

# ECE 683-001 Fall 2005 Computer Network Design and Analysis Lecture 4

Professor Nirwan Ansari  
Department of Electrical and  
Computer Engineering  
New Jersey Institute of Technology



## Source:

- **Communication Networks 2<sup>nd</sup> Edition Chapter 4**  
by Alberto Leon-Garcia and Indra Widjaja



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

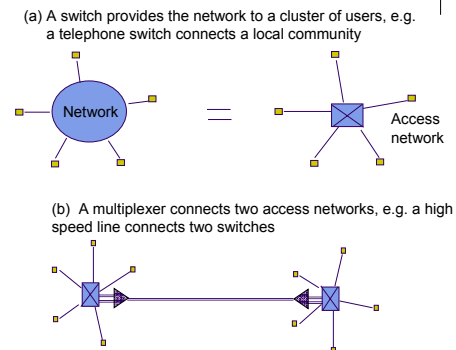


## Circuit Switching Networks

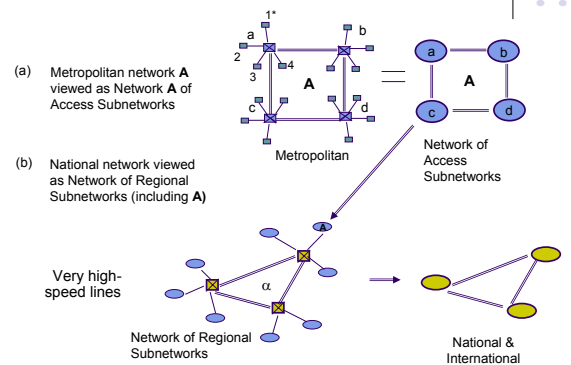


- End-to-end dedicated circuits between clients
  - Client can be a person or equipment (router or switch)
- Circuit can take different forms
  - Dedicated path for the transfer of electrical current
  - Dedicated time slots for transfer of voice samples
  - Dedicated frames for transfer of Nx51.84 Mbps 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 lecture

## How a network grows



## A Network Keeps Growing



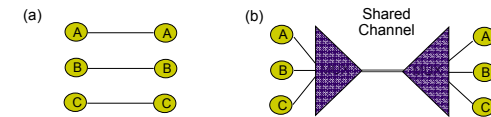
## Lecture 4 Circuit-Switching Networks

### Multiplexing



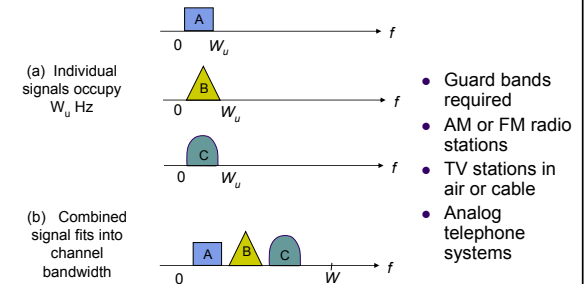
## Multiplexing

- 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.



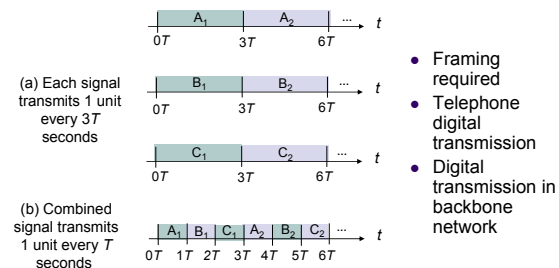
## Frequency-Division Multiplexing

- Channel divided into frequency slots



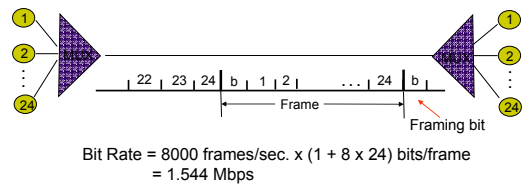
## Time-Division Multiplexing

- High-speed digital channel divided into time slots

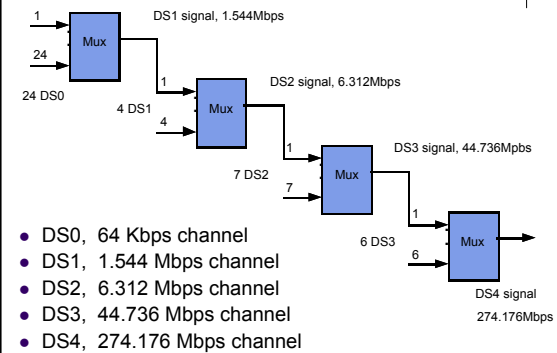


## T-Carrier System

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



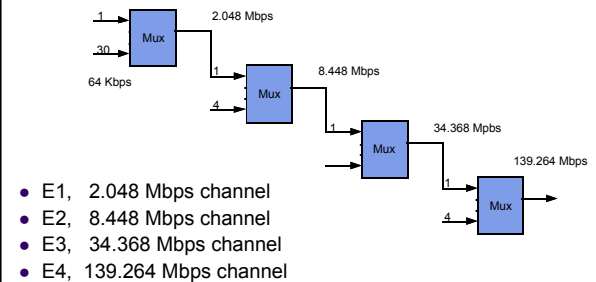
## North American Digital Multiplexing Hierarchy



- 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

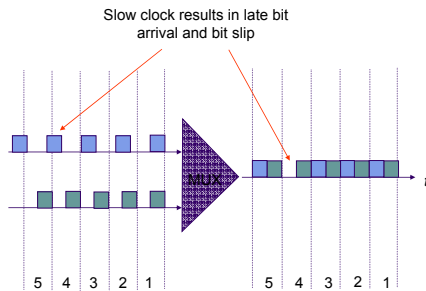
- CCITT digital hierarchy based on 30 PCM channels



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

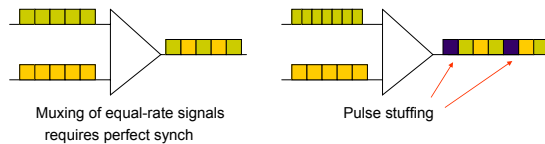
## Clock Synch & Bit Slips

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



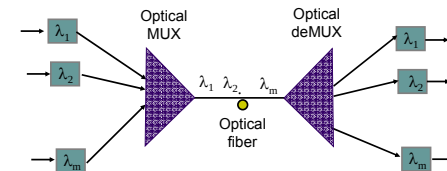
## Pulse Stuffing

- Pulse Stuffing: synchronization to avoid data loss due to slips
- Output rate  $> R_1 + R_2$ 
  - 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.

