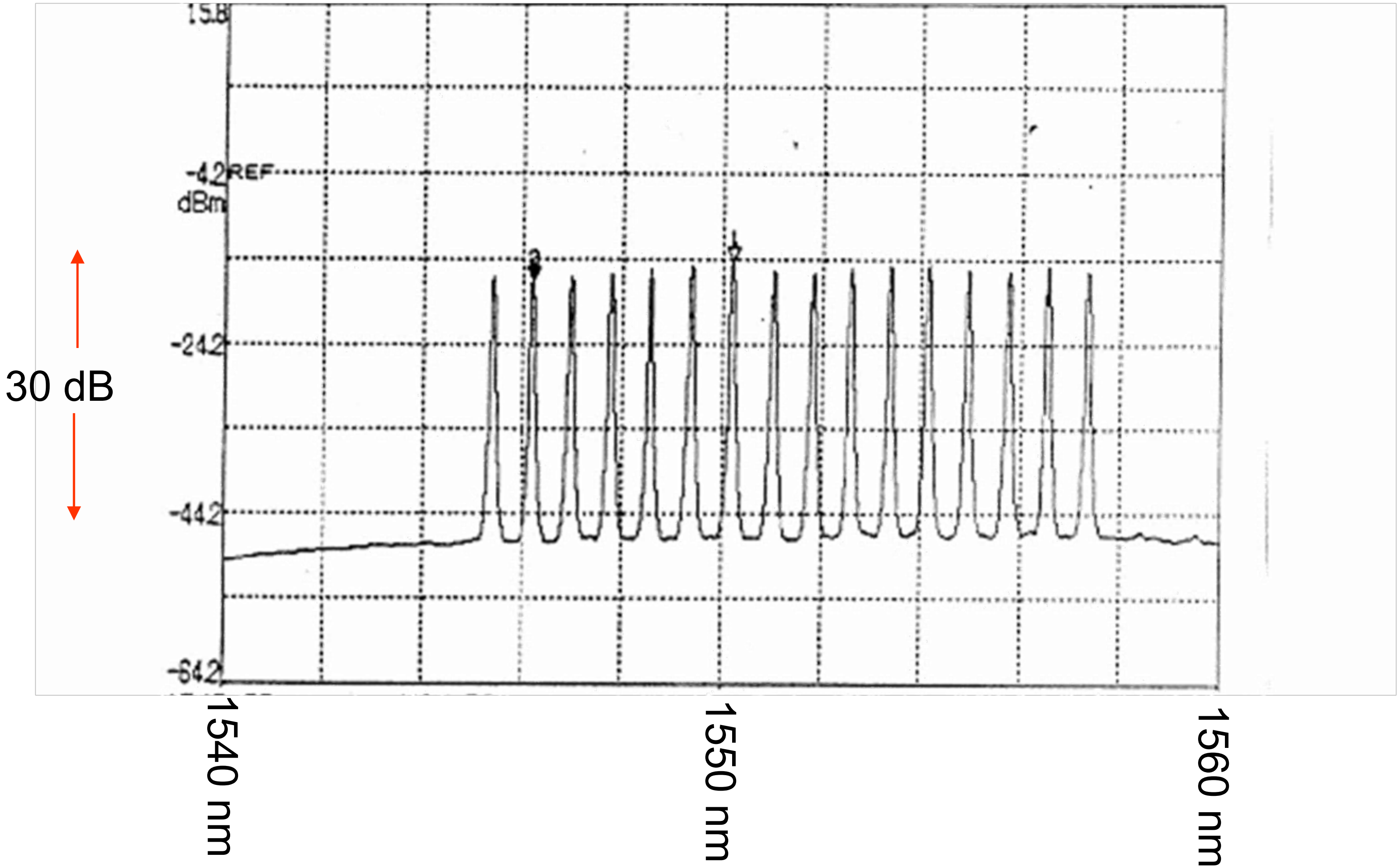
Pulse stuffing

Wavelength-Division Multiplexing

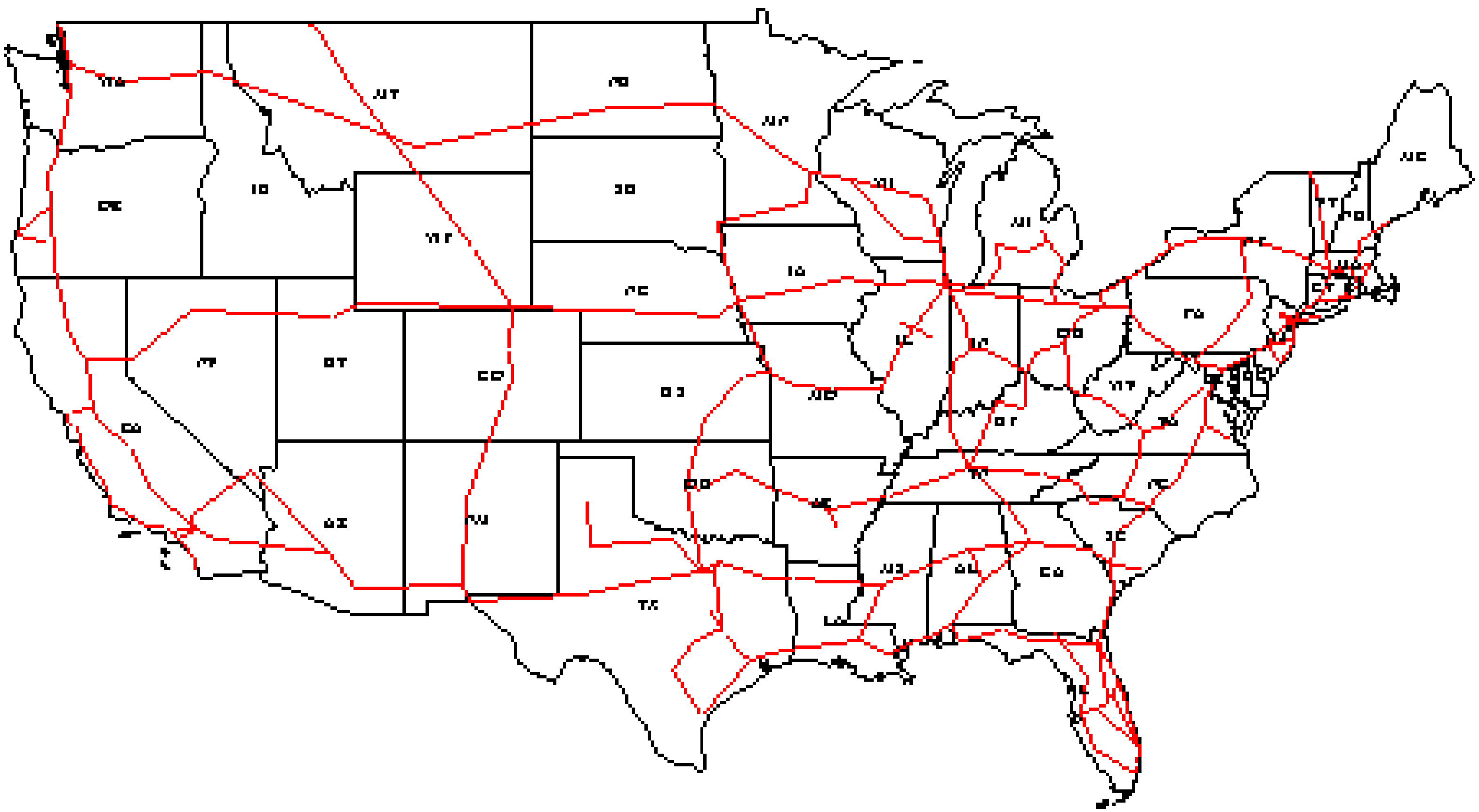
- Optical fiber link carries several wavelengths
  - From few (4-8) to many (64-160) wavelengths per fiber
- Imagine prism combining different colors into single beam
- Each wavelength carries a high-speed stream
  - Each wavelength can carry different format signal
  - e.g. 1 Gbps, 2.5 Gbps, or 10 Gbps



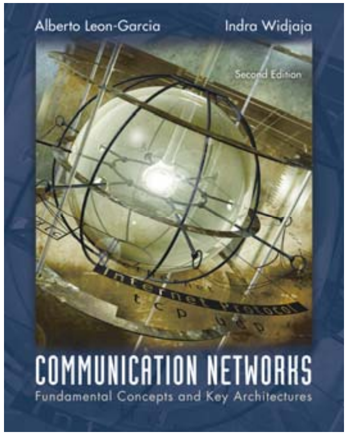
Example: WDM with 16 wavelengths



Typical U.S. Optical Long-Haul Network



Chapter 4
Circuit-Switching Networks



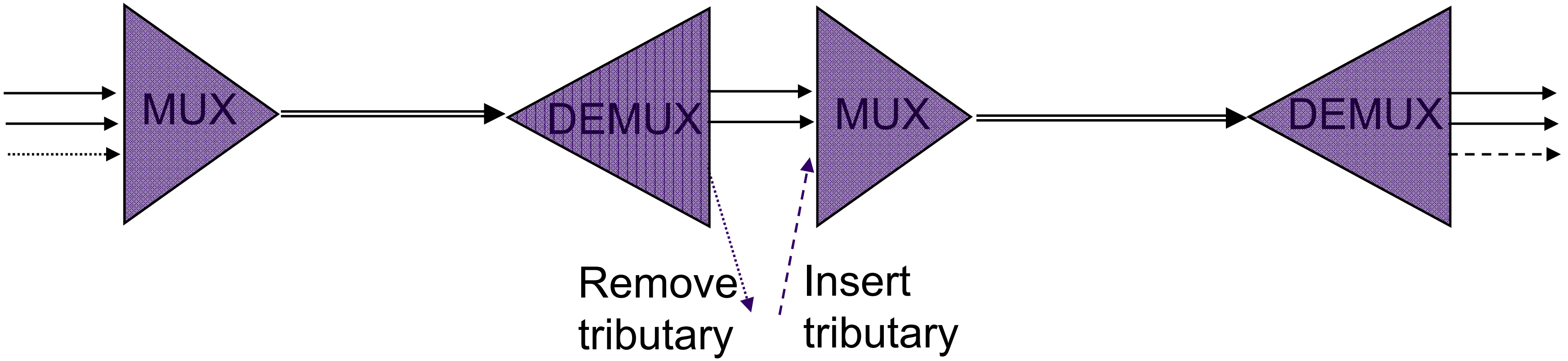
SONET

SONET: Overview

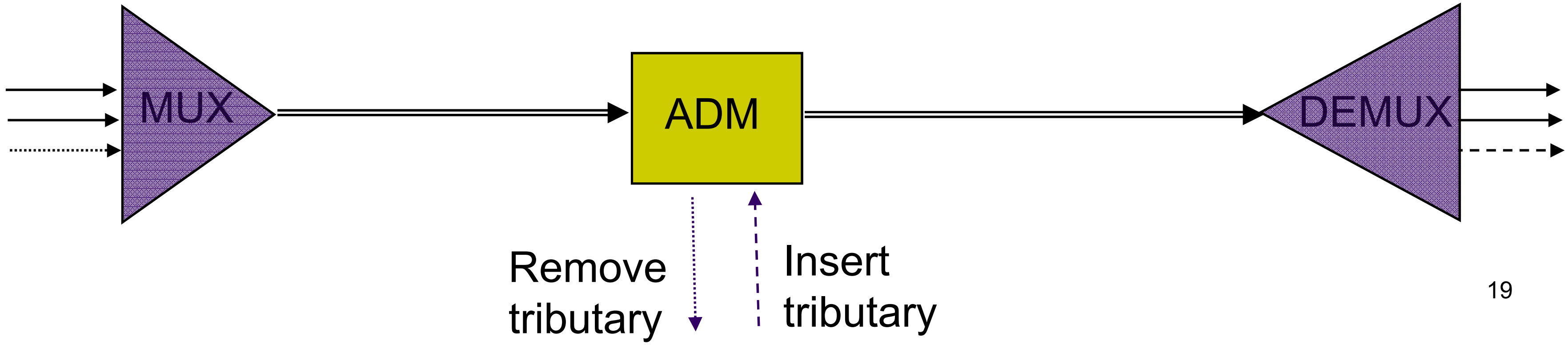
- *Synchronous* Optical NETwork
- North American TDM physical layer standard for optical fiber communications
- 8000 frames/sec. (T_{frame} = 125 μsec)
  - compatible with North American digital hierarchy
- SDH (Synchronous Digital Hierarchy) elsewhere
  - Needs to carry E1 and E3 signals
  - Compatible with SONET at higher speeds
- Greatly simplifies multiplexing in network backbone
- OA&M support to facilitate network management
- Protection & restoration

SONET simplifies multiplexing

Pre-SONET multiplexing: Pulse stuffing required demultiplexing ***all*** channels



SONET Add-Drop Multiplexing: Allows taking individual channels in and out without full demultiplexing



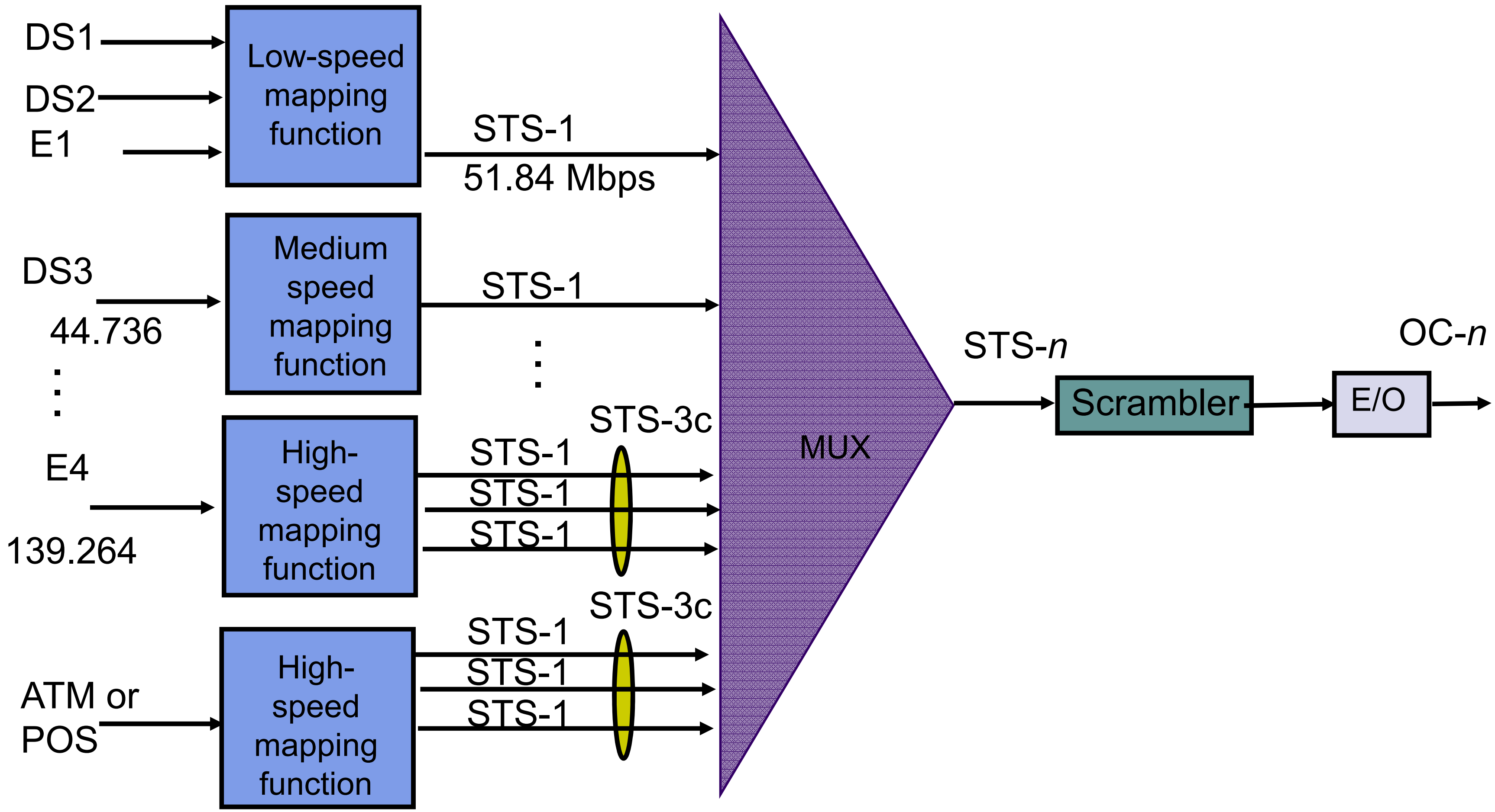
SONET Specifications

- Defines electrical & optical signal interfaces
- Electrical
  - Multiplexing, Regeneration performed in electrical domain
  - STS – Synchronous Transport Signals defined
  - Very short range (e.g., within a switch)
- Optical
  - Transmission carried out in optical domain
  - Optical transmitter & receiver
  - OC – Optical Carrier

SONET & SDH Hierarchy

SONET Electrical Signal	***Optical Signal***	***Bit Rate (Mbps)***	***SDH Electrical Signal***
STS-1	OC-1	51.84	N/A
STS-3	OC-3	155.52	STM-1
STS-9	OC-9	466.56	STM-3
STS-12	OC-12	622.08	STM-4
STS-18	OC-18	933.12	STM-6
STS-24	OC-24	1244.16	STM-8
STS-36	OC-36	1866.24	STM-12
STS-48	OC-48	2488.32	STM-16
STS-192	OC-192	9953.28	STM-64
STS: Synchronous Transport Signal	*OC: Optical Channel*		*STM: Synchronous Transfer Module*

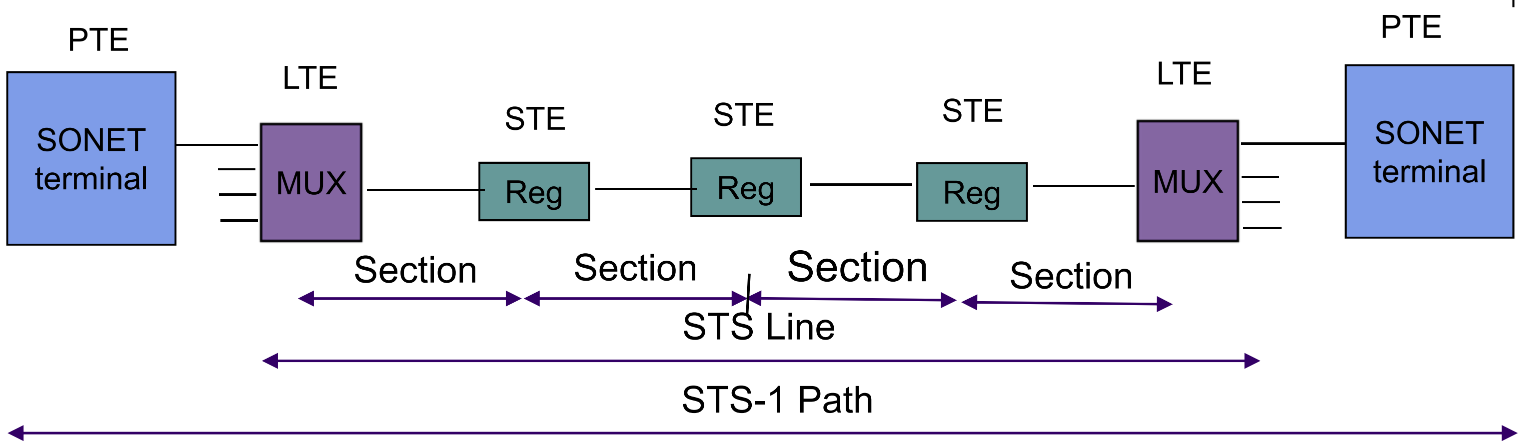
SONET Multiplexing



SONET Equipment

- By Functionality
  - ADMs: dropping & inserting tributaries
  - Regenerators: digital signal regeneration
  - Cross-Connects: interconnecting SONET streams
- By Signaling between elements
  - Section Terminating Equipment (STE): span of fiber between adjacent devices, e.g. regenerators
  - Line Terminating Equipment (LTE): span between adjacent multiplexers, encompasses multiple sections
  - Path Terminating Equipment (PTE): span between SONET terminals at end of network, encompasses multiple lines

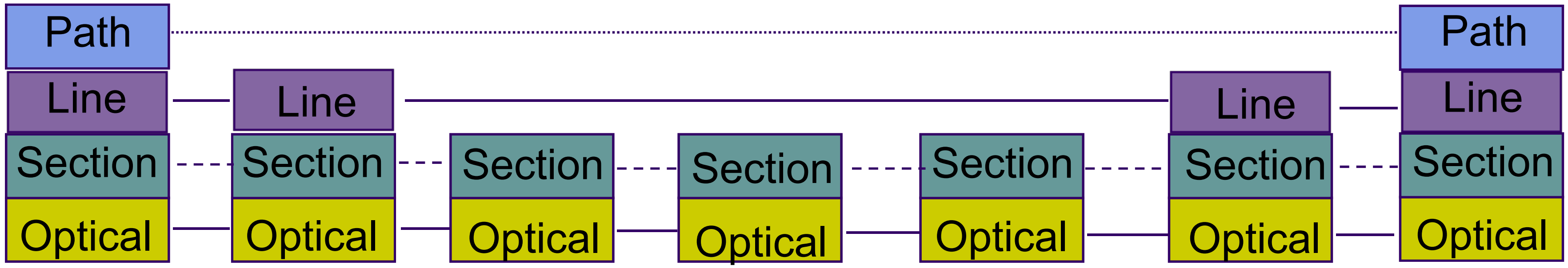
Section, Line, & Path in SONET



STE = Section Terminating Equipment, e.g., a repeater/regenerator
LTE = Line Terminating Equipment, e.g., a STS-1 to STS-3 multiplexer
PTE = Path Terminating Equipment, e.g., an STS-1 multiplexer

- Often, PTE and LTE equipment are the same
  - Difference is based on function and location
  - PTE is at the ends, e.g., STS-1 multiplexer.
  - LTE in the middle, e.g., STS-3 to STS-1 multiplexer.