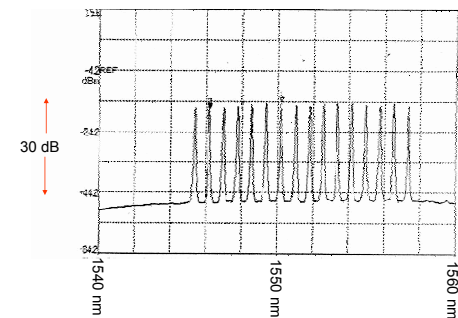


## Wavelength-Division Multiplexing

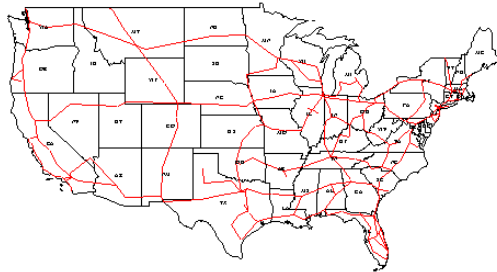
- Optical fiber link carries several wavelengths
  - From few (4-8) to many (64-160) wavelengths per fiber
- Imagine prism combining different colors into single beam
- Each wavelength carries a high-speed stream
  - Each wavelength can carry different format signal
  - e.g. 1 Gbps, 2.5 Gbps, or 10 Gbps



## Example: WDM with 16 wavelengths



## Typical U.S. Optical Long-Haul Network



## Lecture 4 Circuit-Switching Networks



### SONET

A detailed reference:

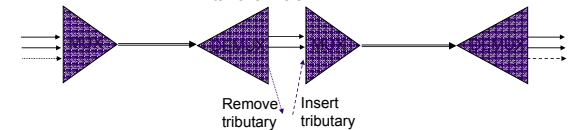
Walter J. Goralski, *SONET/SDH 3<sup>rd</sup> Edition*, ISBN: 0072225246, McGraw-Hill Osborne (October 4, 2002)

## SONET: Overview

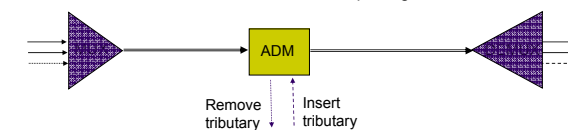
- **Synchronous Optical NETwork**
- North American TDM physical layer standard for optical fiber communications
- 8000 frames/sec. ( $T_{\text{frame}} = 125 \mu\text{sec}$ )
  - compatible with North American digital hierarchy
- SDH (Synchronous Digital Hierarchy) elsewhere
  - Needs to carry E1 and 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



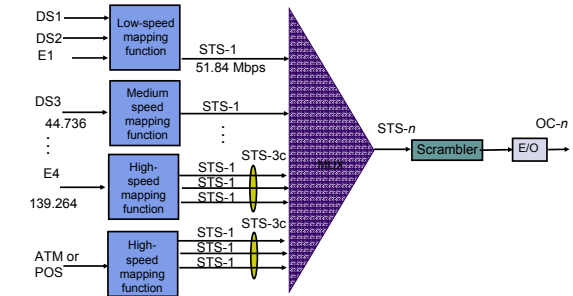
## SONET Specifications

- 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 |

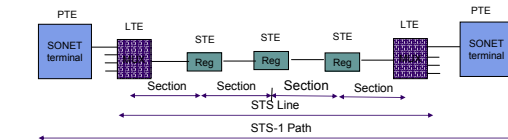
## SONET Multiplexing



## 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

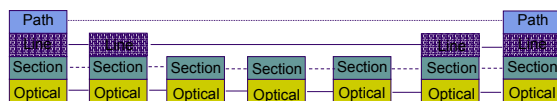
## Section, Line, & Path in SONET



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-1 to STS-3 multiplexer.

## Section, Line, & Path Layers in SONET



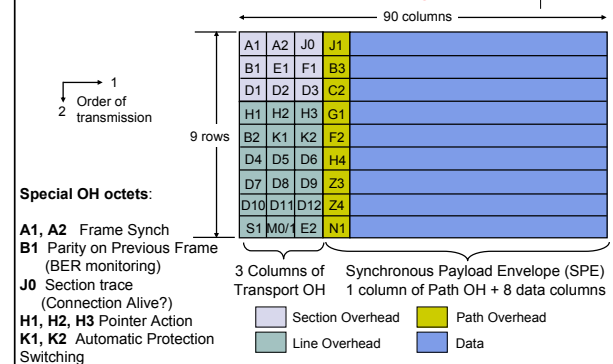
- SONET has four layers
  - Optical, section, line, path
  - Each layer is concerned with the integrity of its own signals
- Each layer has its own protocols
  - SONET provides signaling channels for elements within a layer

## SONET STS Frame

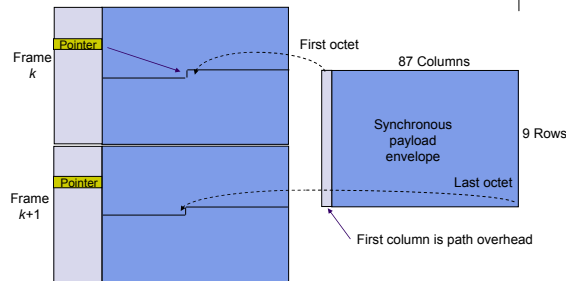
- SONET streams carry two types of overhead
- *Path overhead (POH)*:
  - inserted & removed at the ends
  - *Synchronous Payload Envelope (SPE)* consisting of Data + POH traverses network as a single unit
- *Transport Overhead (TOH)*:
  - processed at every SONET node
  - TOH occupies a portion of each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

## STS-1 Frame

810x64kbps=51.84 Mbps  
 810 Octets per frame @ 8000 frames/sec



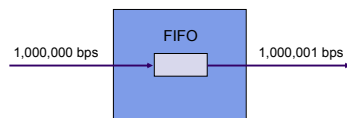
## SPE Can Span Consecutive Frames



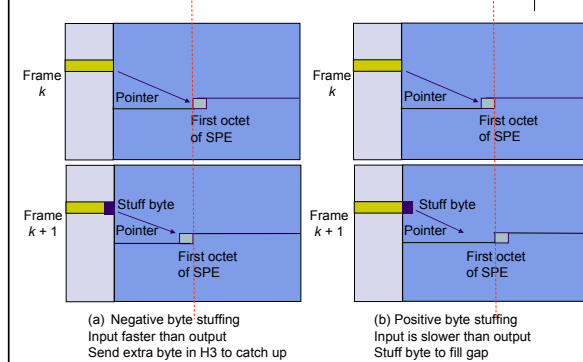
- Pointer indicates where SPE begins within a frame
- **Pointer enables add/drop capability**

## Stuffing in SONET

- Consider system with different clocks (faster out than in)
- Use buffer (e.g., 8 bit FIFO) to manage difference
- Buffer empties eventually
- One solution: send "stuff"
- Problem:
  - Need to signal "stuff" to receiver

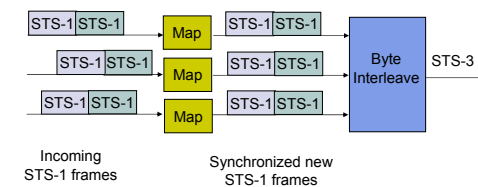


## Negative & Positive Stuff

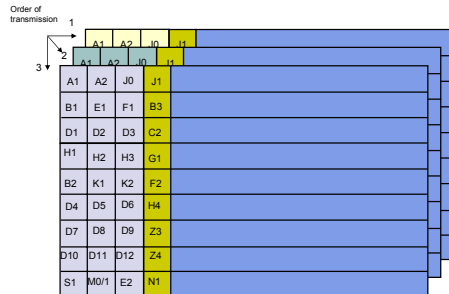


## Synchronous Multiplexing

- Synchronize each incoming STS-1 to local clock
  - Terminate section & line OH and map incoming SPE into a new STS-1 synchronized to the local clock
  - This can be done on-the-fly by adjusting the pointer
- All STS-1s are synced to local clock so bytes can be interleaved to produce STS-n



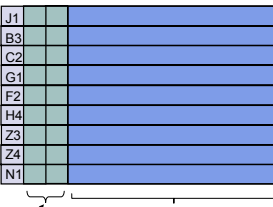
## Octet Interleaving



## Concatenated Payloads

Concatenated Payload OC-Nc

$N \times 87$  columns



$(N/3) - 1$   
columns of  
fixed stuff

$87N - (N/3)$   
columns of  
payload

- Needed if payloads of interleaved frames are "locked" into a bigger unit
- Data systems send big blocks of information grouped together, e.g., a router operating at 622 Mbps
  - SONET/SDH needs to handle these as a single unit
- H1, H2, H3 tell us if there is concatenation
- STS-3c has more payload than 3 STS-1s
- STS-Nc payload =  $N \times 780$  bytes
- OC-3c = 149.760 Mb/s
- OC-12c = 599.040 Mb/s
- OC-48c = 2.3961 Gb/s
- OC-192c = 9.5846 Gb/s

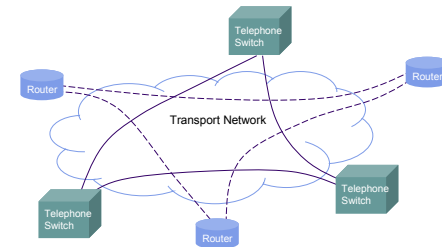
## Lecture 4 Circuit-Switching Networks



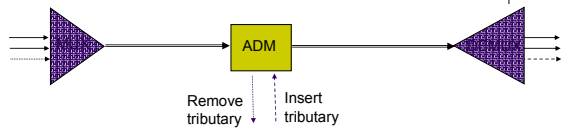
### Transport Networks

## Transport Networks

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



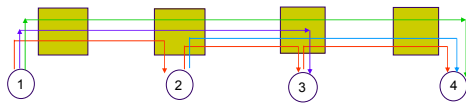
## SONET ADM Networks



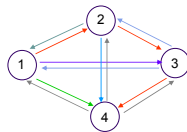
- SONET ADMs: the heart of existing transport networks
- ADMs interconnected in linear and ring topologies
- SONET signaling enables fast restoration (within 50 ms) of transport connections

## Linear ADM Topology

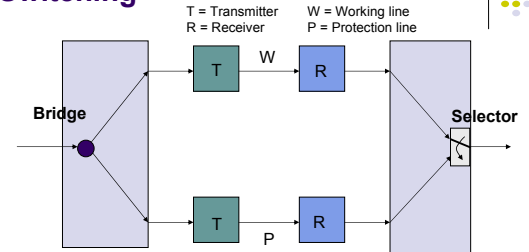
- ADMs connected in linear fashion
- Tributaries inserted and dropped to connect clients