Section, Line, & Path Layers in SONET



- SONET has four layers
  - Optical, section, line, path
  - Each layer is concerned with the integrity of its own signals
- Each layer has its own protocols
  - SONET provides signaling channels for elements within a layer

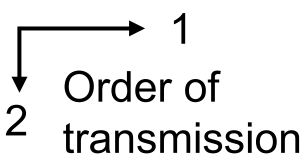
SONET STS Frame

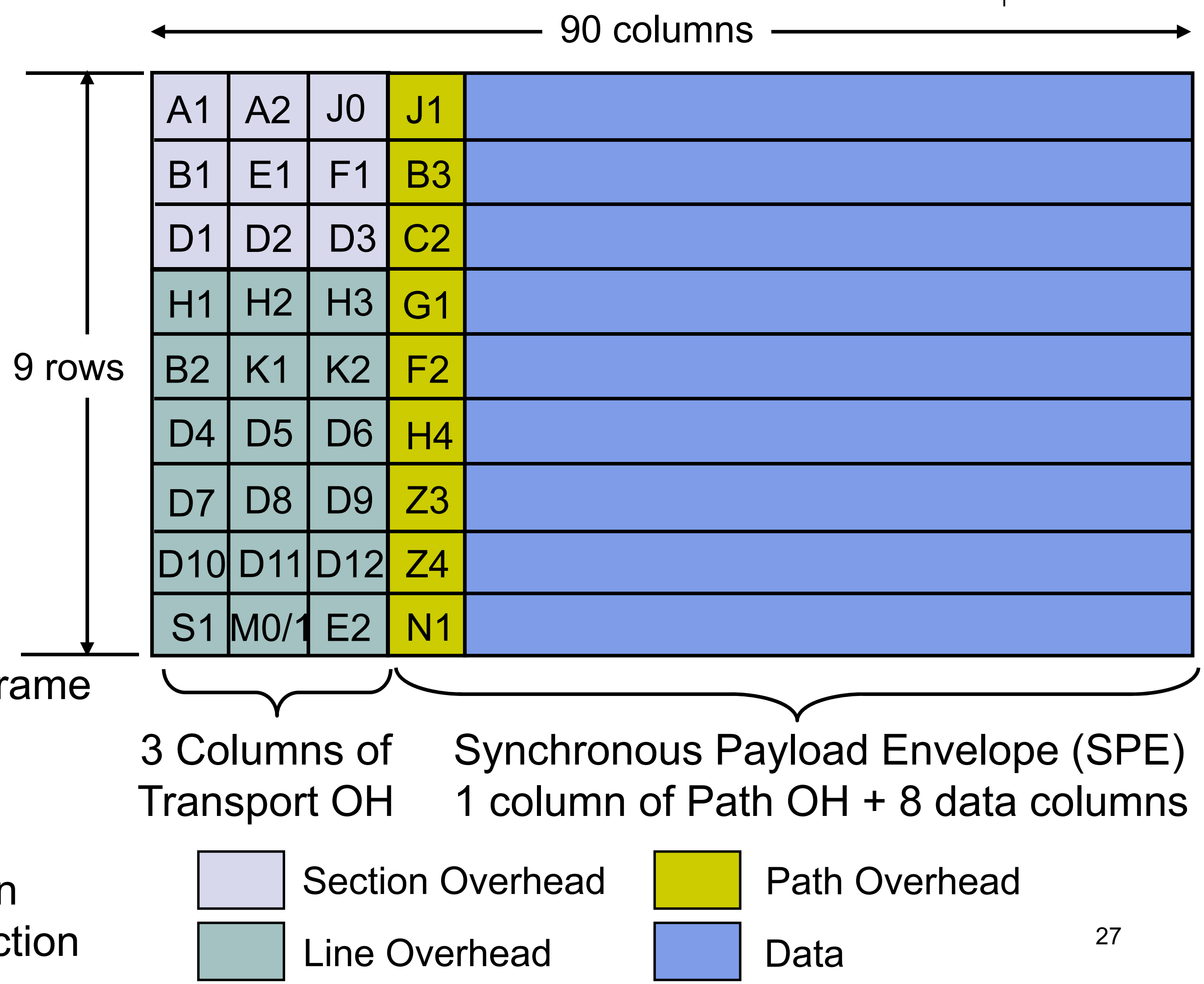
- SONET streams carry two types of overhead
- *Path overhead (POH)*:
  - inserted & removed at the ends
  - *Synchronous Payload Envelope* (SPE) consisting of Data + POH traverses network as a single unit
- *Transport Overhead (TOH):*
  - processed at every SONET node
  - TOH occupies a portion of each SONET frame
  - TOH carries management & link integrity information

STS-1 Frame

810x64kbps=51.84 Mbps

810 Octets per frame @ 8000 frames/sec





Special OH octets:

A1, A2 Frame Synch

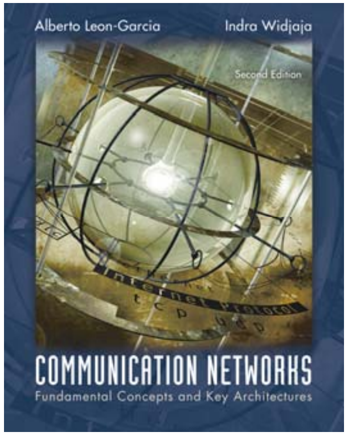
B1 Parity on Previous Frame (BER monitoring)

J0 Section trace (Connection Alive?)

H1, H2, H3 Pointer Action

K1, K2 Automatic Protection Switching

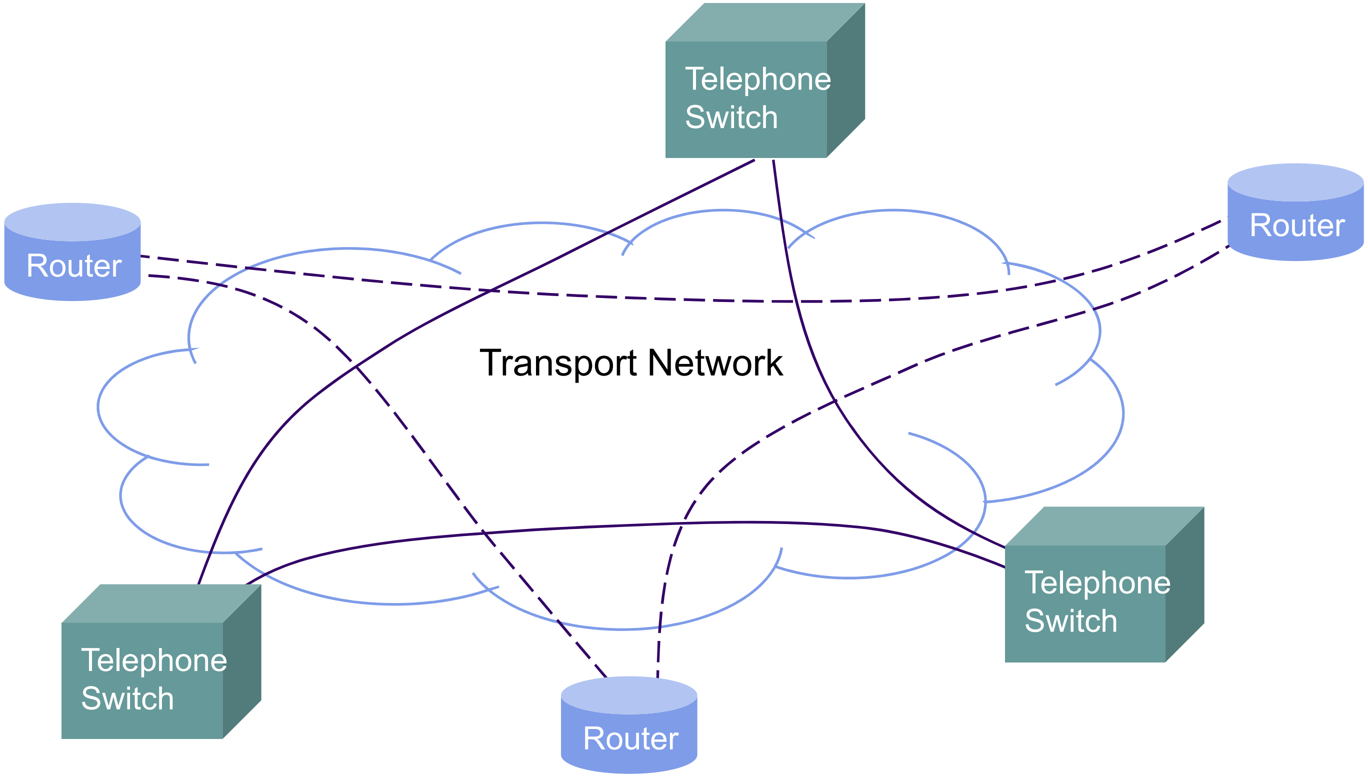
Chapter 4
Circuit-Switching Networks



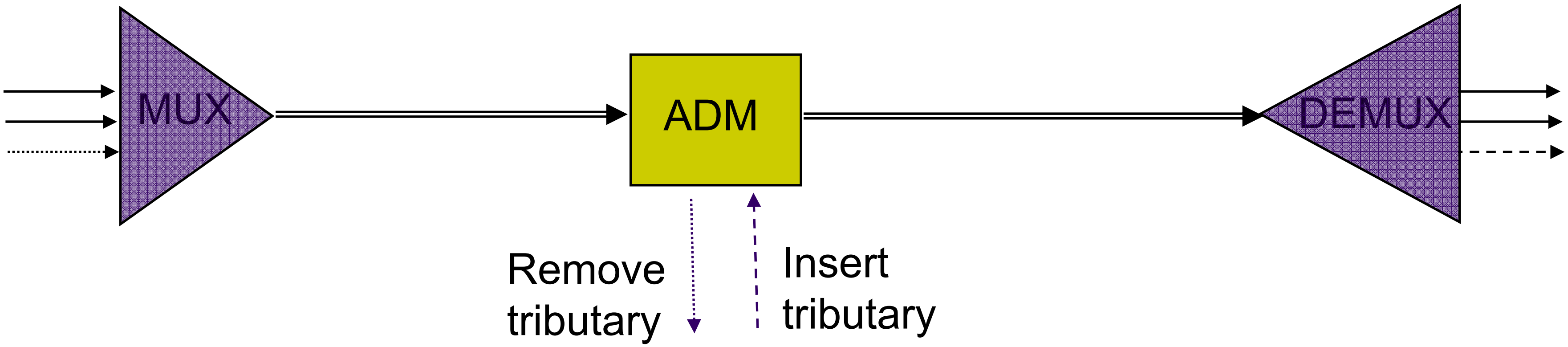
Transport Networks

Transport Networks

- Backbone of modern networks
- Provide high-speed connections: Typically STS-1 up to OC-192
- Clients: large routers, telephone switches, regional networks
- Very high reliability required because of consequences of failure
  - 1 STS-1 = 783 voice calls; 1 OC-48 = 32000 voice calls;



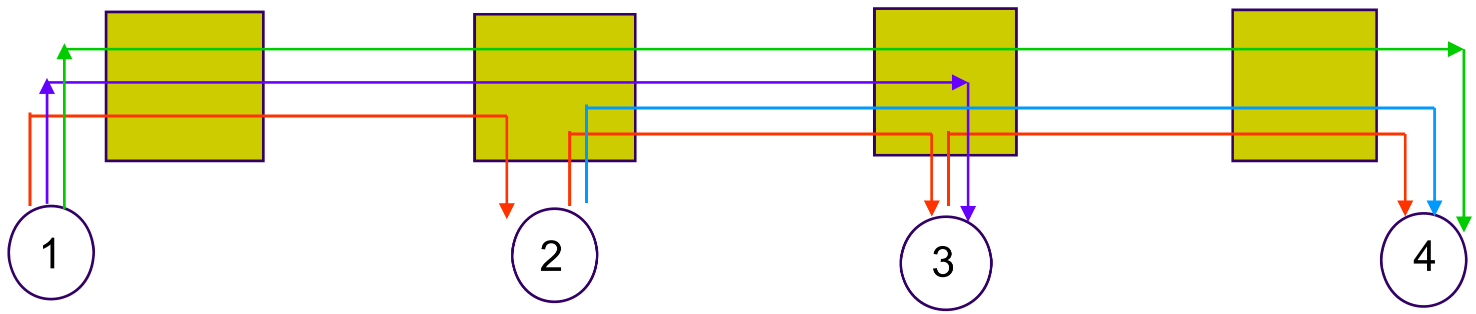
SONET ADM Networks



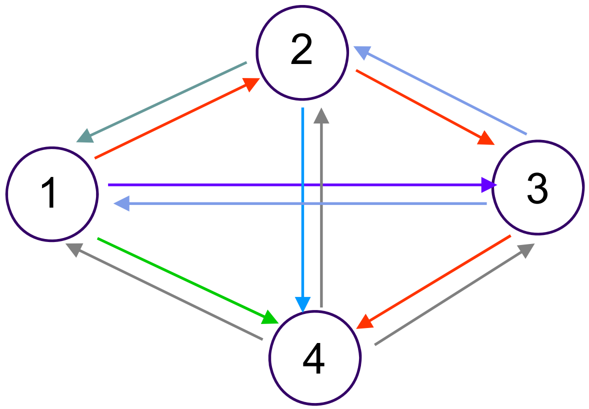
- SONET ADMs: the heart of existing transport networks
- ADMs interconnected in linear and ring topologies
- SONET signaling enables fast restoration (within 50 ms) of transport connections

Linear ADM Topology

- ADMs connected in linear fashion
- Tributaries inserted and dropped to connect clients

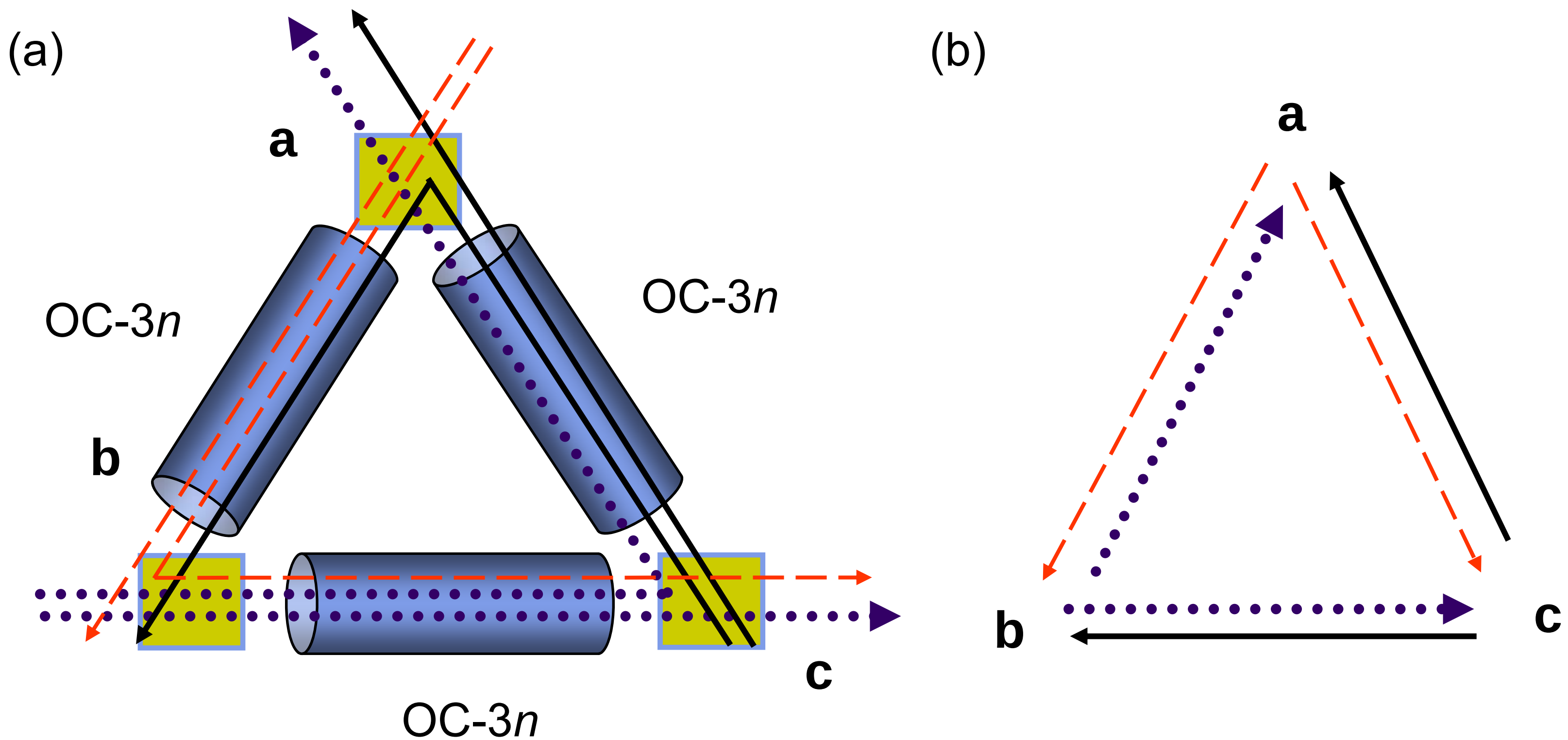


- Tributaries traverse ADMs transparently
- Connections create a *logical* topology seen by clients
- Tributaries from right to left are not shown



SONET Rings

- ADMs can be connected in ring topology
- Clients see *logical* topology created by tributaries



Three ADMs connected in physical ring topology

Logical fully connected topology

SONET Ring Options

- 2 vs. 4 Fiber Ring Network
- Unidirectional vs. bidirectional transmission
- Path vs. Link protection

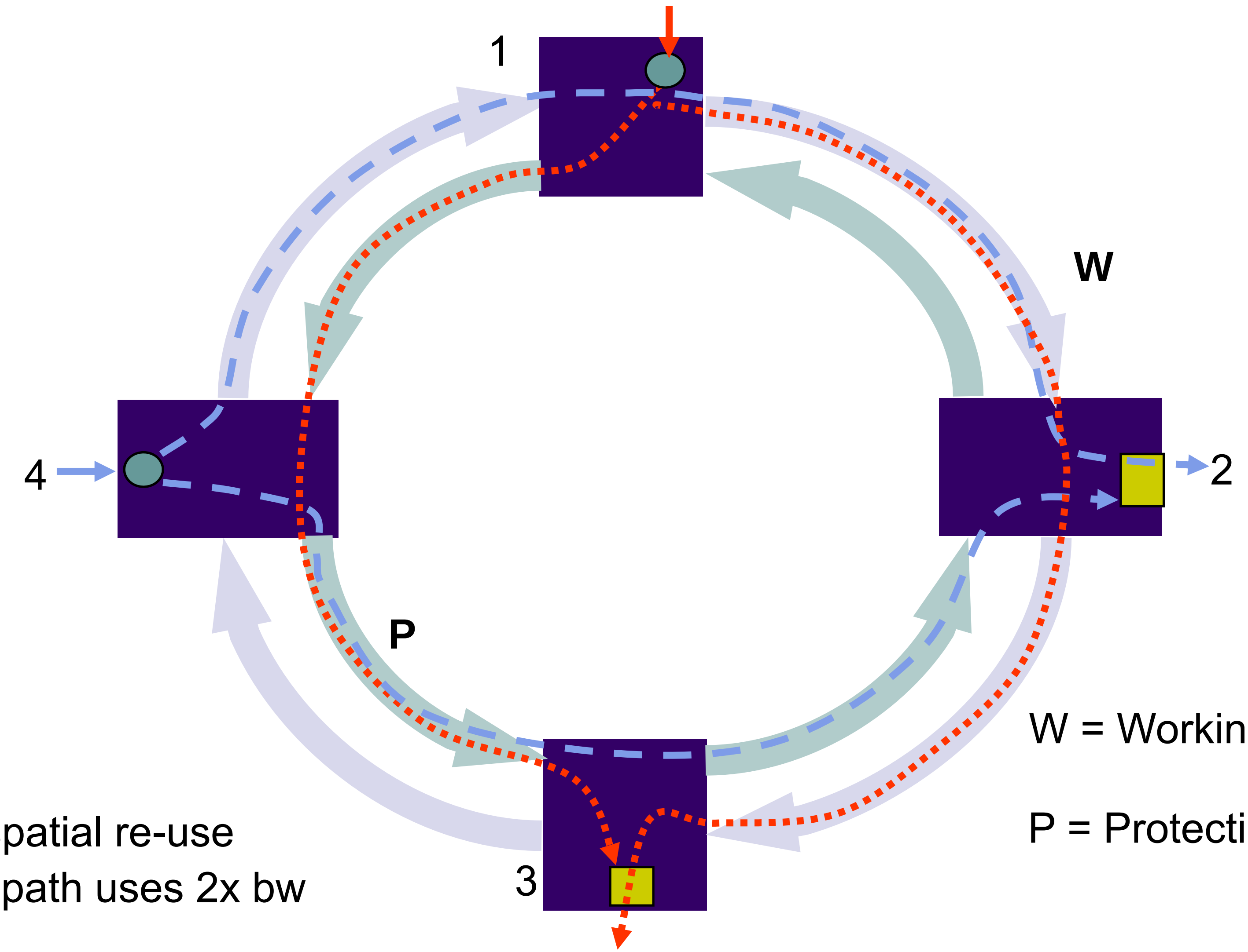
- Spatial capacity re-use & bandwidth efficiency
- Signalling requirements