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

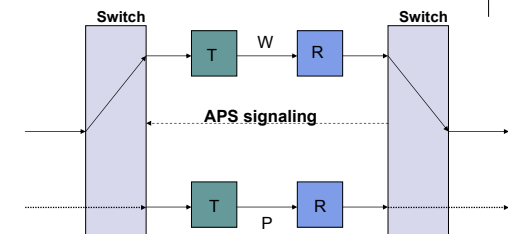


## 1+1 Linear Automatic Protection Switching



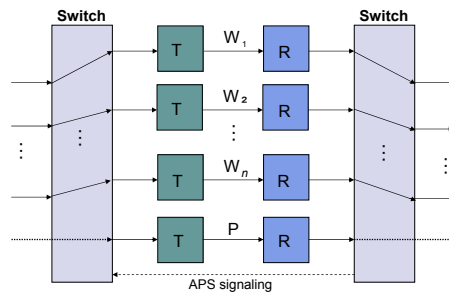
- Simultaneous transmission over diverse routes
- Monitoring of signal quality
- Fast switching in response to signal degradation
- 100% redundant bandwidth

## 1:1 Linear APS



- Transmission on working fiber
- Signal for switch to protection route in response to signal degradation
- Can carry extra (preemptible traffic) on protection line

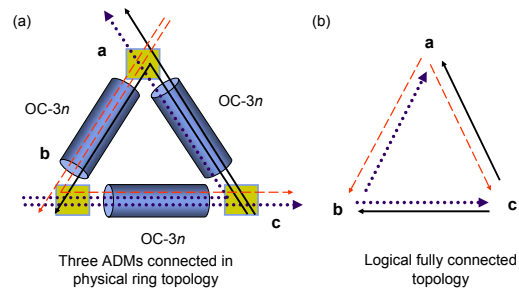
## 1:N Linear APS



- Transmission on diverse routes; protect for 1 fault
- Reverts to original working channel after repair
- More bandwidth efficient

## SONET Rings

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



## SONET Ring Options

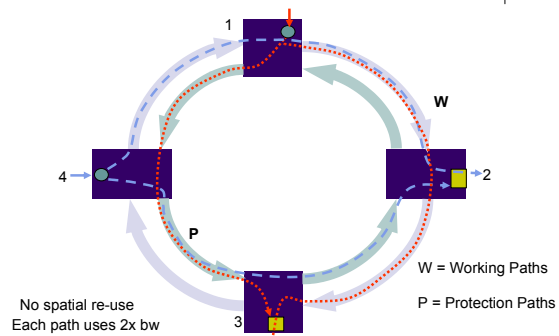
- 2 vs. 4 Fiber Ring Network
- Unidirectional vs. bidirectional transmission
- Path vs. Link protection
- Spatial capacity re-use & bandwidth efficiency
- Signalling requirements

## Two-Fiber Unidirectional Path Switched Ring

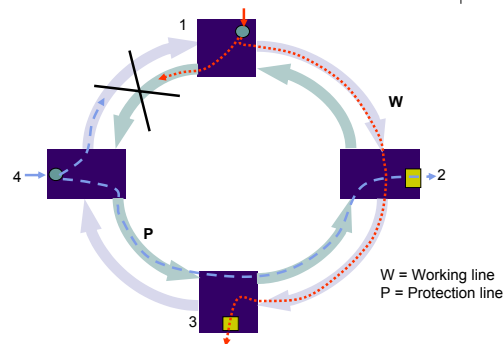
Two fibers transmit in opposite directions

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

## UPSR



## UPSR path recovery



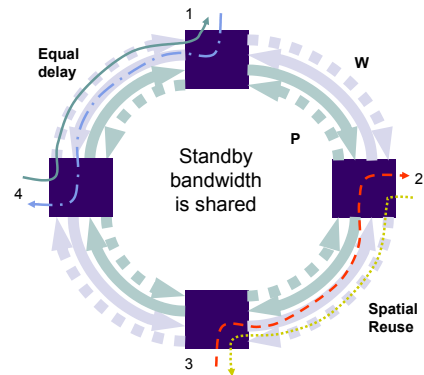
## UPSR Properties

- 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

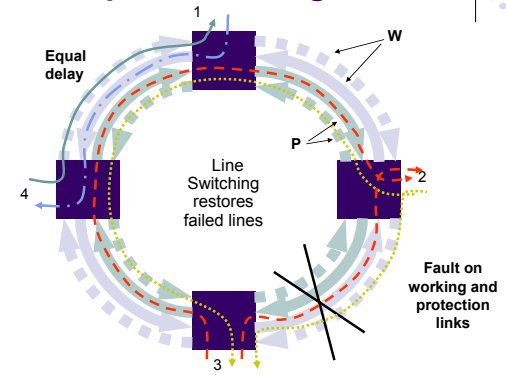
## Four-Fiber Bidirectional Line Switched Ring

- 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

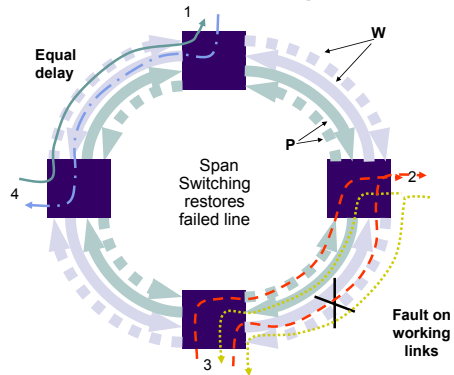
## 4-BLSR



## BLSR Span Switching



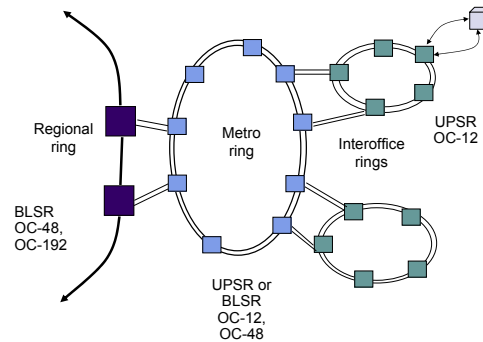
## BLSR Span Switching



## 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



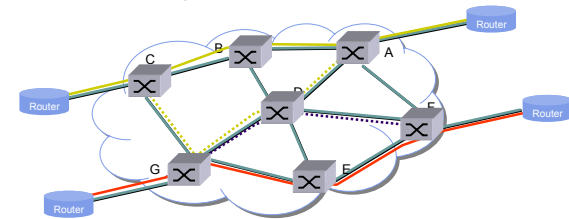
## The Problem with Rings

- Managing bandwidth can be complex
- Increasing transmission rate in one span affects all equipment in the ring
- Introducing WDM means stacking SONET ADMs to build parallel rings
- Distance limitations on ring size implies many rings need to be traversed in long distance
- End-to-end protection requires ring-interconnection mechanisms