Two-Fiber Unidirectional Path Switched Ring

Two fibers transmit in opposite directions

- Unidirectional
  - Working traffic flows clockwise
  - Protection traffic flows counter-clockwise
  - 1+1 like
- Selector at receiver does *path protection switching*

UPSR

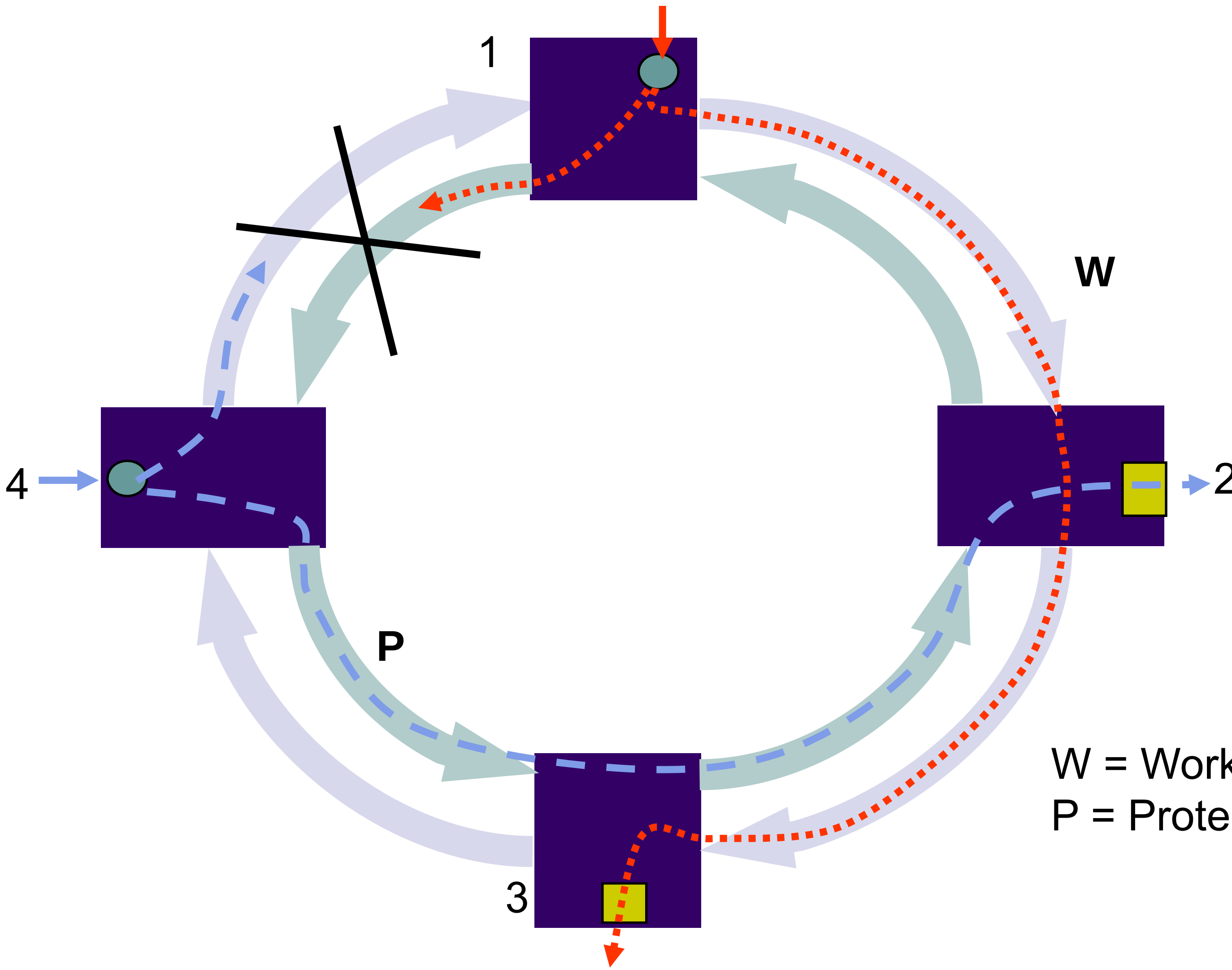


W = Working Paths

P = Protection Paths

No spatial re-use
Each path uses 2x bw

UPSR path recovery



W = Working line
P = Protection line

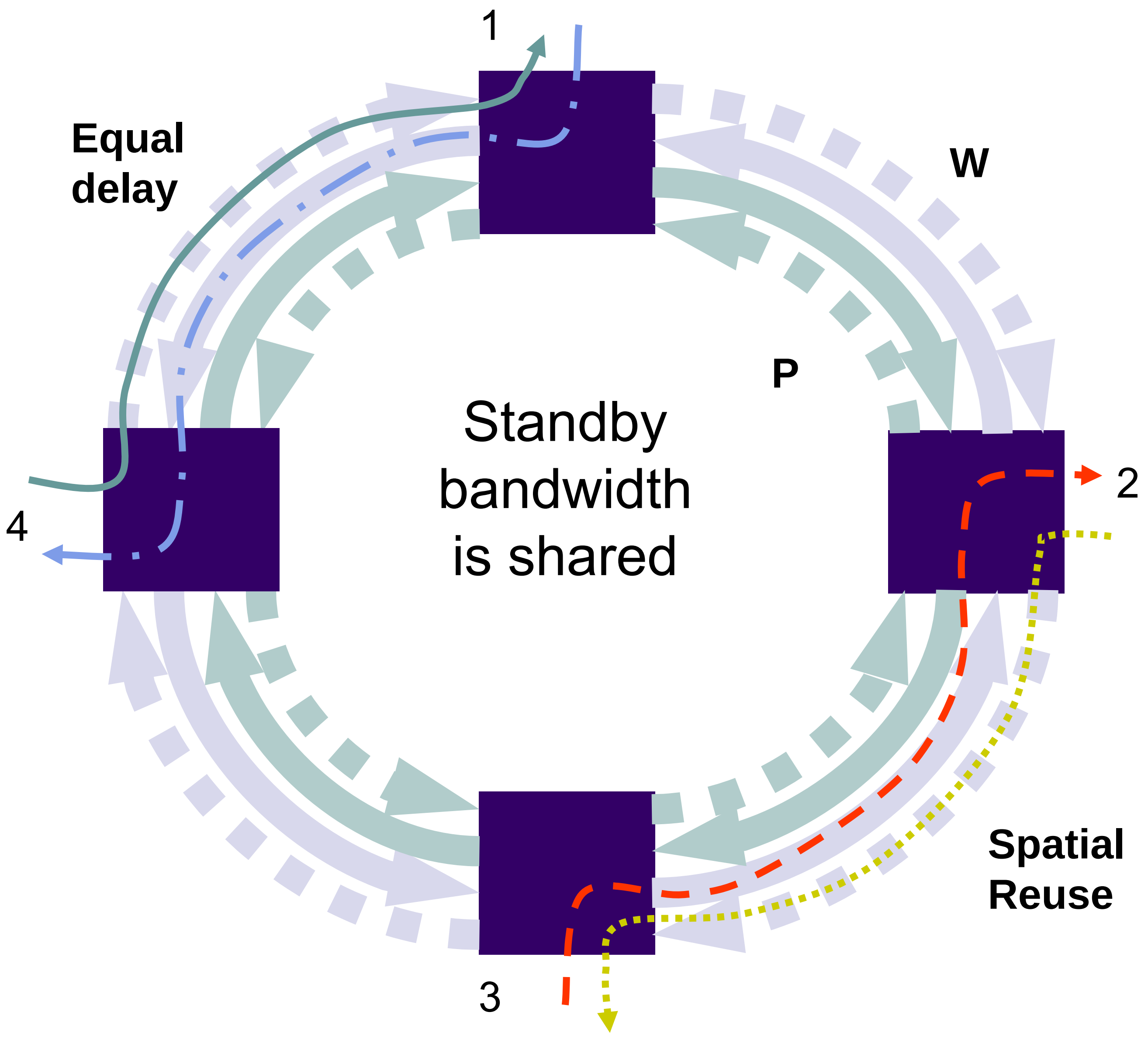
UPSR Properties

- Low complexity
- Fast path protection
- 2 TX, 2 RX
- No spatial re-use; ok for hub traffic pattern
- Suitable for lower-speed access networks
- Different delay between W and P path

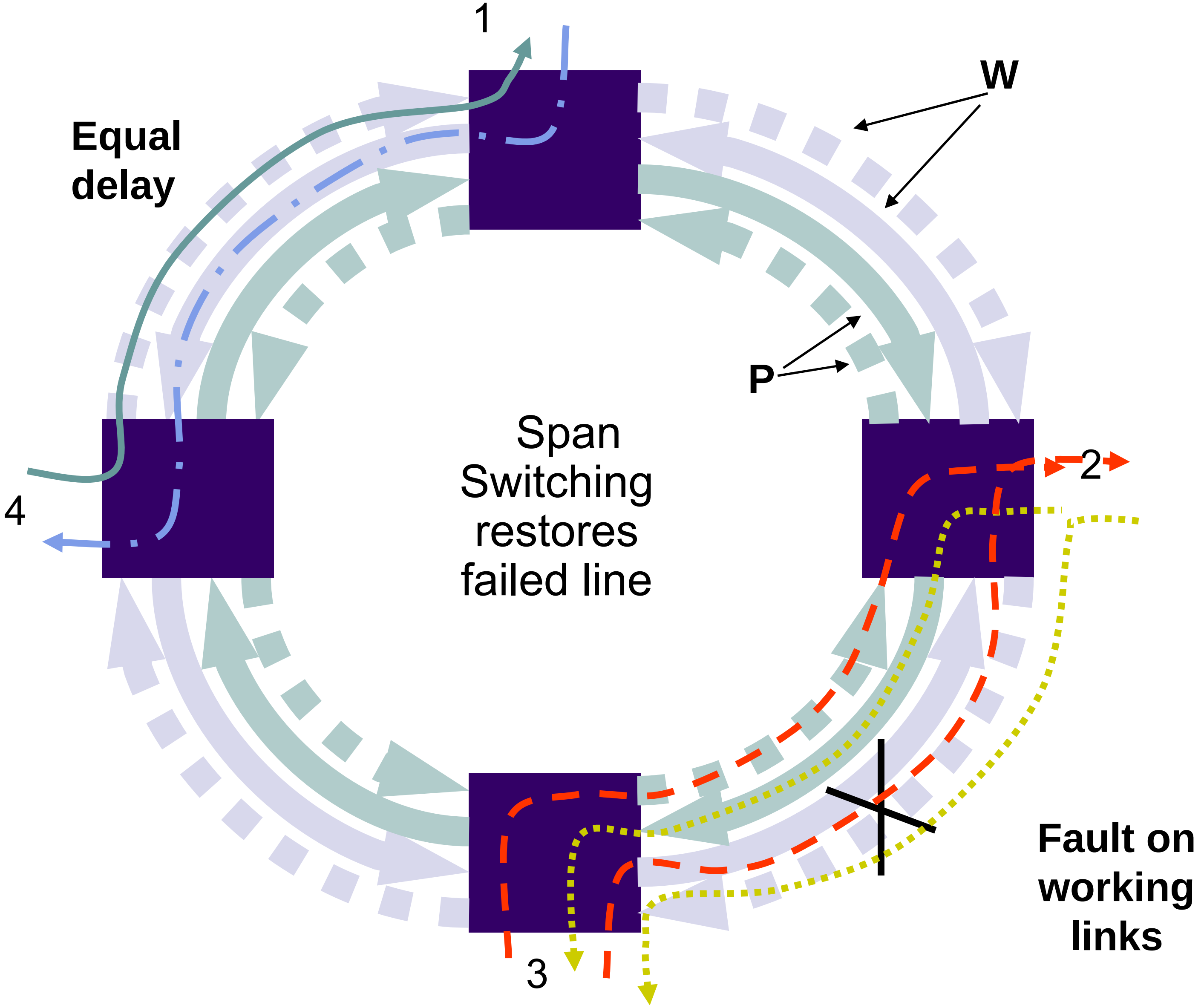
Four-Fiber Bidirectional Line Switched Ring

- 1 working fiber pair; 1 protection fiber pair
- Bidirectional
  - Working traffic & protection traffic use *same route* in working pair
  - 1:N like
- *Line* restoration provided by either:
  - Restoring a failed span
  - Switching the line around the ring

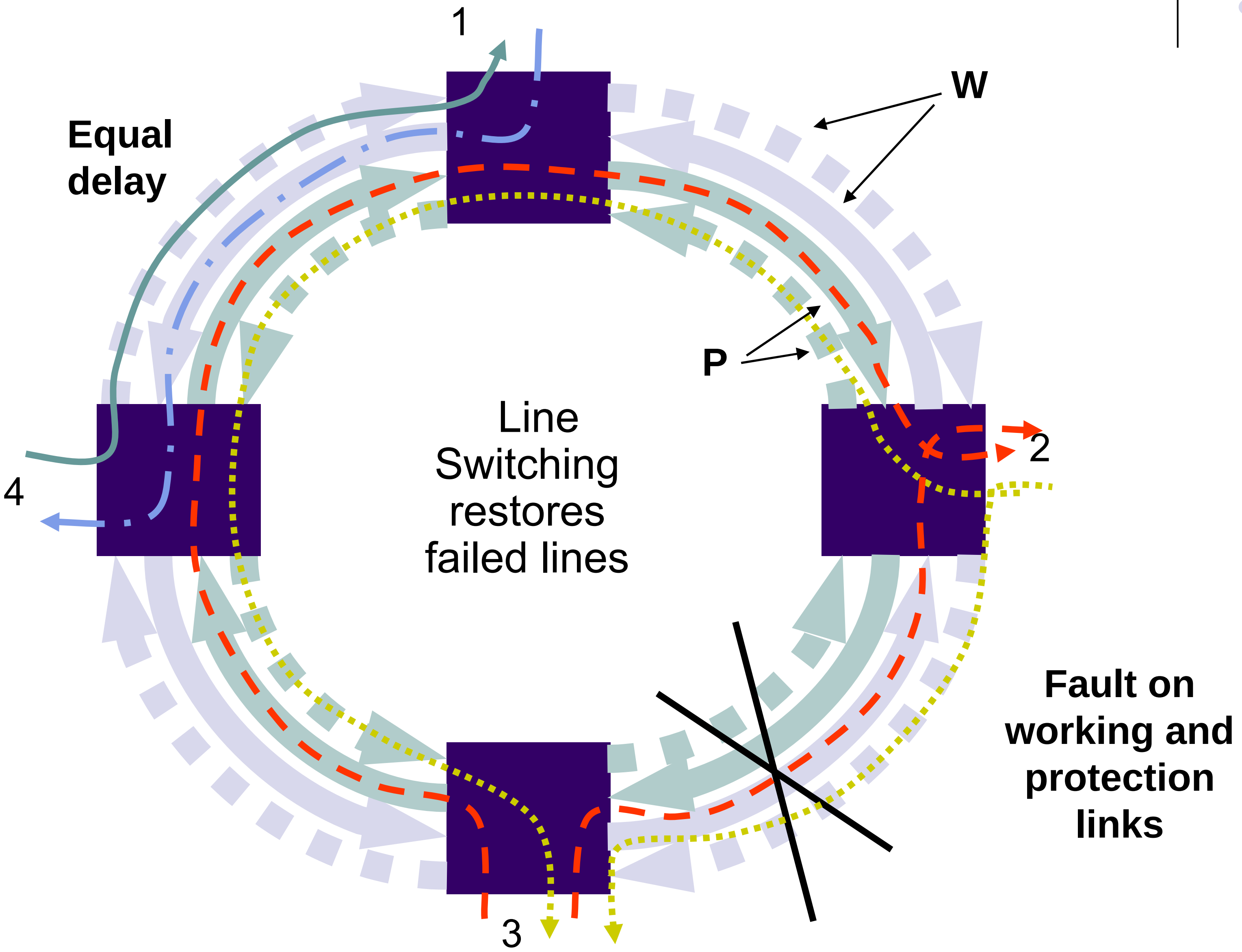
4-BLSR


1
Equal
delay
W
P
Standby
bandwidth
is shared
2
4
Spatial
Reuse
3

BLSR Span Switching



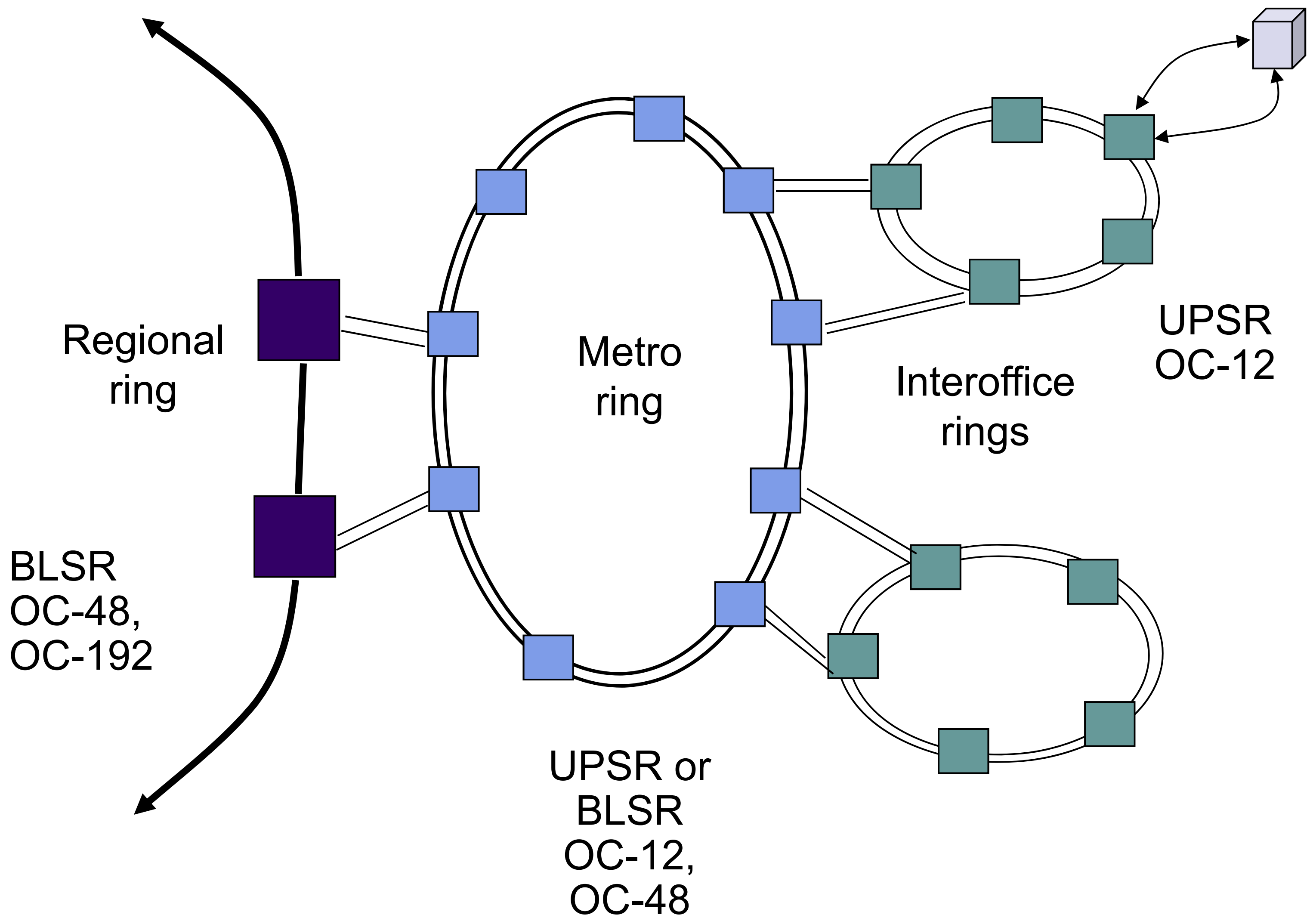
BLSR Span Switching



4-BLSR Properties

- High complexity: signalling required
- Fast line protection for restricted distance (1200 km) and number of nodes (16)
- 4 TX, 4 RX
- Spatial re-use; higher bandwidth efficiency
- Good for uniform traffic pattern
- Suitable for high-speed backbone networks
- Multiple simultaneous faults can be handled

Backbone Networks consist of Interconnected Rings



From SONET to WDM

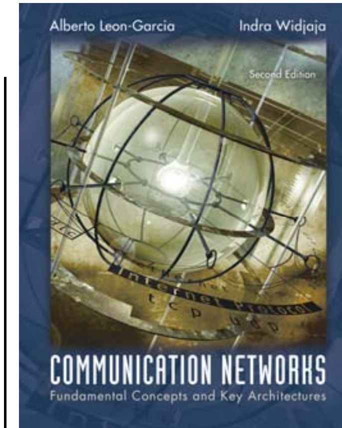
SONET

- combines multiple SPEs into high speed digital stream
- ADMs and crossconnects interconnected to form networks
- SPE paths between clients from logical topology
- High reliability through protection switching

WDM

- combines multiple wavelengths into a common fiber
- Optical ADMs can be built to insert and drop wavelengths in same manner as in SONET ADMS
- Optical crossconnects can also be built
- All-optical backbone networks will provide end-to-end wavelength connections
- Protection schemes for recovering from failures are being developed to provide high reliability in all-optical networks

Chapter 4
Circuit-Switching Networks

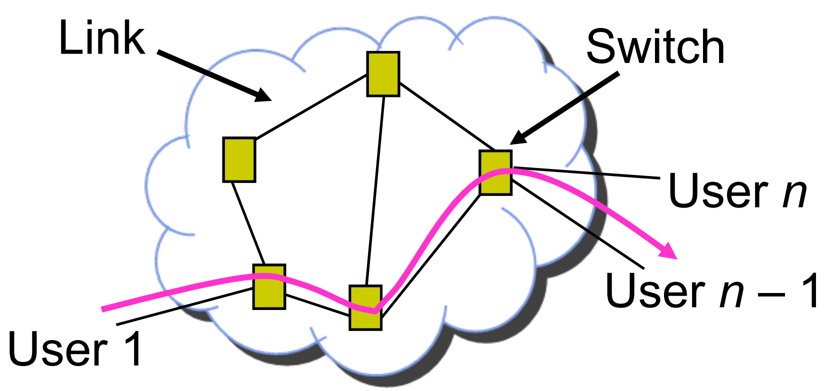


Circuit Switches

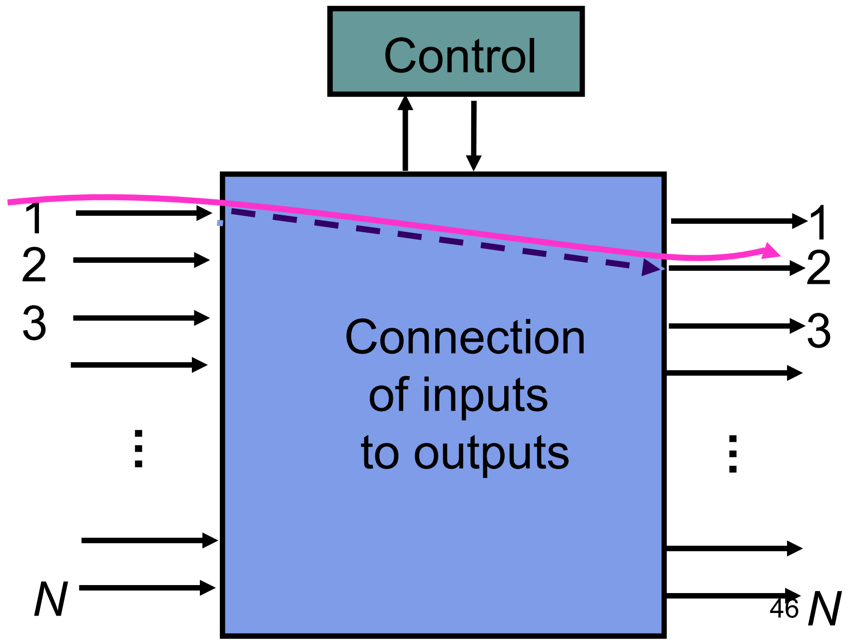
Network: Links & switches

- Circuit consists of dedicated resources in sequence of links & switches across network
- *Circuit switch* connects input links to output links

Network



Switch

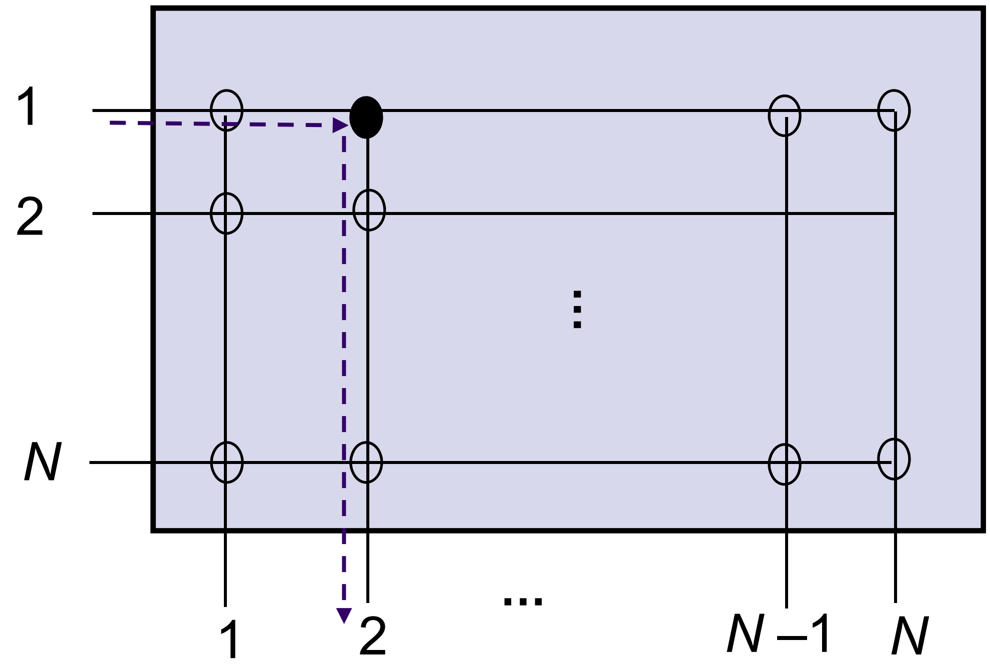


Circuit Switch Types

- Space-Division switches
  - Provide separate physical connection between inputs and outputs
  - Crossbar switches
  - Multistage switches
- Time-Division switches
  - Time-slot interchange technique
  - Time-space-time switches
- Hybrids combine Time & Space switching

Crossbar Space Switch

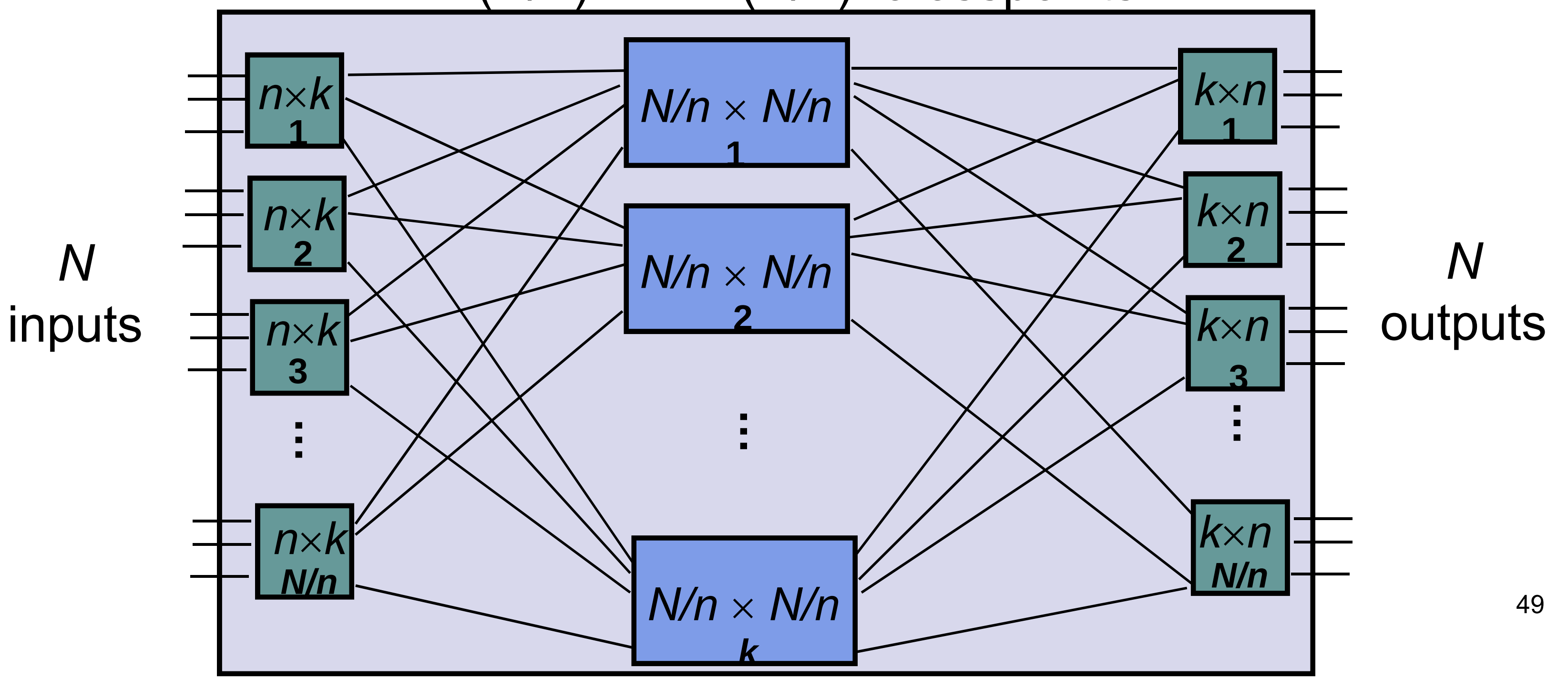
- *N* x *N* array of crosspoints
- Connect an input to an output by closing a crosspoint
- Nonblocking: Any input can connect to idle output
- Complexity: N^2 crosspoints



Multistage Space Switch

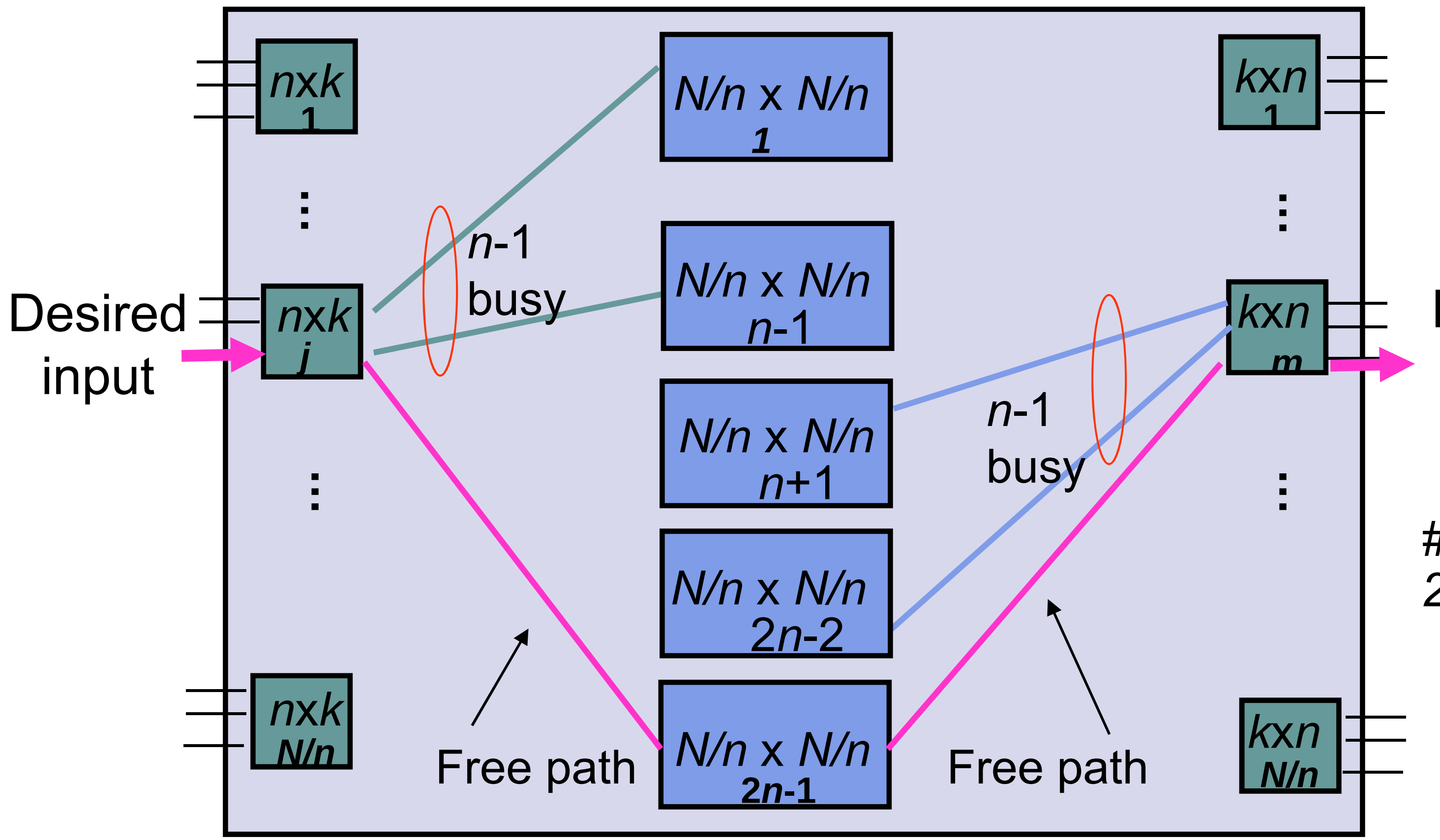
- Large switch built from multiple stages of small switches
- The n inputs to a first-stage switch share k paths through intermediate crossbar switches
- Larger k (more intermediate switches) means more paths to output
- In 1950s, Clos asked, “How many intermediate switches required to make switch nonblocking?”

$2(N/n)nk + k\,(N/n)^2$ crosspoints



Clos Non-Blocking Condition: *k=2n-1*

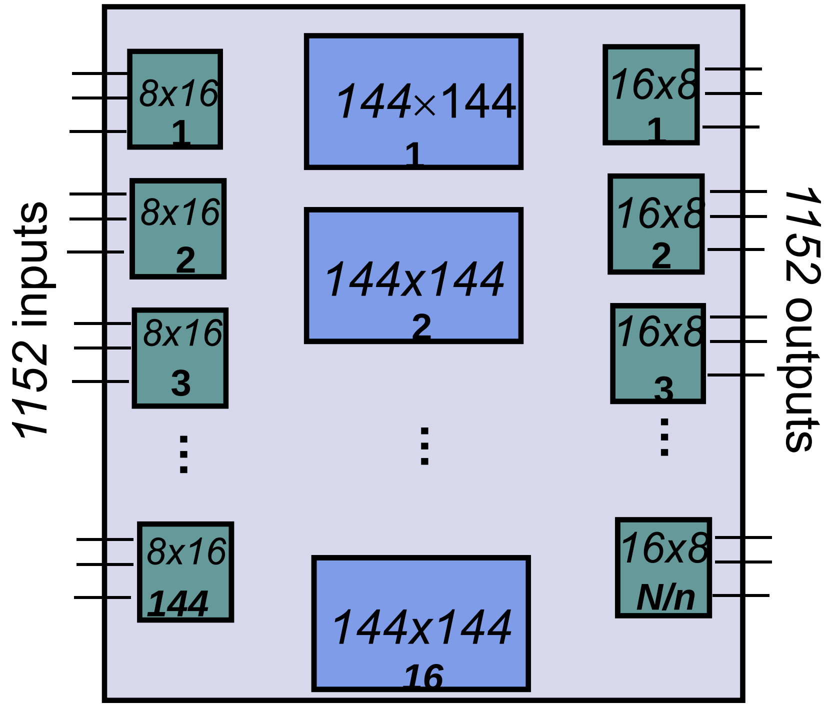
- Request connection from last input to input switch j to last output in output switch m
- Worst Case: All other inputs have seized top n-1 middle switches AND all other outputs have seized next n-1 middle switches
- If ***k=2n-1***, there is another path left to connect desired input to desired output



 # internal links = 2x # external links

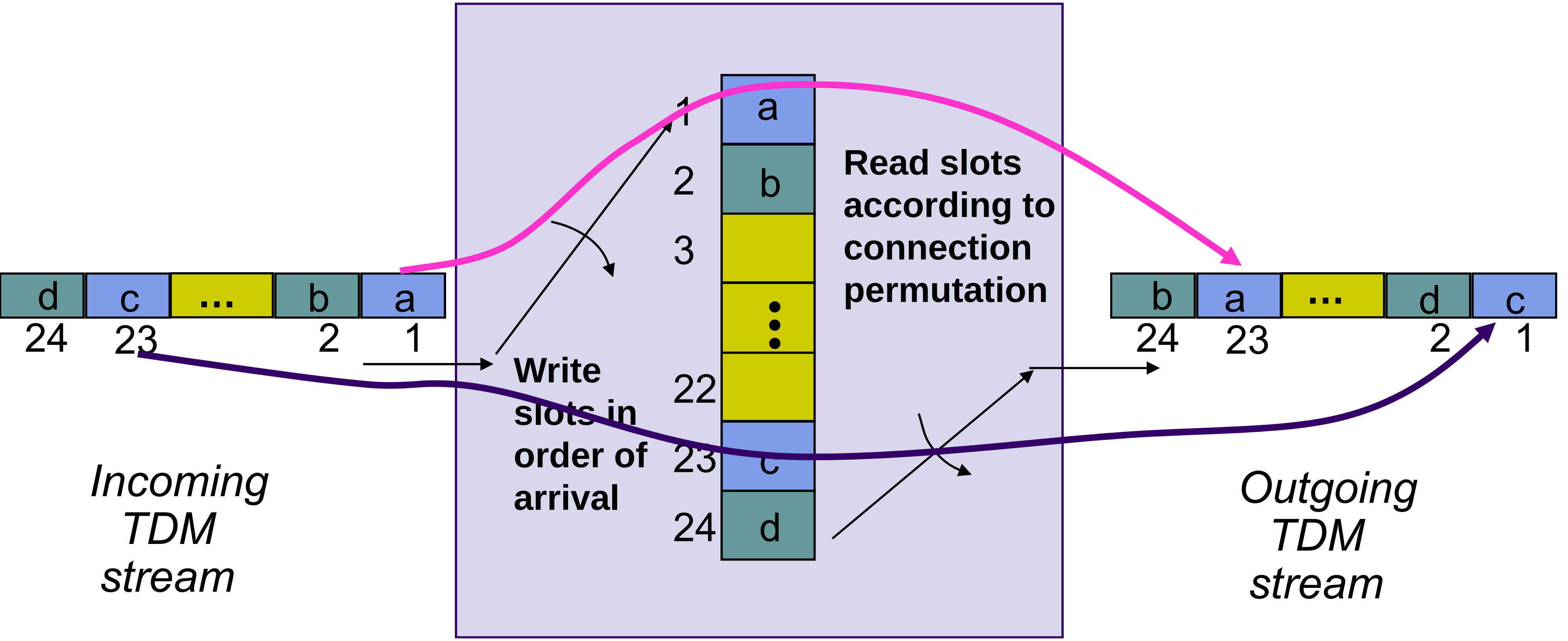
Example: Clos Switch Design

- Circa 2002, Mindspeed offered a Crossbar chip with the following specs:
  - 144 inputs x 144 outputs, 3.125 Gbps/line
  - Aggregate Crossbar chip throughput: 450 Gbps
- Clos Nonblocking Design for 1152x1152 switch
  - N=1152, n=8, k=16
  - N/n=144 8x16 switches in first stage
  - 16 144x144 in centre stage
  - 144 16x8 in third stage
  - Aggregate Throughput: 3.6 Tbps!
  - Note: the 144x144 crossbar can be partitioned into multiple smaller switches



Time-Slot Interchange (TSI) Switching

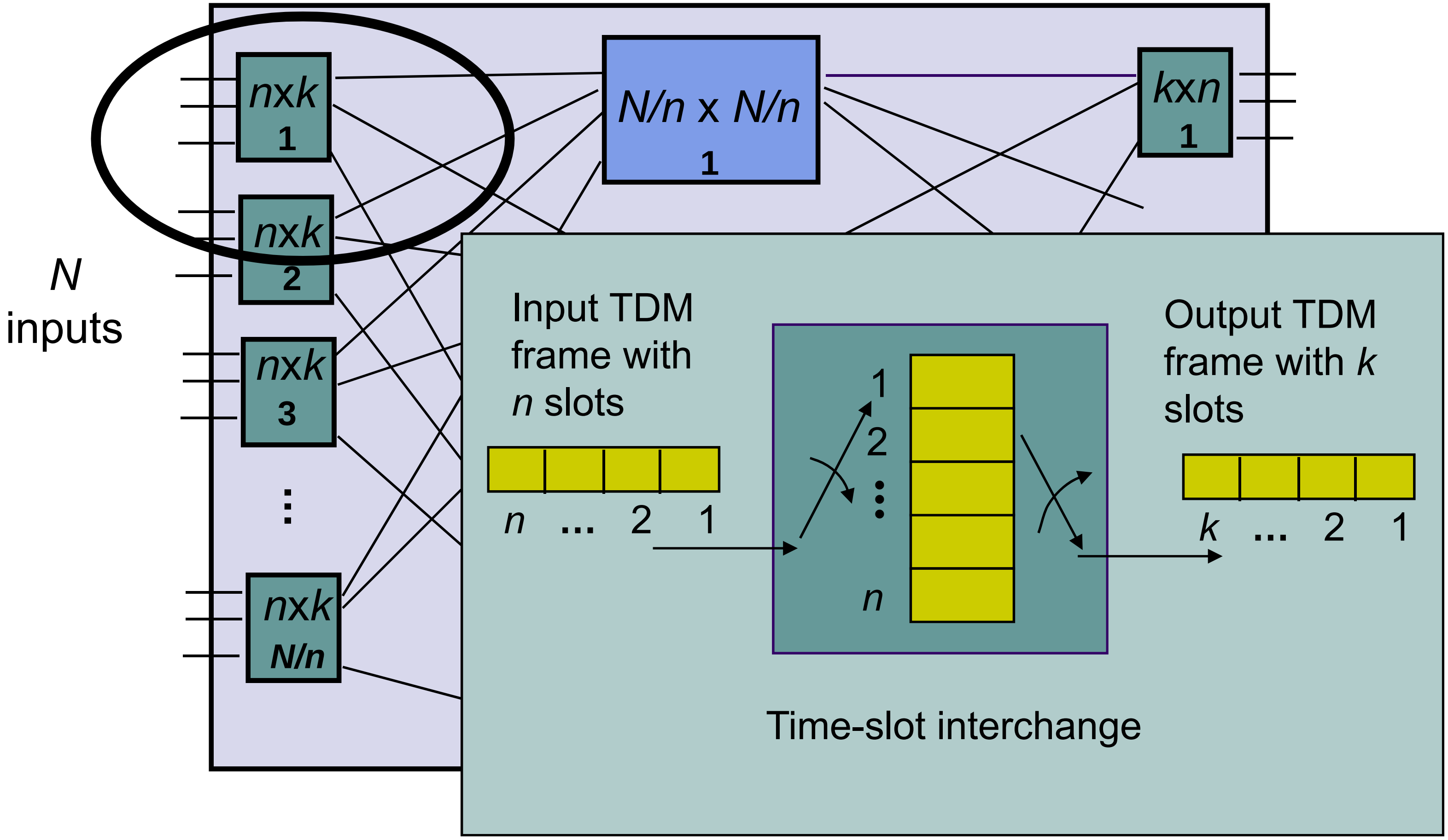
- Write bytes from arriving TDM stream into memory
- Read bytes in permuted order into outgoing TDM stream
- Max # slots = 125 μsec / (2 x memory cycle time)