*Managing 1 ring is simple; Managing many rings is very complex*

## Mesh Topology Networks using SONET Cross-Connects

- Cross-Connects are nxn switches
- Interconnects SONET streams
- More flexible and efficient than rings
- Need mesh protection & restoration



## From SONET to WDM

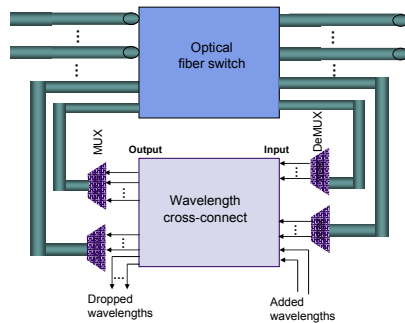
### SONET

- 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

## Optical Switching



**Justice is not blind**

The state of New York Unified Court System is leveraging its huge network capacity to run an advanced IP video surveillance and recording system.

1 IP video streams from 350 Axis IP cameras, and analog cameras with IP converters, are sent over the court system's backbone.

2 Court security officers can view any camera in any room through the state's courthouses, whether in a command center or patrolling with a Wi-Fi-enabled PDA.

3 Up to 3500 bytes of video is recorded per day on six Dell servers with a total of 50T bytes of storage capacity. Security footage is archived for three months.

Network World, Volume 22, Number 31, August 8, 2005

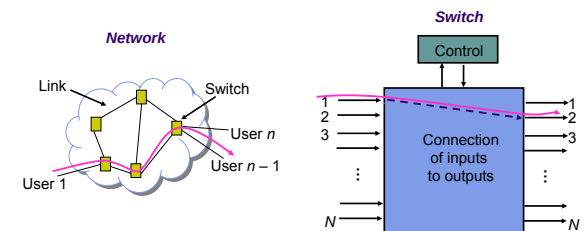
## Lecture 4 Circuit-Switching Networks



### 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

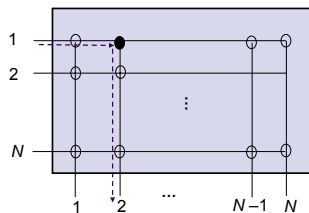


## Circuit Switch Types

- 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

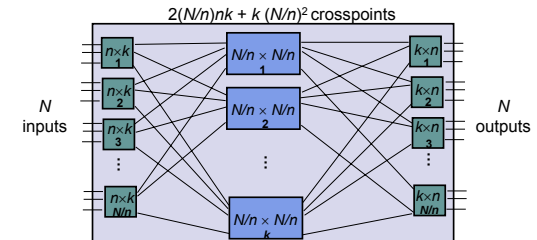
## Crossbar Space Switch

- $N \times N$  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



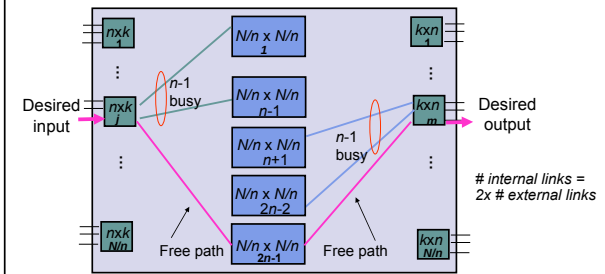
## Multistage Space Switch

- 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?"



## 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



## Minimum Complexity Clos Switch

$C(n)$  = number of crosspoints in Clos switch

$$= 2Nk + k\left(\frac{N}{n}\right)^2 = 2N(2n-1) + (2n-1)\left(\frac{N}{n}\right)^2$$

Differentiate with respect to  $n$ :

$$0 = \frac{\delta C}{\delta n} = 4N - \frac{2N^2}{n^2} + \frac{2N^2}{n^3} \approx 4N - \frac{2N^2}{n^2} \Rightarrow n \approx \sqrt{\frac{N}{2}}$$

The minimized number of crosspoints is then:

$$C^* = (2N + \frac{N^2}{N/2}) \left(2\left(\frac{N}{2}\right)^{1/2} - 1\right) \approx 4N \sqrt{2N} = 4\sqrt{2}N^{1.5}$$

This is lower than  $N^2$  for large  $N$

## Example: Clos Switch Design

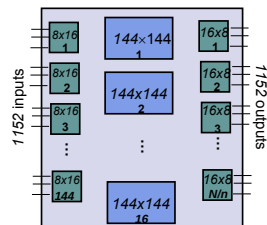
- Circa 2002, Mindspeed offered a Crossbar chip with the following specs:

- 144 inputs x 144 outputs, 3.125 Gbps/line
- Aggregate Crossbar chip throughput: 450 Gbps

- Clos Nonblocking Design for 1152x1152 switch

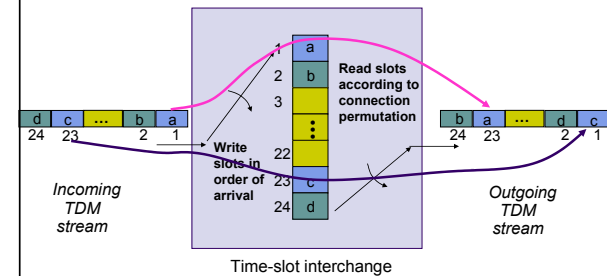
- $N=1152$ ,  $n=8$ ,  $k=16$
- $N/n=144$  8x16 switches in first stage
- 16 144x144 in centre stage
- 144 16x8 in third stage
- Aggregate Throughput: 3.6 Tbps!