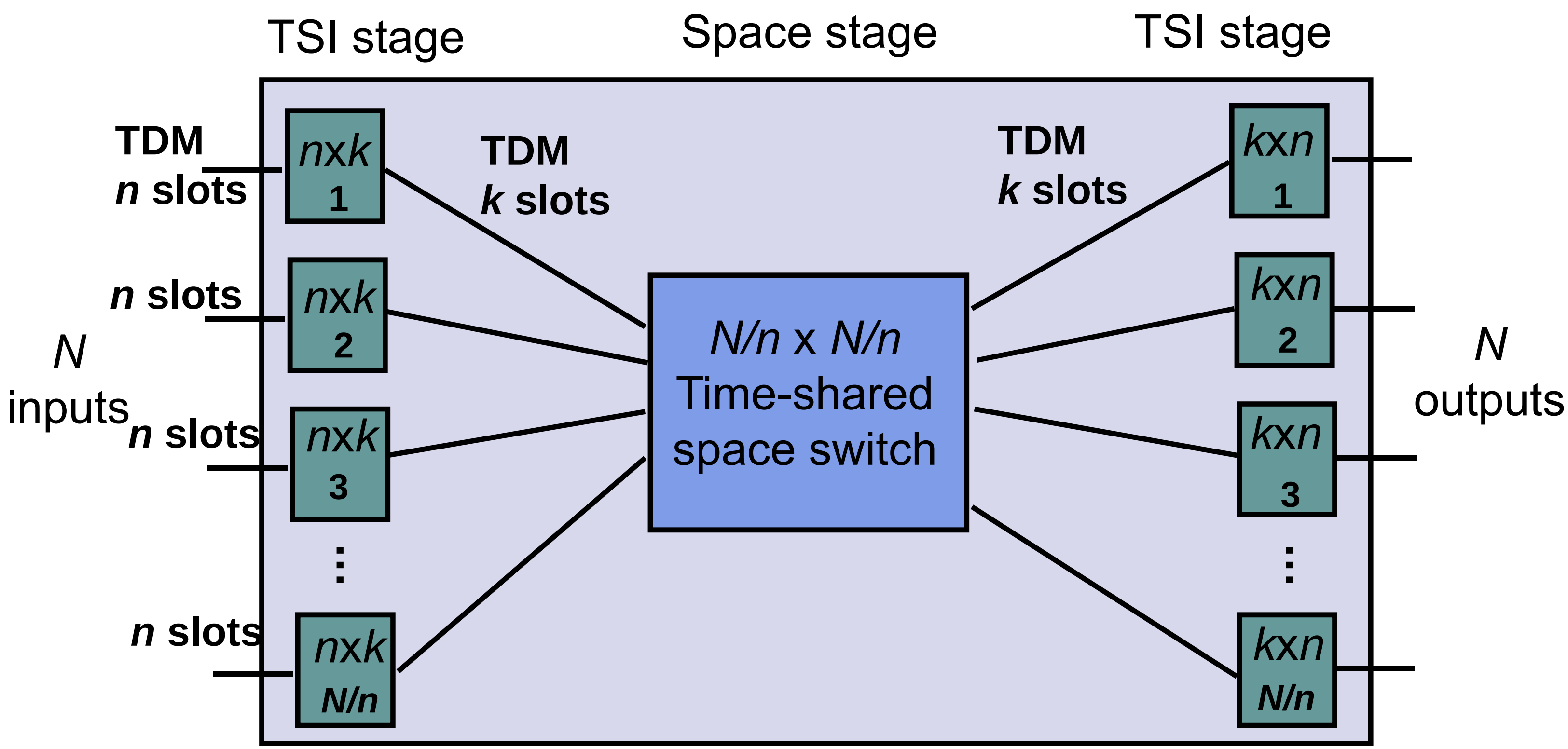
Time-slot interchange

Time-Space-Time Hybrid Switch

- Use TSI in first & third stage; Use crossbar in middle
- Replace n input x k output space switch by TSI switch that takes n-slot input frame and switches it to k-slot output frame



Time-Share the Crossbar Switch



- Interconnection pattern of space switch is reconfigured every time slot
- Very compact design: fewer lines because of TDM & less space because of time-shared crossbar

Available TSI Chips circa 2002

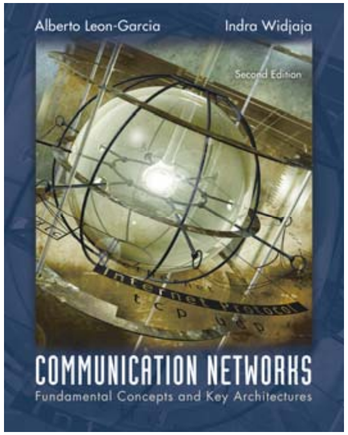
- OC-192 SONET Framer Chips
  - Decompose 192 STS1s and perform (restricted) TSI

- Single-chip TST
  - 64 inputs x 64 outputs
  - Each line @ STS-12 (622 Mbps)
  - Equivalent to 768x768 STS-1 switch

Pure Optical Switching

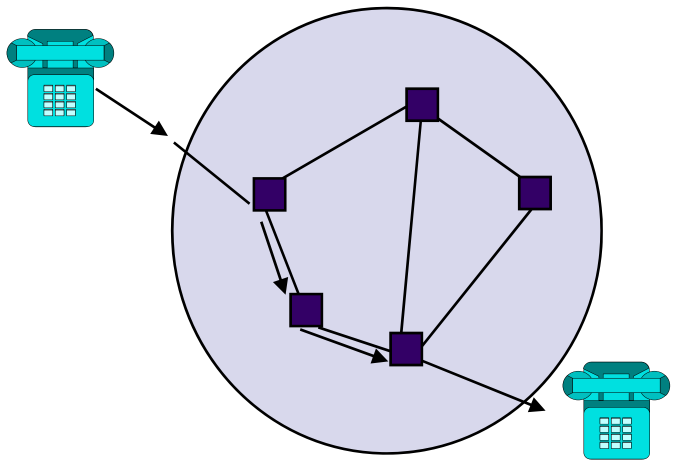
- Pure Optical switching: light-in, light-out, without optical-to-electronic conversion
- Space switching theory can be used to design optical switches
  - Multistage designs using small optical switches
  - Typically 2x2 or 4x4
  - MEMs and Electro-optic switching devices
- Wavelength switches
  - Very interesting designs when space switching is combined with wavelength conversion devices

Chapter 4
Circuit-Switching Networks

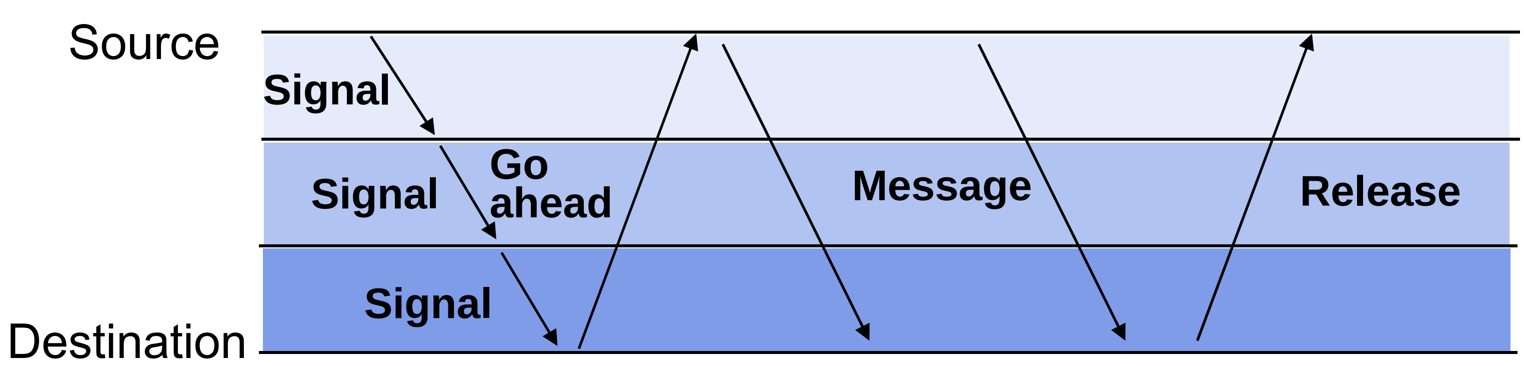


The Telephone Network

Telephone Call

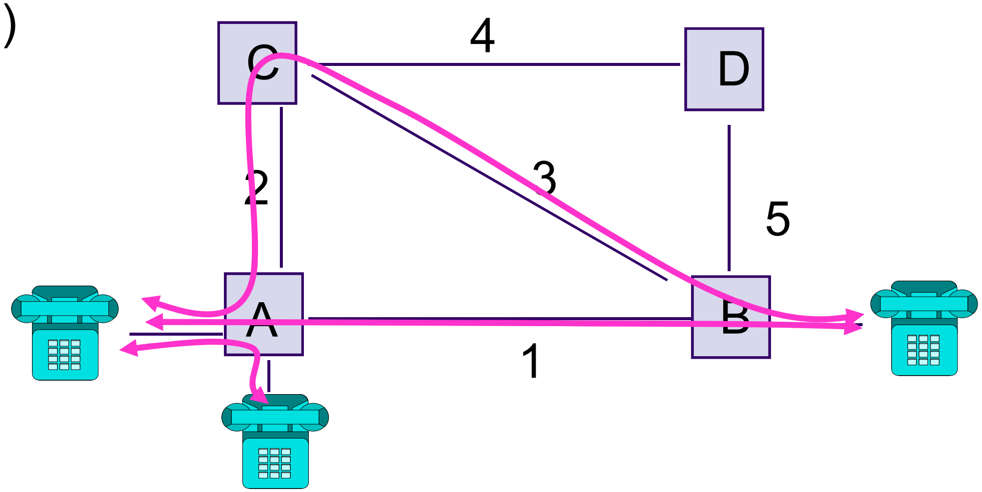


- User requests connection
- Network signaling establishes connection
- Speakers converse
- User(s) hang up
- Network releases connection resources



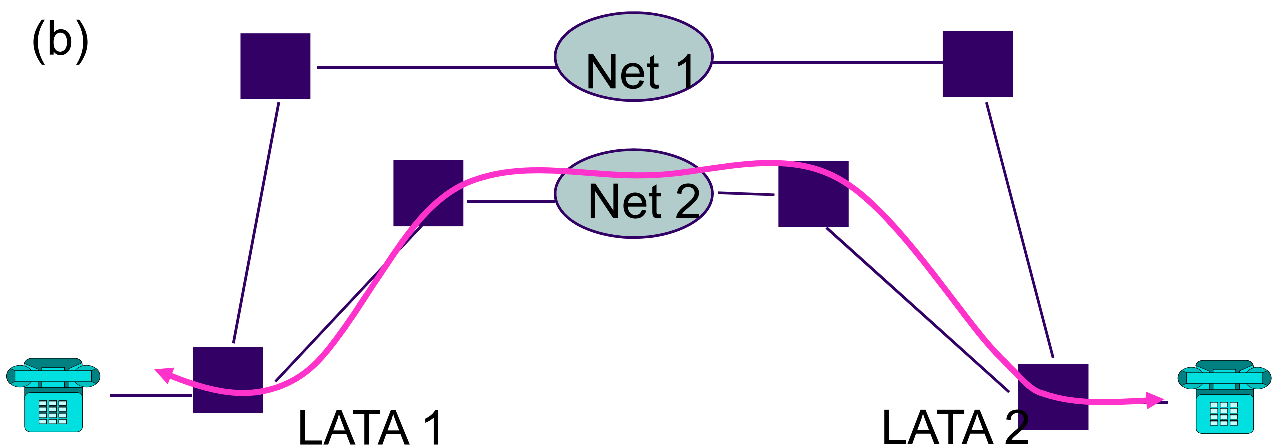
Call Routing

(a)



- Local calls routed through local network (In U.S. Local Access & Transport Area)
- Long distance calls routed to long distance service provider

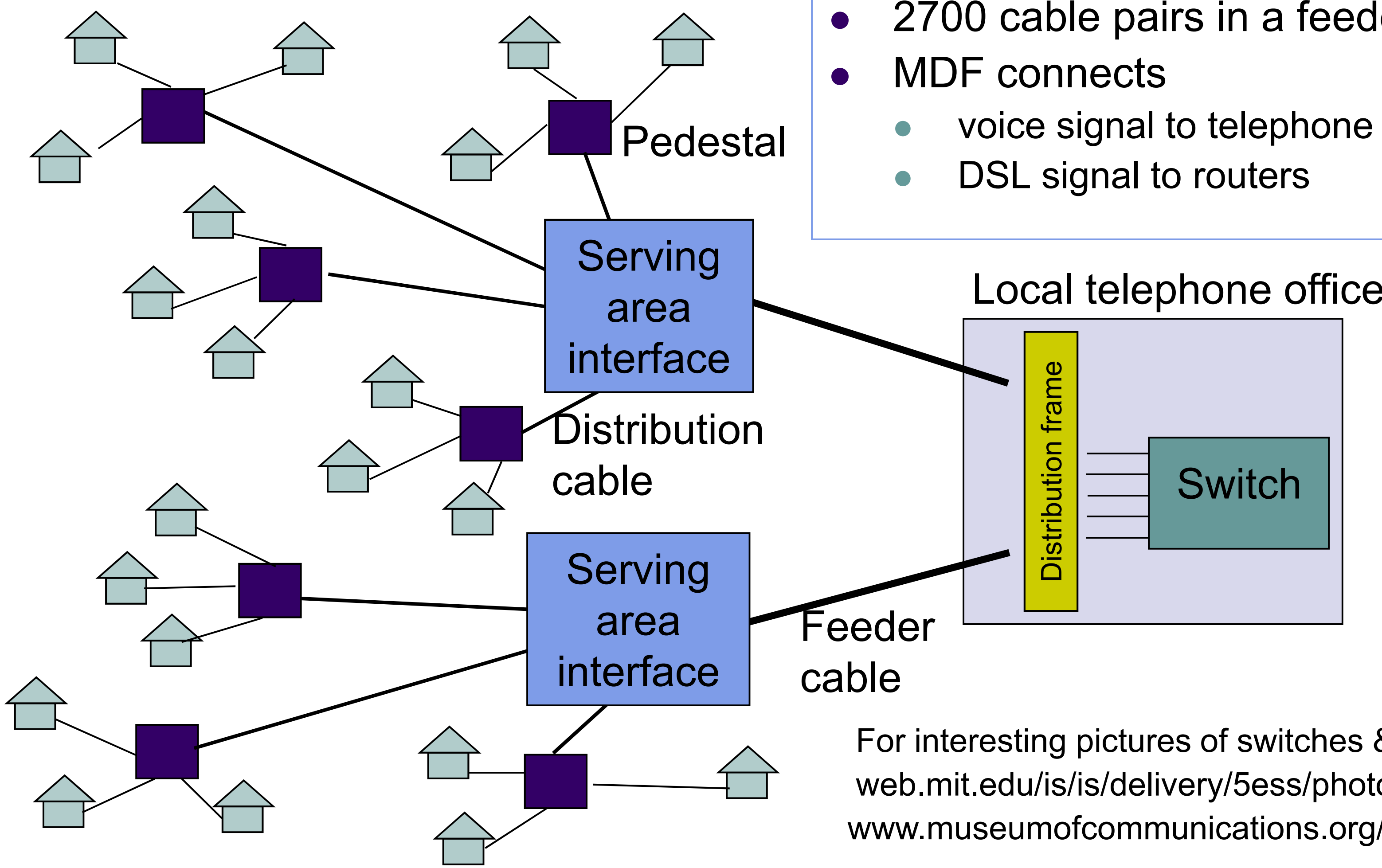
(b)



Telephone Local Loop

Local Loop: "Last Mile"

- Copper pair from telephone to CO
- Pedestal to SAI to Main Distribution Frame (MDF)
- 2700 cable pairs in a feeder cable
- MDF connects
  - voice signal to telephone switch
  - DSL signal to routers



For interesting pictures of switches & MDF, see
web.mit.edu/is/is/delivery/5ess/photos.html
www.museumofcommunications.org/coe.html

Fiber-to-the-Home or Fiber-to-the-Curve?

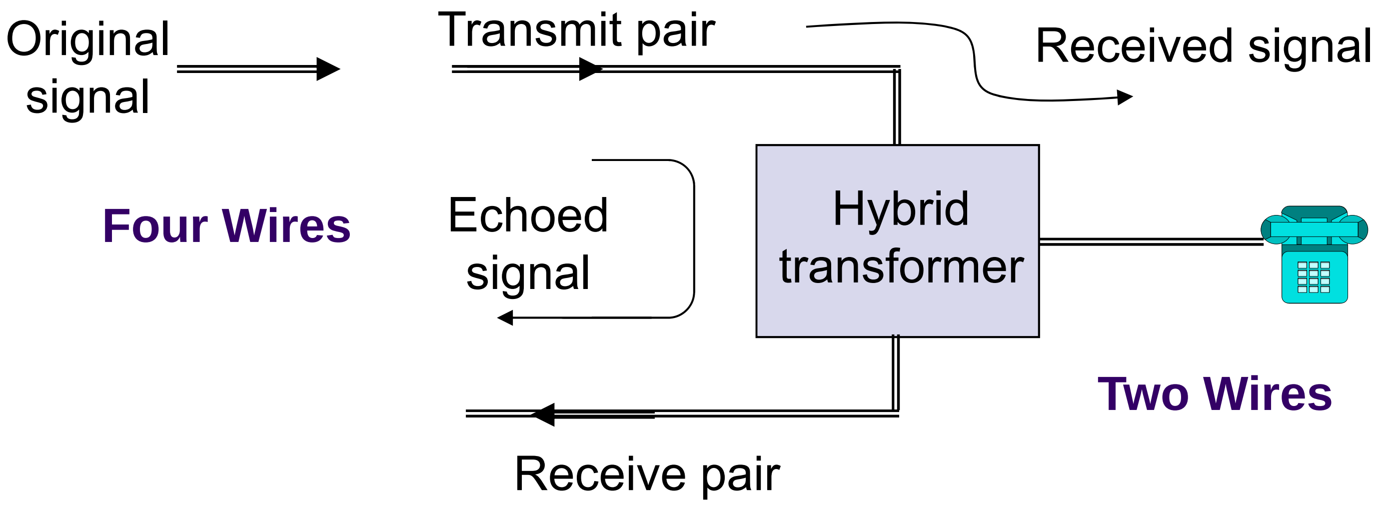
Table 3.5 Data rates of 24-gauge twisted pair

Standard	Data Rate	Distance
T-1	1.544 Mbps	18,000 feet, 5.5 km
DS2	6.312 Mbps	12,000 feet, 3.7 km
1/4 STS-1	12.960 Mbps	4500 feet, 1.4 km
1/2 STS-1	25.920 Mbps	3000 feet, 0.9 km
STS-1	51.840 Mbps	1000 feet, 300 m

- Fiber connection to the home provides huge amount of bandwidth, but cost of optical modems still high
- Fiber to the curve (pedestal) with shorter distance from pedestal to home can provide high speeds over copper pairs