- Note: the 144x144 crossbar can be partitioned into multiple smaller switches



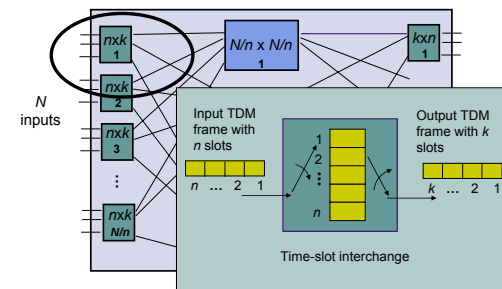
## Time-Slot Interchange (TSI) Switching

- Write bytes from arriving TDM stream into memory
- Read bytes in permuted order into outgoing TDM stream
- Max # slots =  $125 \mu\text{sec} / (2 \times \text{memory cycle time})$

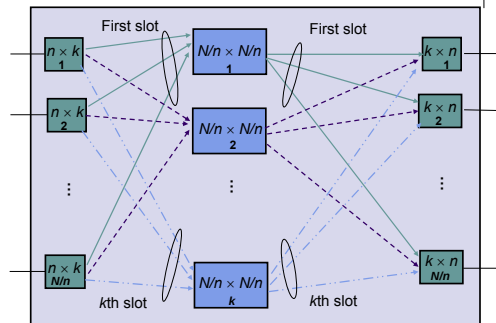


## Time-Space-Time Hybrid Switch

- 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

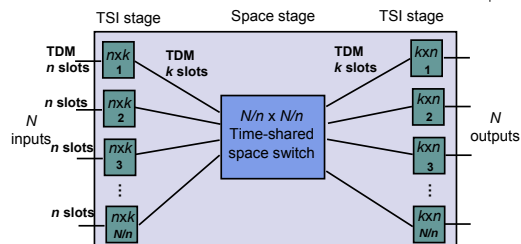


### Flow of time slots between switches



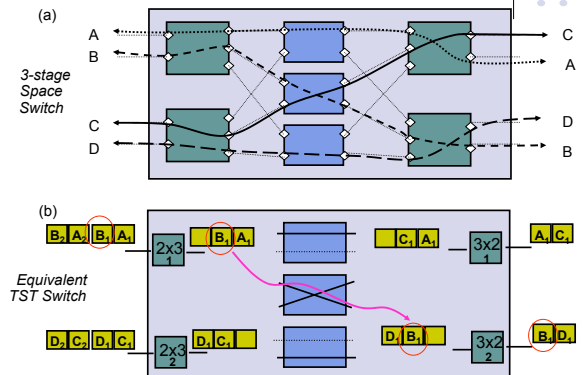
- Only one space switch active in each time slot

### 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

### Example: A → 2, B → 4, C → 1, D → 3



### Example: T-S-T Switch Design

For  $N = 960$

- Single stage space switch ~ 1 million crosspoints
- T-S-T
  - Let  $n = 120$   $N/n = 8$  TSIs
  - $k = 2n - 1 = 239$  for non-blocking
  - Pick  $k = 240$  time slots
  - Need  $8 \times 8$  time-multiplexed space switch

For  $N = 96,000$

- T-S-T
  - Let  $n = 120$   $k = 239$
  - $N/n = 800$
  - Need  $800 \times 800$  space switch

## 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

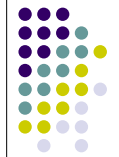


- Pure Optical switching: light-in, light-out, without optical-to-electronic conversion
- Space switching theory can be used to design optical switches
  - Multistage designs using small optical switches
  - Typically 2x2 or 4x4
  - MEMs and Electro-optic switching devices
- Wavelength switches
  - Very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

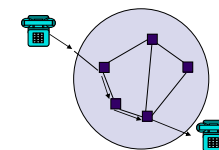
## Lecture 4 Circuit-Switching Networks



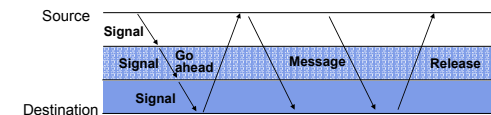
### *The Telephone Network*



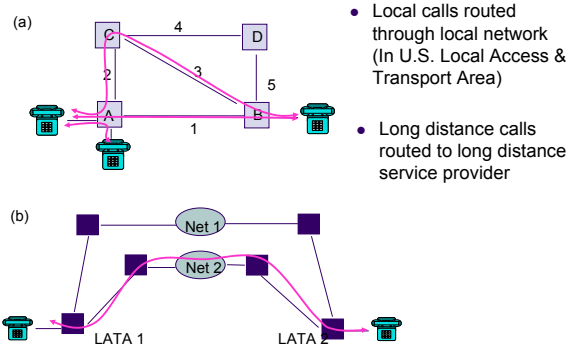
## Telephone Call



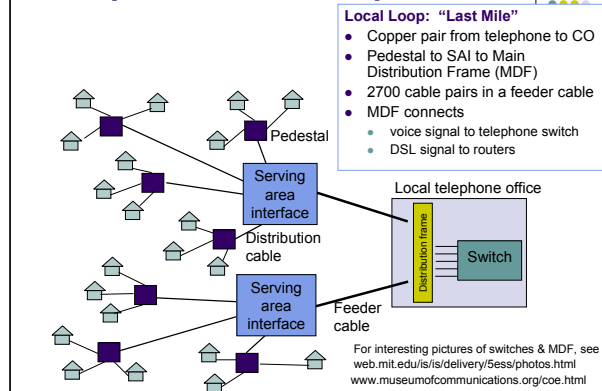
- User requests connection
- Network signaling establishes connection
- Speakers converse
- User(s) hang up
- Network releases connection resources



## Call Routing



## Telephone Local Loop



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

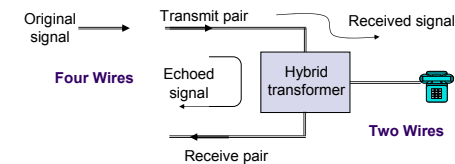
Table 3.5 Data rates of 24-gauge twisted pair

| 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

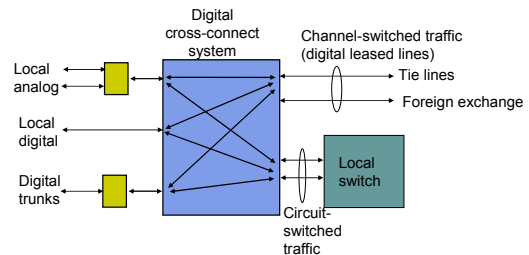
## Two- & Four-wire connections

- 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



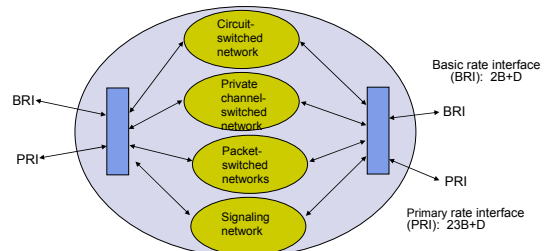
## Digital Cross-connect System

- To interconnect various types of traffic flows in a telephone central office



## Integrated Services Digital Network (ISDN)

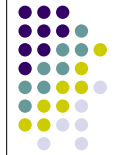
- First effort to provide end-to-end digital connections
- B channel = 64 kbps, D channel = 16 kbps
- ISDN defined interface to network
- Network consisted of separate networks for voice, data, signaling



## Lecture 4 Circuit-Switching Networks



### Signaling



## Setting Up Connections

### Manually

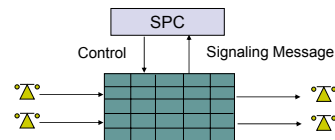
- Human Intervention
- Telephone
  - Voice commands & switchboard operators
- Transport Networks
  - Order forms & dispatching of craftpersons

### 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

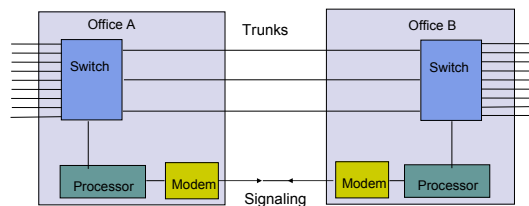
## Stored-Program Control Switches

- 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



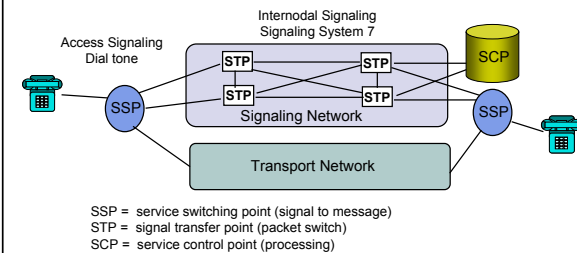
## Message Signaling

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

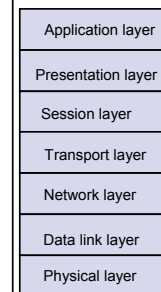
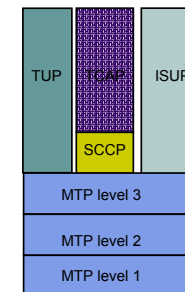


## Signaling Network

- 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



## 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  
 SCCP = signaling connection control part  
 TUP = telephone user part

MTP = message transfer part  
 TCAP = transaction capabilities part

## Future Signaling: Calls, Sessions, & Connections



### Call/Session

- An agreement by two end parties to communicate
  - Answering a ringing phone (after looking at caller ID)
  - TCP three-way handshake
- Applies in connection-less & connection-oriented networks
- *Session Initiation Protocol (SIP)* provides for establishment of sessions in many Internet applications

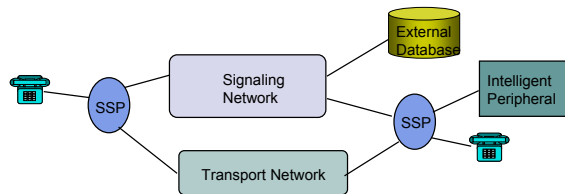
### Connection

- Allocation of resources to enable information transfer between communicating parties
  - Path establishment in telephone call
- Does not apply in connectionless networks
- *ReSerVation Protocol (RSVP)* provides for resource reservation along paths in Internet

## Network Intelligence



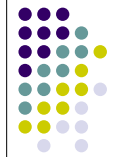
- Intelligent Peripherals provide additional service capabilities
- Voice Recognition & Voice Synthesis systems allow users to access applications via speech commands
- "Voice browsers" currently under development (See: [www.voicexml.org](http://www.voicexml.org))
- Long-term trend is for IP network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



## Lecture 4 Circuit-Switching Networks



### Traffic and Overload Control in Telephone Networks

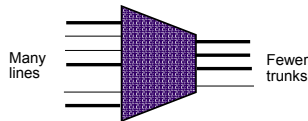


## Traffic Management & Overload Control



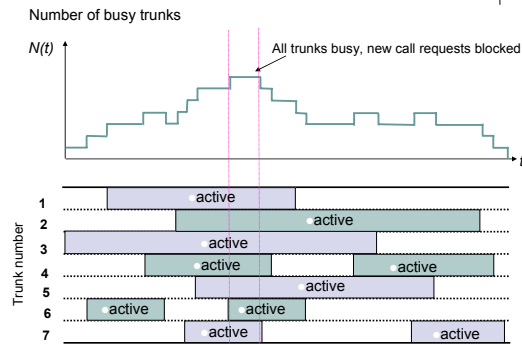
- Telephone calls come and go
- People activity follow patterns
  - Mid-morning & mid-afternoon at office
  - Evening at home
  - Summer vacation
- Outlier Days are extra busy
  - Mother's Day, Christmas, ...
- Disasters & other events cause surges in traffic
- Need traffic management & overload control