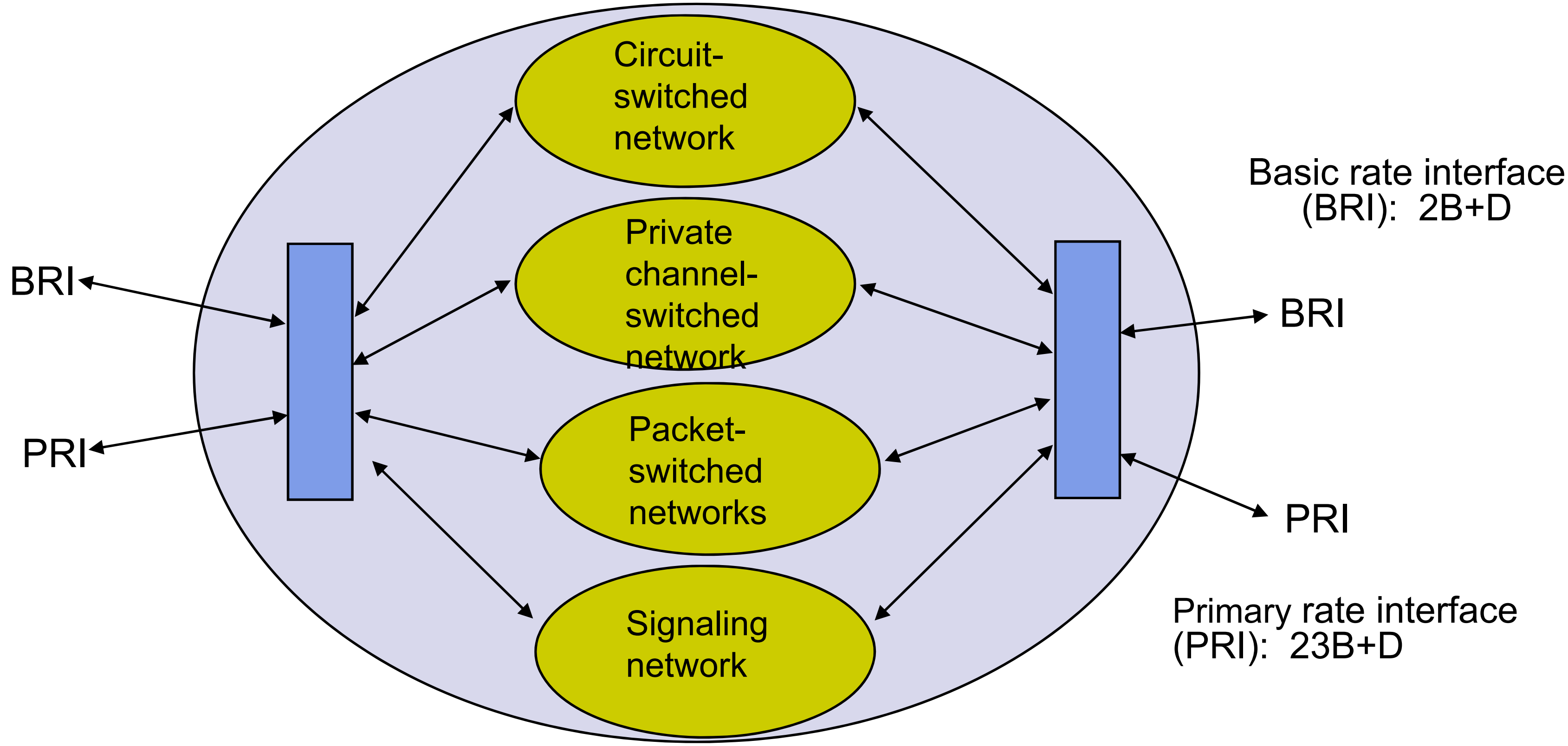
Two- & Four-wire connections

- From telephone to CO, two wires carry signals in both directions
- Inside network, 1 wire pair per direction
- Conversion from 2-wire to 4-wire occurs at hybrid transformer in the CO
- Signal reflections can occur causing speech echo
- Echo cancellers used to subtract the echo from the voice signals

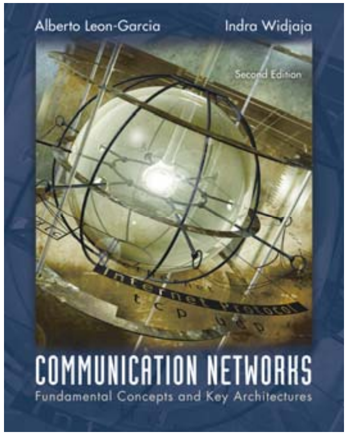


Integrated Services Digital Network (ISDN)

- First effort to provide end-to-end digital connections
- B channel = 64 kbps, D channel = 16 kbps
- ISDN defined interface to network
- Network consisted of separate networks for voice, data, signaling



Chapter 4
Circuit-Switching Networks



Signaling

Setting Up Connections

Manually

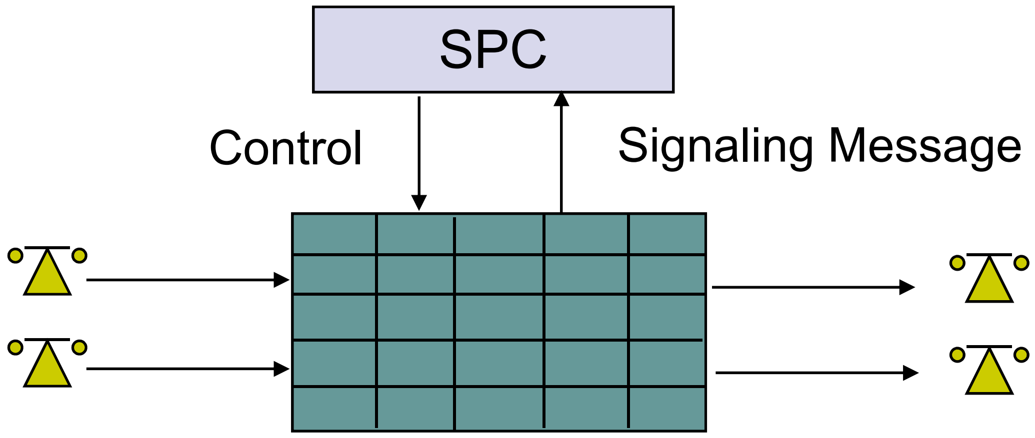
- Human Intervention
- Telephone
  - Voice commands & switchboard operators
- Transport Networks
  - Order forms & dispatching of craftpersons

Automatically

- Management Interface
  - Operator at console sets up connections at various switches
- Automatic signaling
  - Request for connection generates signaling messages that control connection setup in switches

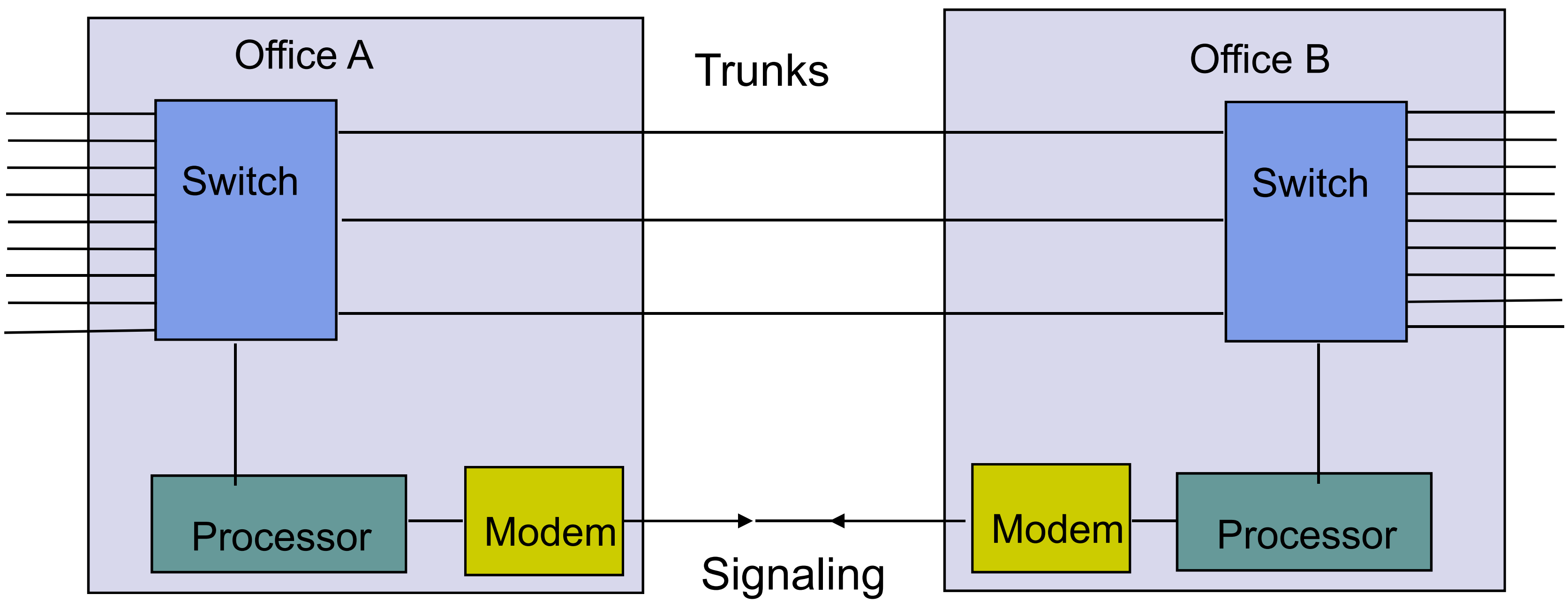
Stored-Program Control Switches

- SPC switches (1960s)
  - Crossbar switches with crossbars built from relays that open/close mechanically through electrical control
  - Computer program controls set up opening/closing of crosspoints to establish connections between switch inputs and outputs
- Signaling required to coordinate path set up across network



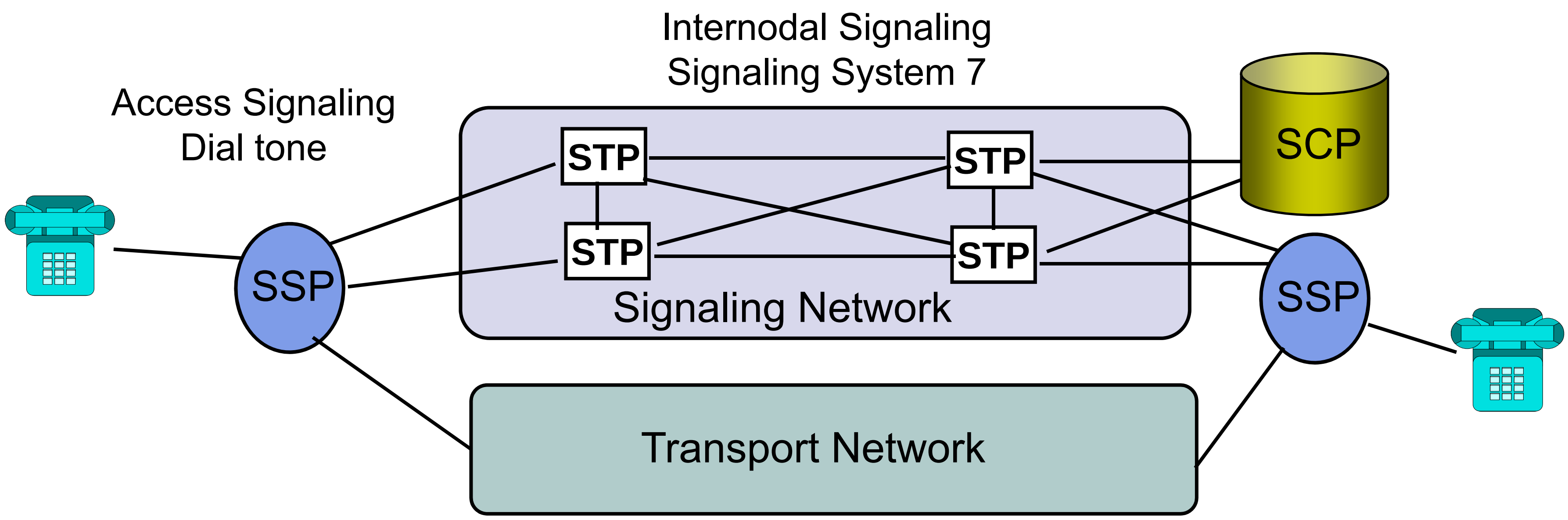
Message Signaling

- Processors that control switches exchange signaling messages
- Protocols defining messages & actions defined
- Modems developed to communicate digitally over converted voice trunks



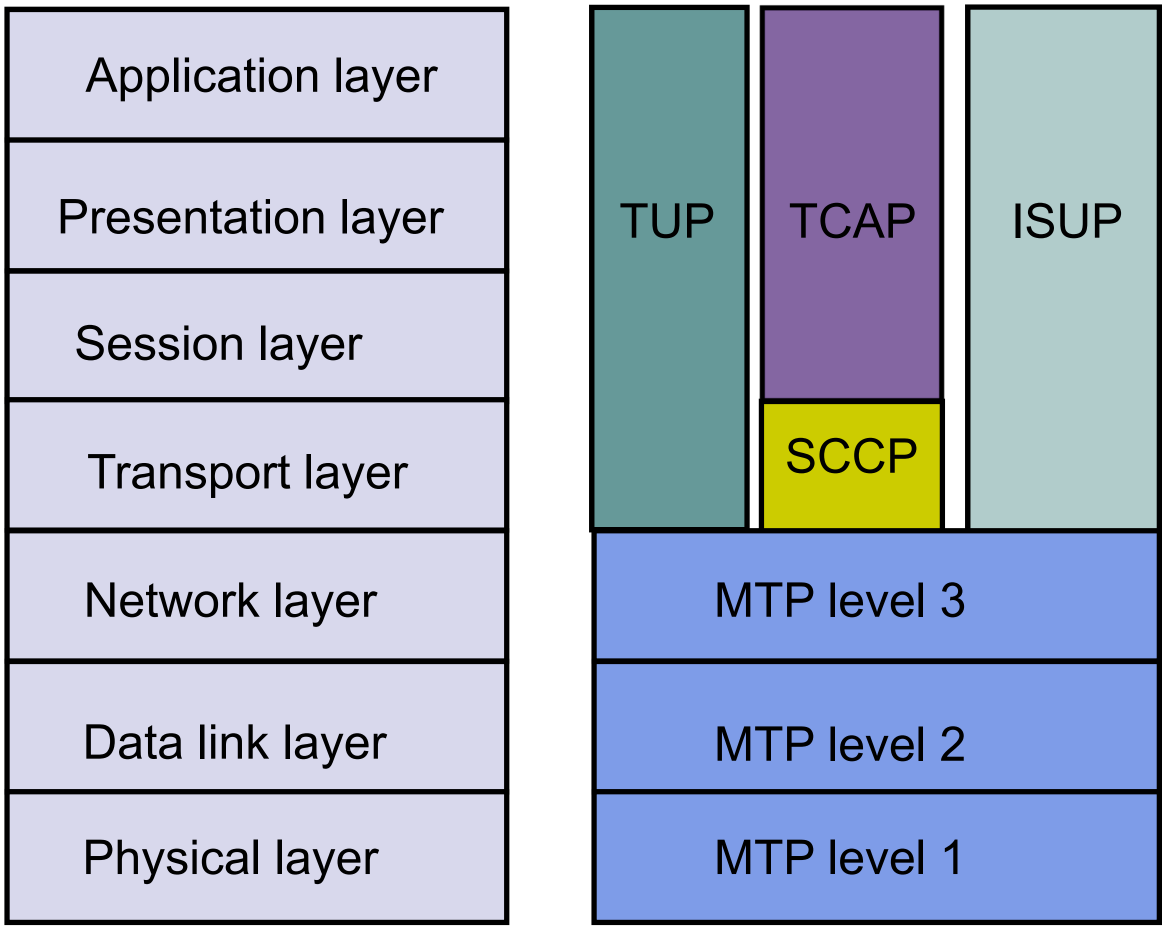
Signaling Network

- Common Channel Signaling (CCS) #7 deployed in 1970s to control call setup
- Protocol stack developed to support signaling
- Signaling network based on highly reliable packet switching network
- Processors & databases attached to signaling network enabled many new services: caller id, call forwarding, call waiting, user mobility



SSP = service switching point (signal to message)
STP = signal transfer point (packet switch)
SCP = service control point (processing)

Signaling System Protocol Stack

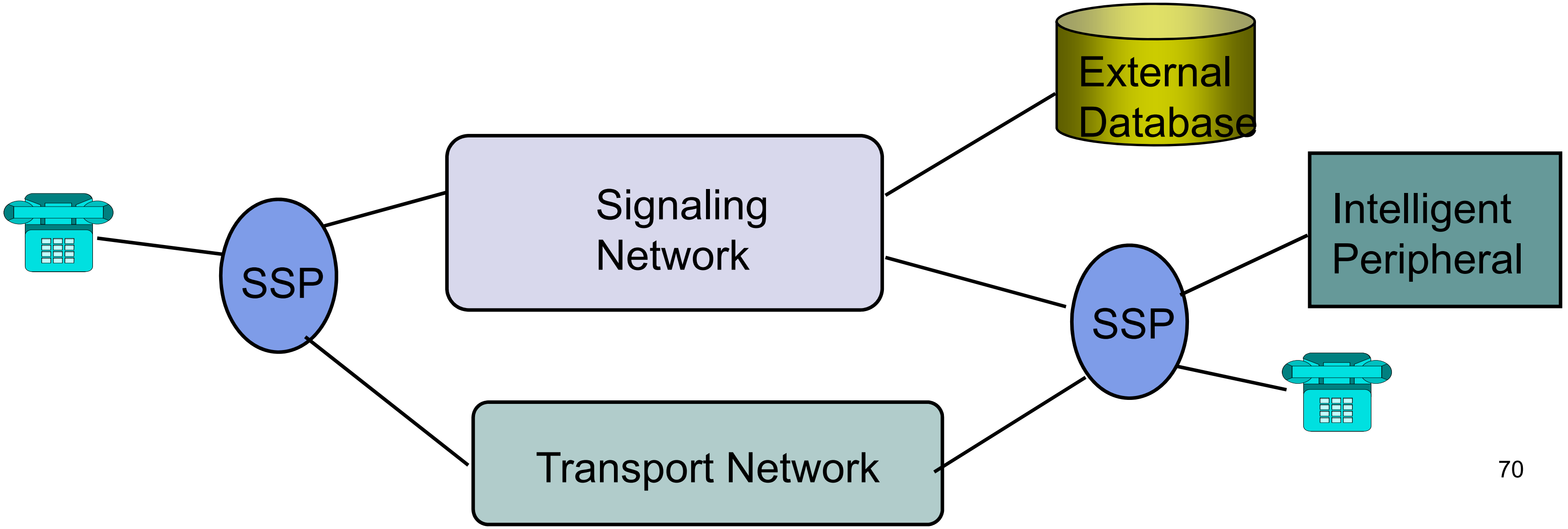


- Lower 3 layers ensure delivery of messages to signaling nodes
- SCCP allows messages to be directed to applications
- TCAP defines messages & protocols between applications
- ISUP performs basic call setup & release
- TUP instead of ISUP in some countries

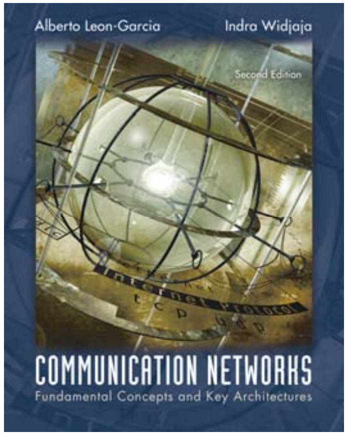
ISUP = ISDN user part
SSCP = signaling connection control part
TUP = telephone user part
MTP = message transfer part
TCAP = transaction capabilities part

Network Intelligence

- Intelligent Peripherals provide additional service capabilities
- Voice Recognition & Voice Synthesis systems allow users to access applications via speech commands
- "Voice browsers" currently under development (See: www.voicexml.org)
- Long-term trend is for IP network to replace signaling system and provide equivalent services
- Services can then be provided by telephone companies as well as new types of service companies



Chapter 4
Circuit-Switching Networks

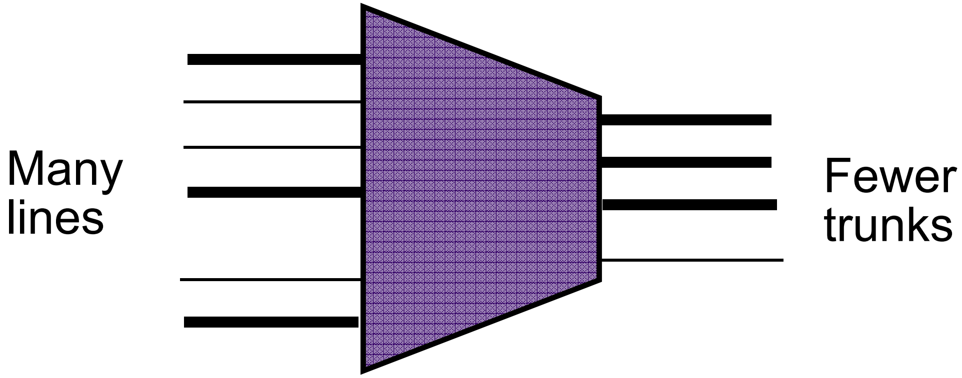


Traffic and Overload Control in Telephone Networks

Traffic Management & Overload Control

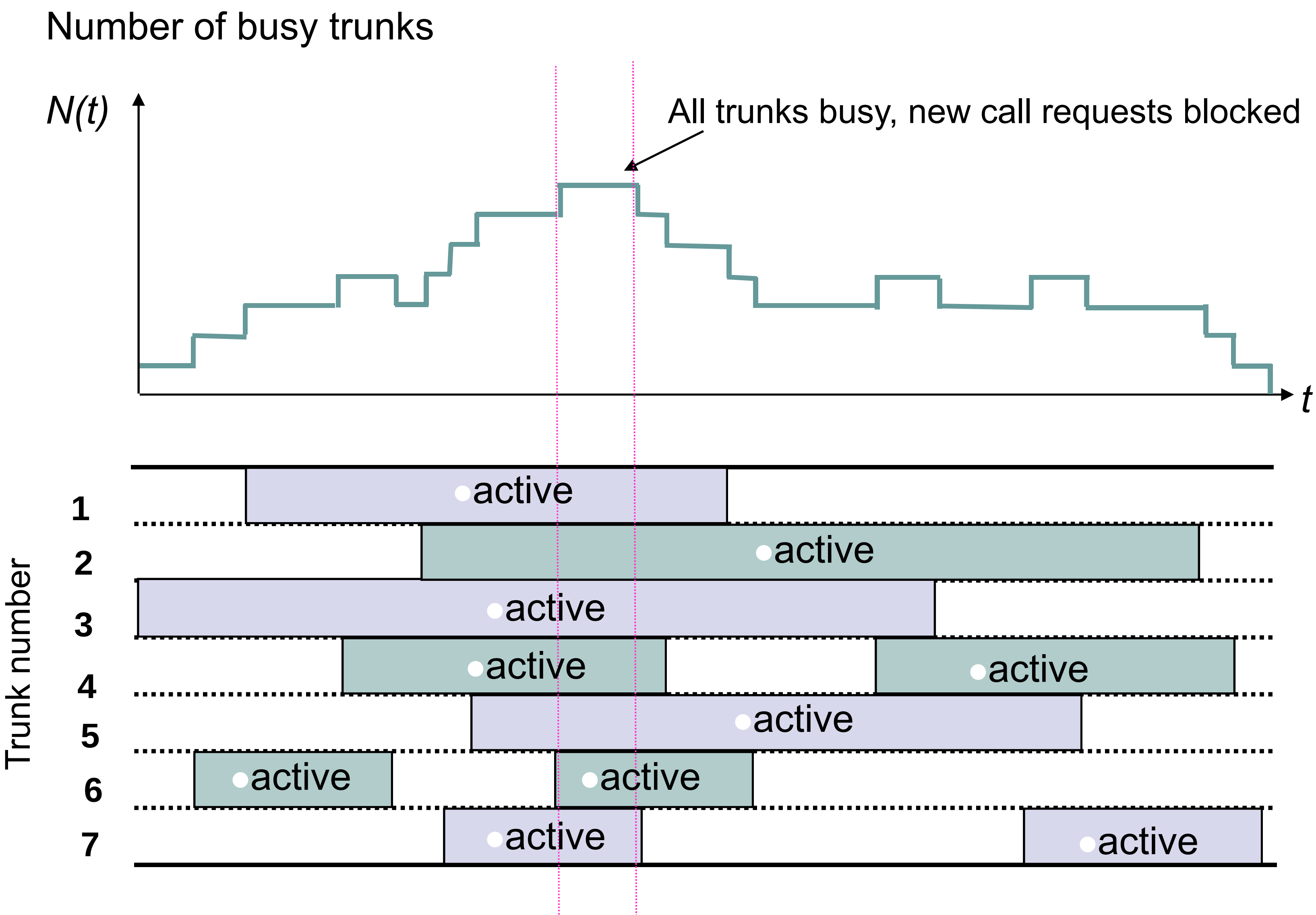
- Telephone calls come and go
- People activity follow patterns
  - Mid-morning & mid-afternoon at office
  - Evening at home
  - Summer vacation
- Outlier Days are extra busy
  - Mother's Day, Christmas, …
- Disasters & other events cause surges in traffic
- Need traffic management & overload control

Traffic concentration



- Traffic fluctuates as calls initiated & terminated
  - Driven by human activity
- Providing resources so
  - Call requests *always* met is too expensive
  - Call requests met *most of the time* cost-effective
- Switches concentrate traffic onto *shared* trunks
  - Blocking of requests will occur from time to time
- Traffic engineering provisions resources to meet blocking performance targets

Fluctuation in Trunk Occupancy



Modeling Traffic Processes

- **Find the statistics of *N(t)* the number of calls in the system**

Model

- Call request ***arrival rate***: λ requests per second
- In a very small time interval Δ,
  - Prob[new request] = $\lambda\Delta$
  - Prob[no new request] = 1 - $\lambda\Delta$
- The resulting random process is a Poisson arrival process:

$$\text{Prob}(k \text{ arrivals in time } T) = \frac{(\lambda T)^k e^{-\lambda T}}{k!}$$

- ***Holding time***: Time a user maintains a connection
  - *X* a random variable with mean *E(X)*
- ***Offered load***: rate at which work is offered by users:
  - $a = \lambda$ calls/sec * E(X) seconds/call (Erlangs)

Blocking Probability & Utilization

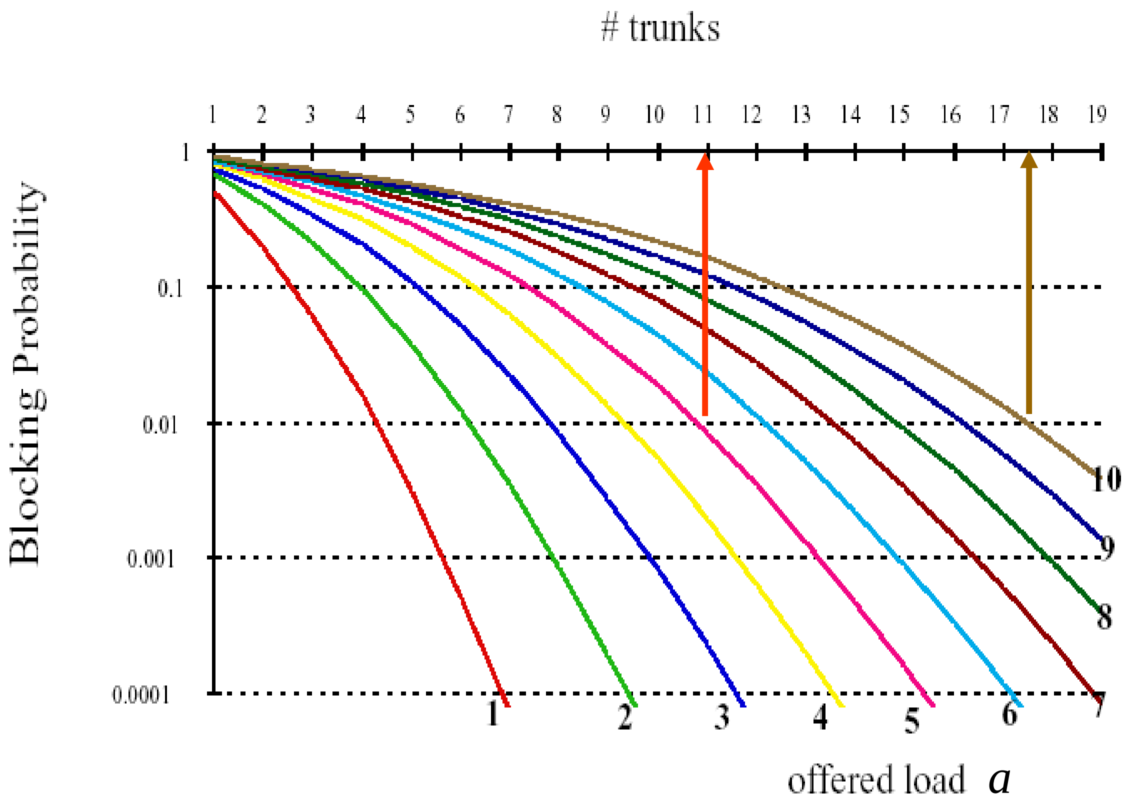
- c = Number of Trunks
- Blocking occurs if all trunks are busy, i.e. $N(t)=c$
- If call requests are Poisson, then blocking probability P_b is given by ***Erlang B Formula***

$$P_b = \frac{a^c / c!}{\sum_{k=0}^{c} a^k / k!}$$

- The *utilization* is the average # of trunks in use

$$\text{Utilization} = \lambda(1 - P_b)\, E[X]/c = (1 - P_b)\, a/c$$

Blocking Performance



To achieve 1% blocking probability:

a = 5 Erlangs requires 11 trunks

a = 10 Erlangs requires 18 trunks

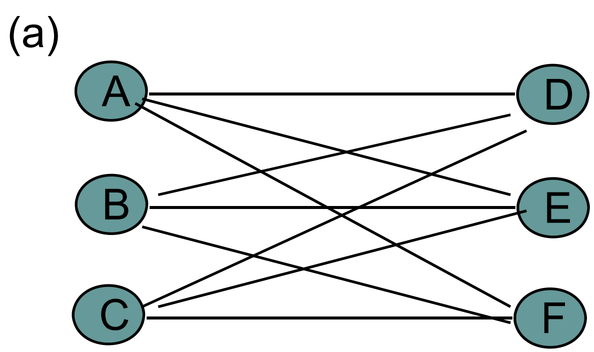
Multiplexing Gain

Load	Trunks@1%	Utilization
1	5	0.20
2	7	0.29
3	8	0.38
4	10	0.40
5	11	0.45
6	13	0.46
7	14	0.50
8	15	0.53
9	17	0.53
10	18	0.56
30	42	0.71
50	64	0.78
60	75	0.80
90	106	0.85
100	117	0.85

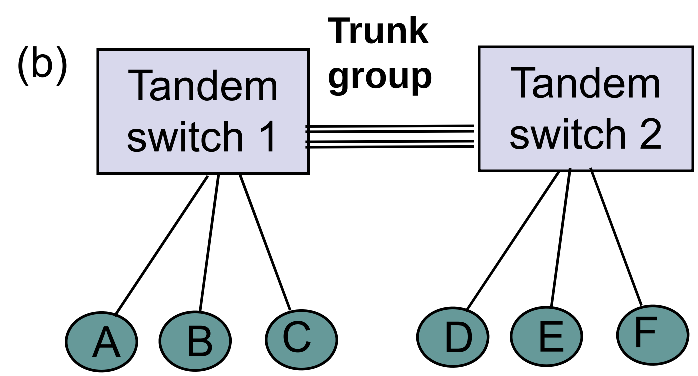
- At a given P_b, the system becomes more efficient in utilizing trunks with increasing system size
- Aggregating traffic flows to share centrally allocated resources is more efficient
- This effect is called *Multiplexing Gain*

Routing Control

- Routing control: selection of connection paths
- Large traffic flows should follow direct route because they are efficient in use of resources
- Useful to combine smaller flows to share resources
- Example: 3 close CO's & 3 other close COs
- 10 Erlangs between each pair of COs



10 Erlangs between each pair

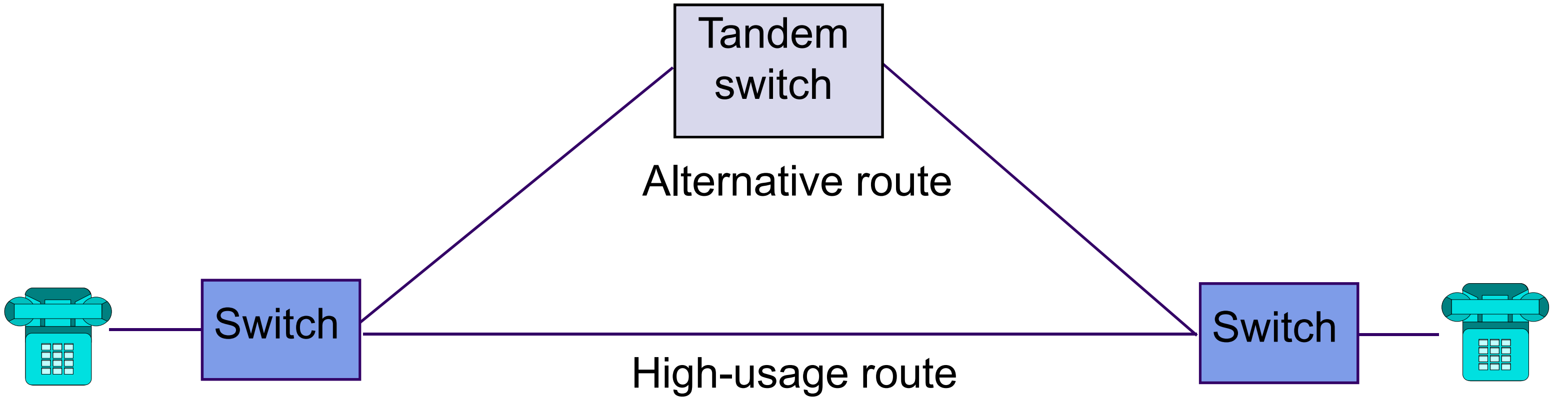


90 Erlangs when combined

17 trunks for 10 Erlangs
9x17=153 trunks
Efficiency = 90/153=53%

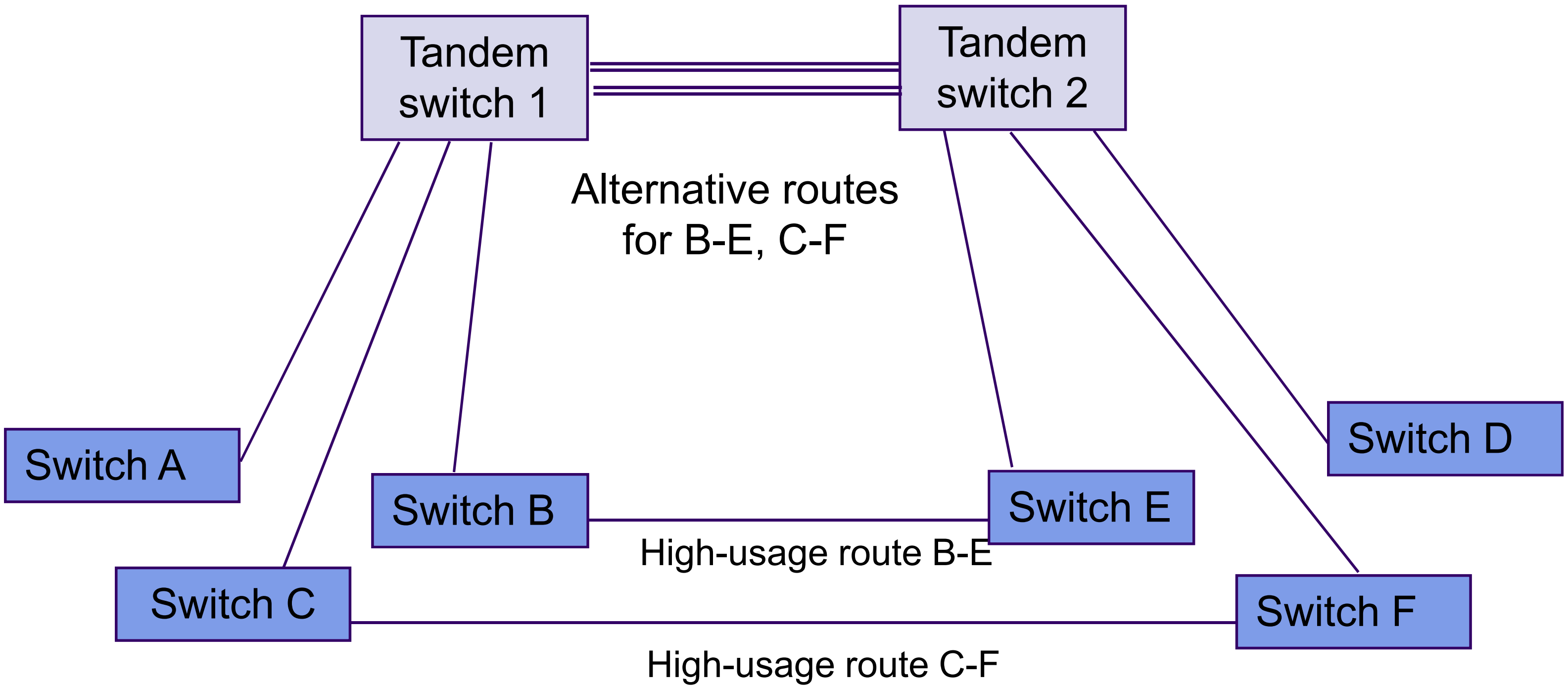
106 trunks for 90 Erlangs
Efficiency = 85%

Alternative Routing

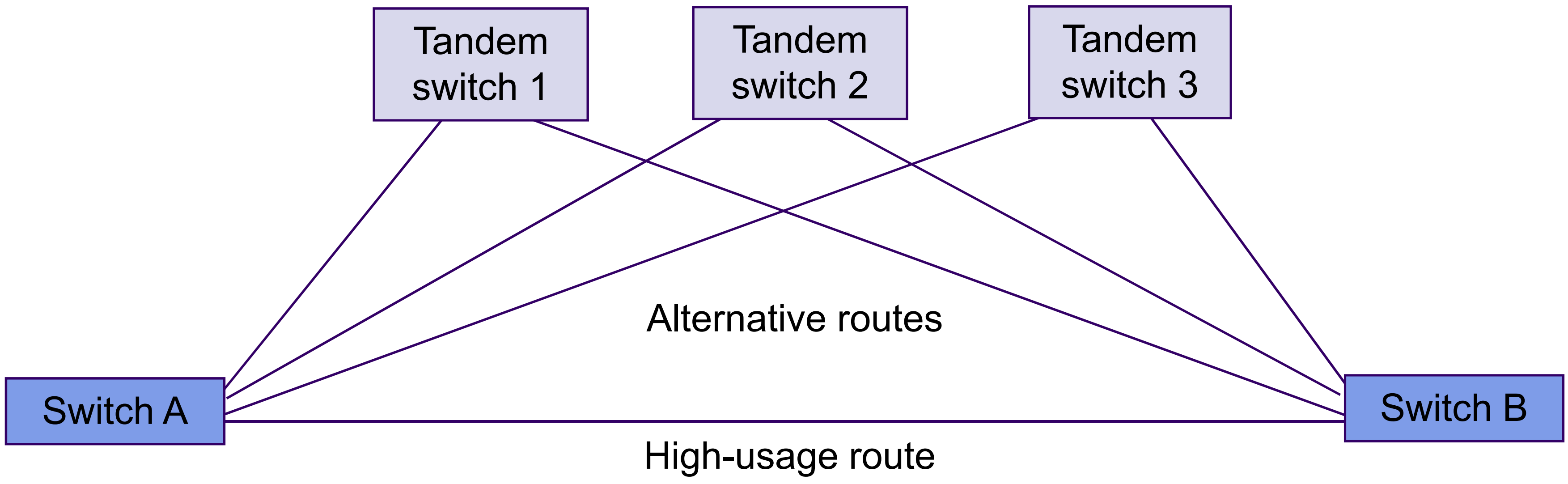


- Deploy trunks between switches with significant traffic volume
- Allocate trunks with high blocking, say 10%, so utilization is high
- Meet 1% end-to-end blocking requirement by overflowing to longer paths over tandem switch
- Tandem switch handles overflow traffic from other switches so it can operate efficiently
- Typical scenario shown in next slide

Typical Routing Scenario

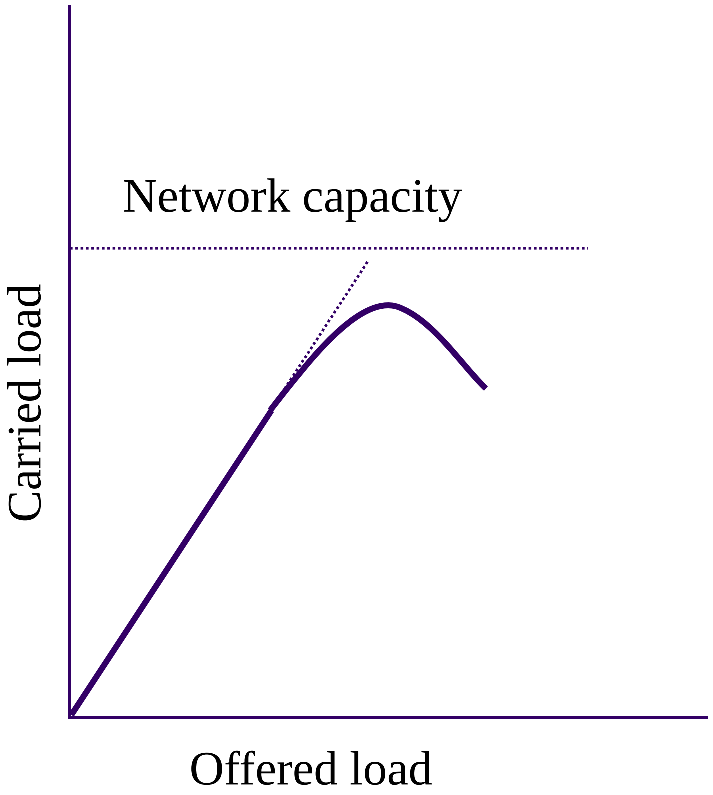


Dynamic Routing



- Traffic varies according to time of day, day of week
  - East coast of North America busy while West coast idle
- Network can use idle resources by adapting route selection dynamically
  - Route some intra-East-coast calls through West-coast switches
- Try high-usage route and overflow to alternative routes

Overload Control



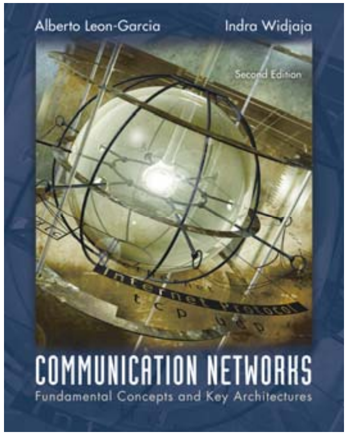
Overload Situations

- Mother's Day, Xmas
- Catastrophes
- Network Faults

Strategies

- Direct routes first
- Outbound first
- Code blocking
- Call request pacing

Chapter 4
Circuit-Switching Networks



Cellular Telephone Networks

Radio Communications

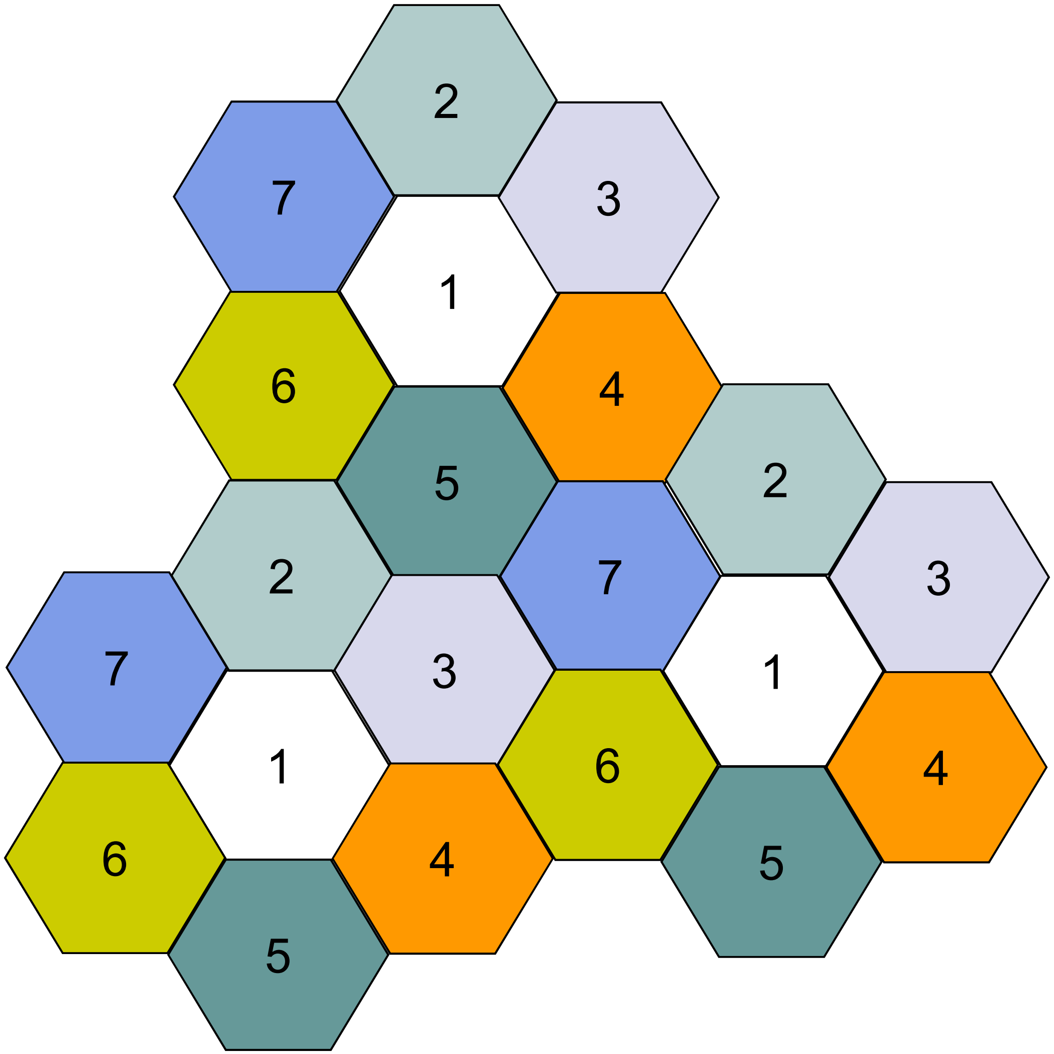
- 1900s: Radio telephony demonstrated
- 1920s: Commercial radio broadcast service
- 1930s: Spectrum regulation introduced to deal with interference
- 1940s: Mobile Telephone Service
  - Police & ambulance radio service
  - Single antenna covers transmission to mobile users in city
  - Less powerful car antennas transmit to network of antennas around a city
  - Very limited number of users can be supported

Cellular Communications

Two basic concepts:

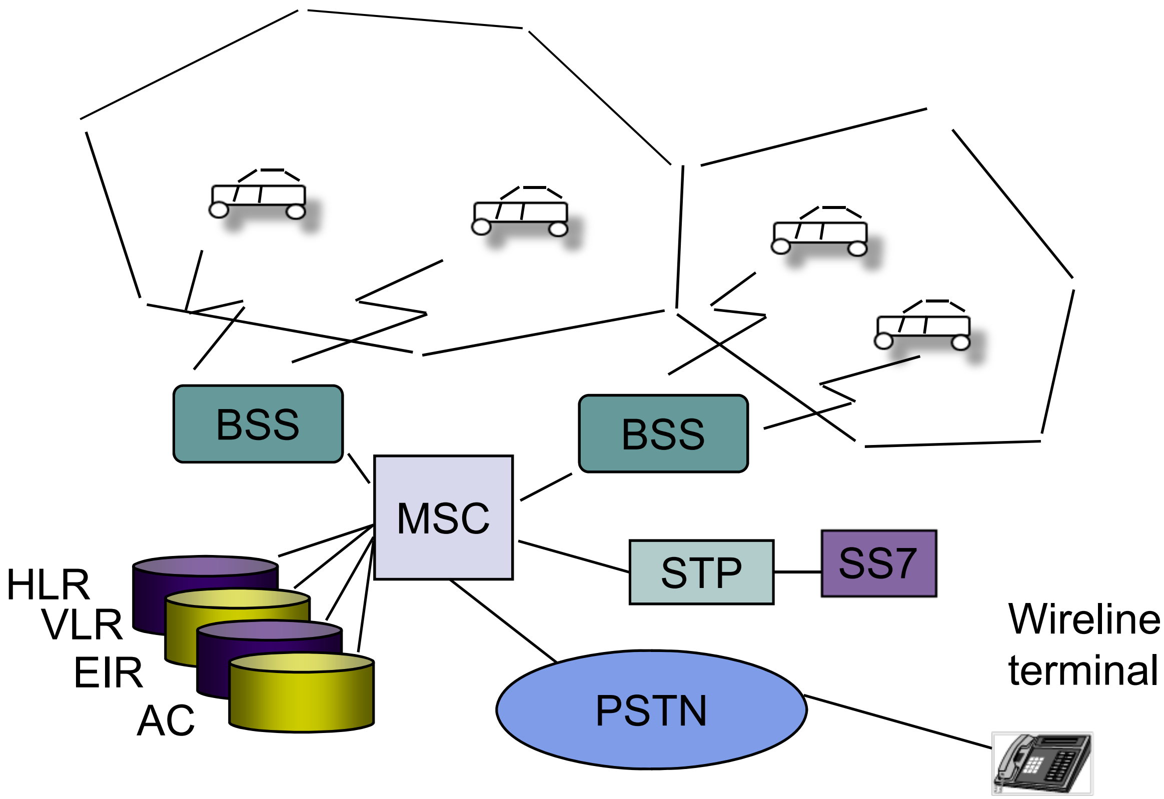
- Frequency Reuse
  - A region is partitioned into *cells*
  - Each cell is covered by *base station*
  - Power transmission levels controlled to minimize inter-cell interference
  - Spectrum can be reused in other cells
- Handoff
  - Procedures to ensure continuity of call as user moves from cell to another
  - Involves setting up call in new cell and tearing down old one

Frequency Reuse



- Adjacent cells may not use same band of frequencies
- Frequency Reuse Pattern specifies how frequencies are reused
- Figure shows 7-cell reuse: frequencies divided into 7 groups & reused as shown
- Also 4-cell & 12-cell reuse possible
- Note: CDMA allows adjacent cells to use same frequencies (Chapter 6)

Cellular Network



Base station

- Transmits to users on *forward channels*
- Receives from users on *reverse channels*

Mobile Switching Center

- Controls connection setup within cells & to telephone network

AC = authentication center
BSS = base station subsystem
EIR = equipment identity register
HLR = home location register

MSC = mobile switching center
PSTN = public switched telephone network
STP = signal transfer point
VLR = visitor location register

Signaling & Connection Control

- *Setup channels* set aside for call setup & handoff
  - Mobile unit selects setup channel with strongest signal & monitors this channel
- **Incoming call to mobile unit**
  - MSC sends call request to all BSSs
  - BSSs broadcast request on all setup channels
  - Mobile unit replies on reverse setup channel
  - BSS forwards reply to MSC
  - BSS assigns forward & reverse voice channels
  - BSS informs mobile to use these
  - Mobile phone rings

Mobile Originated Call

- Mobile sends request in reverse setup channel
- Message from mobile includes serial # and possibly authentication information
- BSS forwards message to MSC
- MSC consults Home Location Register for information about the subscriber
- MSC may consult Authentication center
- MSC establishes call to PSTN
- BSS assigns forward & reverse channel

Handoff

- Base station monitors signal levels from its mobiles
- If signal level drops below threshold, MSC notified & mobile instructed to transmit on setup channel
- Base stations in vicinity of mobile instructed to monitor signal from mobile on setup channel
- Results forward to MSC, which selects new cell
- Current BSS & mobile instructed to prepare for handoff
- MSC releases connection to first BSS and sets up connection to new BSS
- Mobile changes to new channels in new cell
- Brief interruption in connection (except for CDMA)

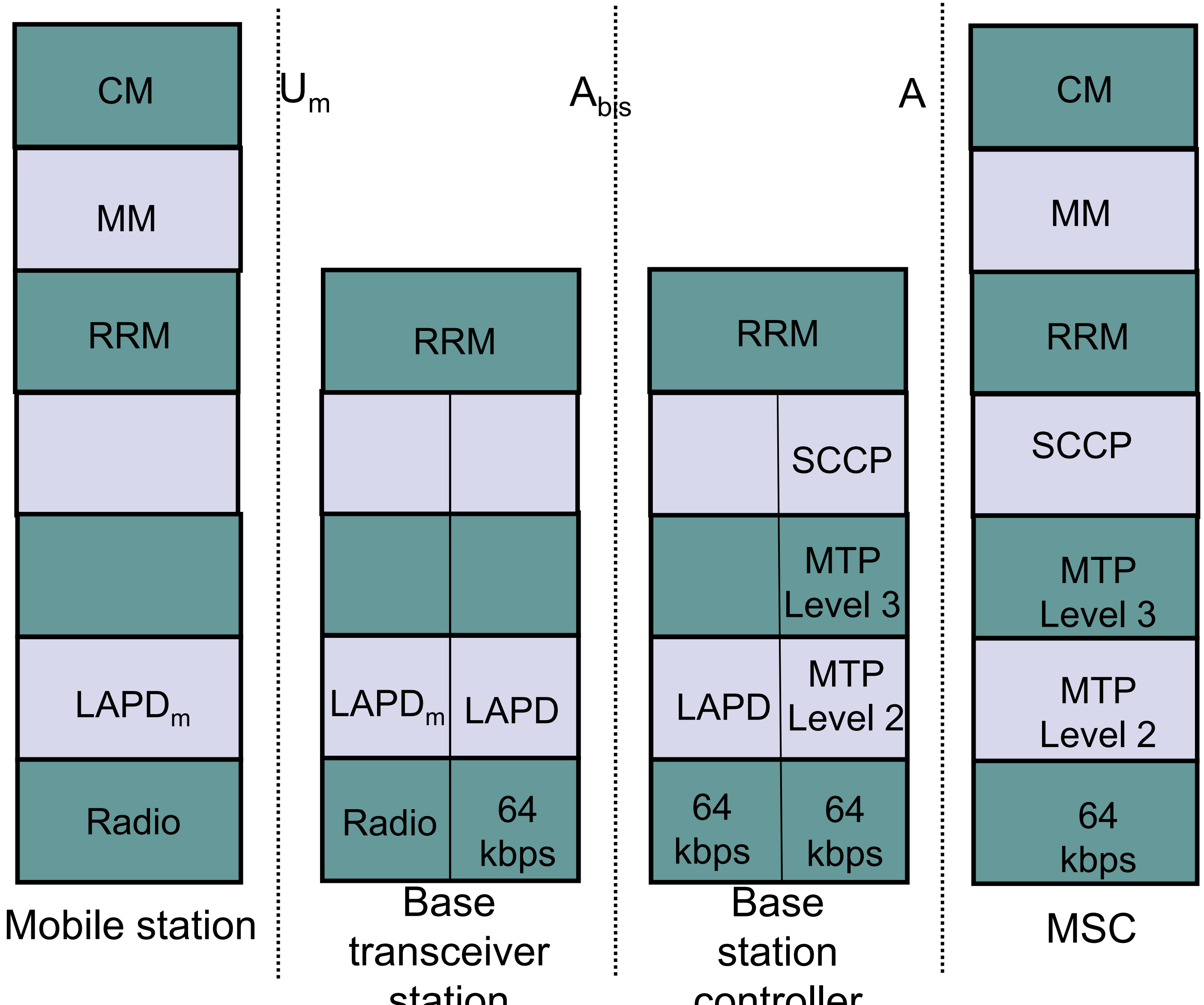
Roaming

- Users subscribe to roaming service to use service outside their home region
- Signaling network used for message exchange between home & visited network
- Roamer uses setup channels to register in new area
- MSC in visited areas requests authorization from users Home Location Register
- Visitor Location Register informed of new user
- User can now receive & place calls

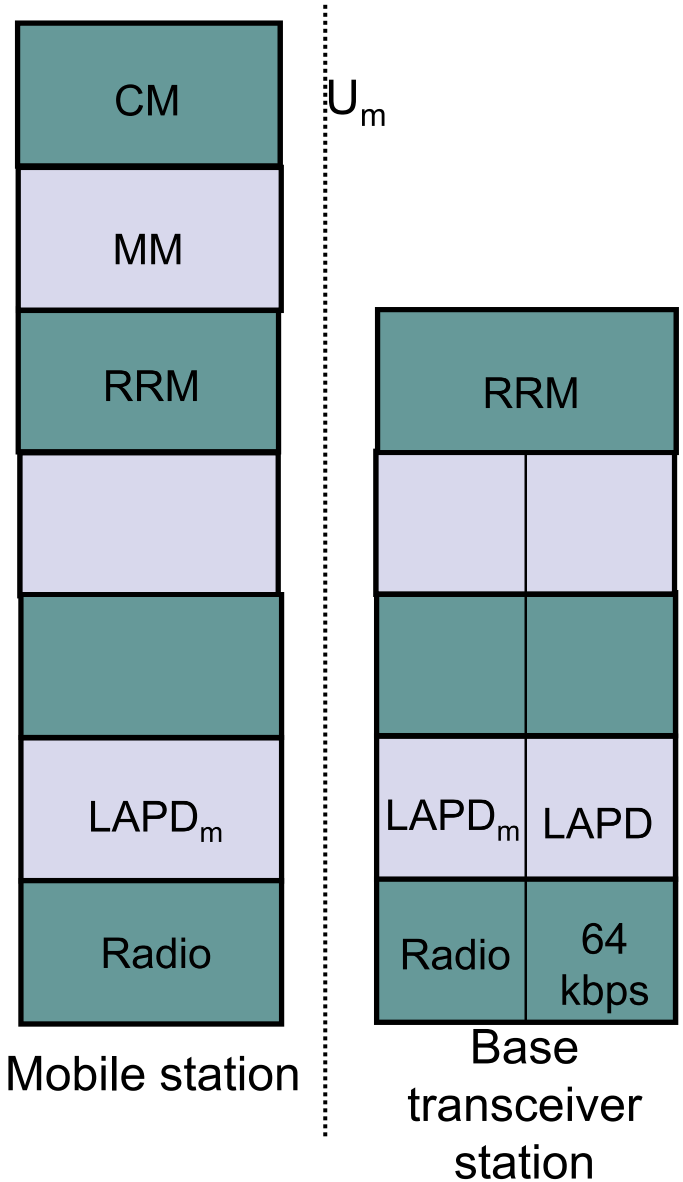
GSM Signaling Standard

- Base station
  - Base Transceiver Station (BTS)
    - Antenna + Transceiver to mobile
    - Monitoring signal strength
  - Base Station Controller
    - Manages radio resources or 1 or more BTSs
    - Set up of channels & handoff
    - Interposed between BTS & MSC
- Mobile & MSC Applications
  - Call Management (CM)
  - Mobility Management (MM)
- Radio Resources Management (RRM) concerns mobile, BTS, BSC, and MSC

Cellular Network Protocol Stack



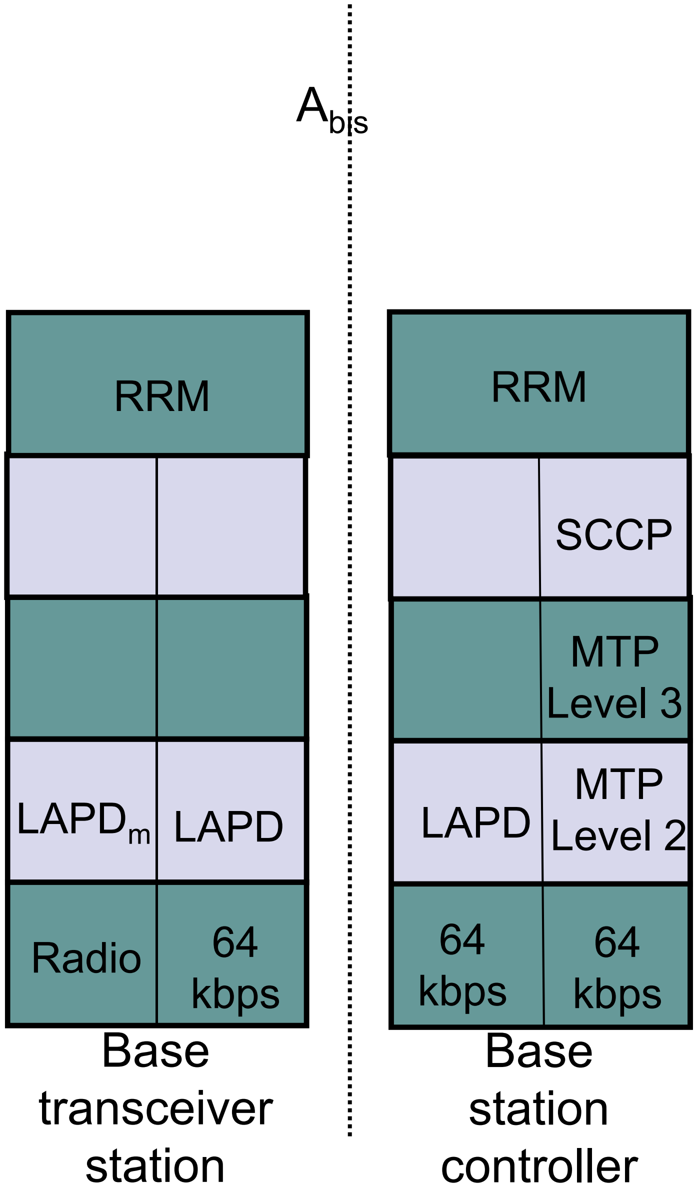
Cellular Network Protocol Stack



Radio Air Interface (U_m)

- $LAPD_m$ is data link control adapted to mobile
- RRM deals with setting up of radio channels & handover

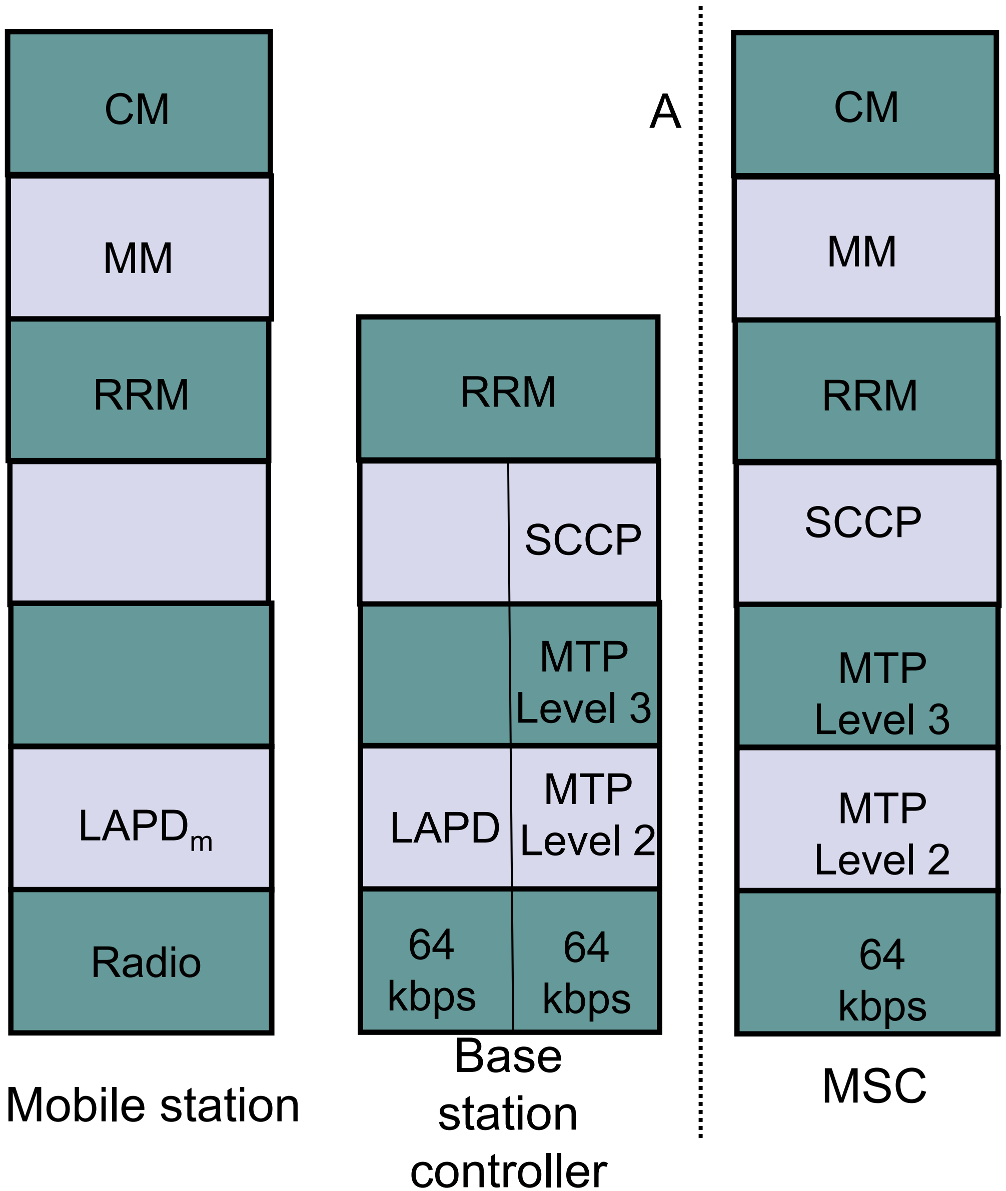
Cellular Network Protocol Stack



A_{bis} Interface

- 64 kbps link physical layer
- $LAPD_m$
- BSC RRM can handle handover for cells within its control

Cellular Network Protocol Stack



Signaling Network (A) Interface

- RRM deals handover involving cells with different BSCs
- MM deals with mobile user location, authentication
- CM deals with call setup & release using modified ISUP