## 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**:  $\lambda$  requests per second
- In a very small time interval  $\Delta$ ,
  - 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:
  - $a = \lambda \text{ calls/sec} * E(X) \text{ seconds/call}$  (Erlangs)

## Blocking Probability & Utilization

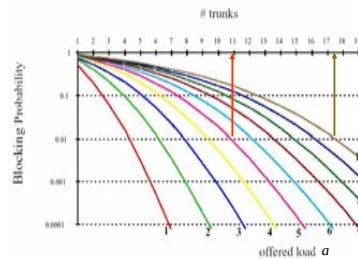
- $c$  = Number of Trunks
- Blocking occurs if all trunks are busy, i.e.  $N(t)=c$
- If call requests are Poisson, then blocking probability  $P_b$  is given by **Erlang B Formula**

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

- 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

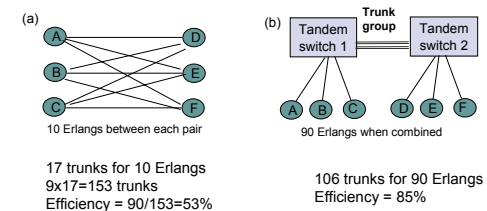
## Multiplexing Gain

| 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        |

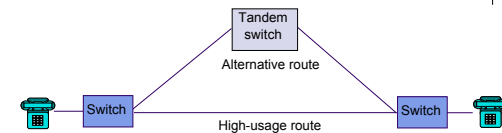
- At a given  $P_b$ , the system becomes more efficient in utilizing trunks with increasing system size
- Aggregating traffic flows to share centrally allocated resources is more efficient
- This effect is called *Multiplexing Gain*

## 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

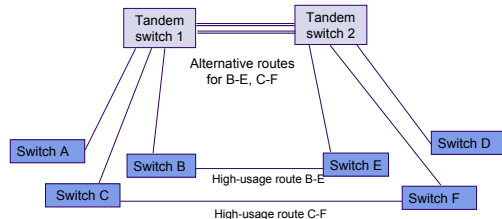


## Alternative Routing

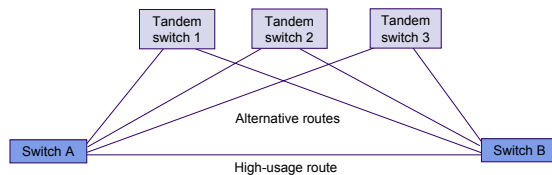


- Deploy trunks between switches with significant traffic volume
- Allocate trunks with high blocking, say 10%, so utilization is high
- Meet 1% end-to-end blocking requirement by overflowing to longer paths over tandem switch
- Tandem switch handles overflow traffic from other switches so it can operate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

## Typical Routing Scenario

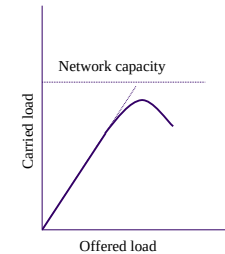


## Dynamic Routing



- 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

## Lecture 4 Circuit-Switching Networks



### Cellular Telephone Networks

## Radio Communications

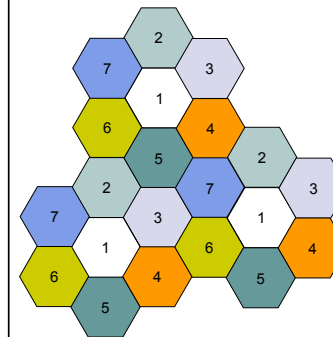
- 1900s: Radio telephony demonstrated
- 1920s: Commercial radio broadcast service
- 1930s: Spectrum regulation introduced to deal with interference
- 1940s: Mobile Telephone Service
  - Police & ambulance radio service
  - Single antenna covers transmission to mobile users in city
  - Less powerful car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

## Cellular Communications

Two basic concepts:

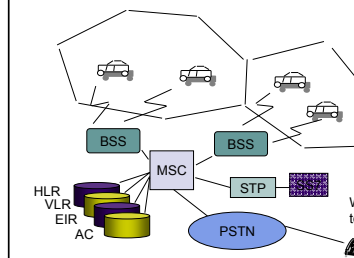
- Frequency Reuse
  - A region is partitioned into *cells*
  - Each cell is covered by *base station*
  - Power transmission levels controlled to minimize inter-cell interference
  - Spectrum can be reused in other cells
- Handoff
  - Procedures to ensure continuity of call as user moves from cell to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



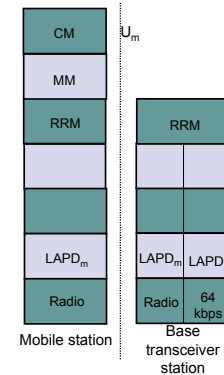
- Users subscribe to roaming service to use service outside their home region
- Signaling network used for message exchange between home & visited network
- Roamer uses setup channels to register in new area
- MSC in visited areas requests authorization from users Home Location Register
- Visitor Location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

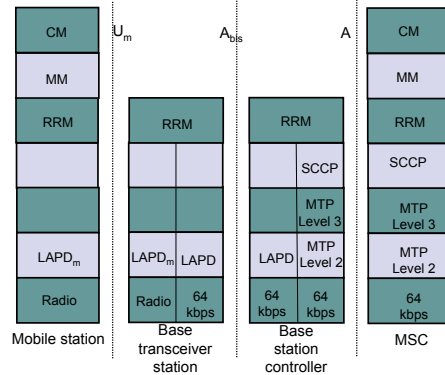


### Radio Air Interface (U<sub>m</sub>)

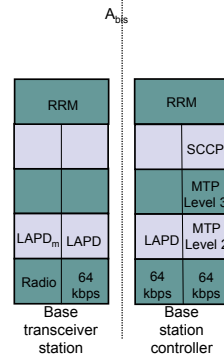
- LAPD<sub>m</sub> is data link control adapted to mobile
- RRM deals with setting up of radio channels & handover



## Cellular Network Protocol Stack



## Cellular Network Protocol Stack

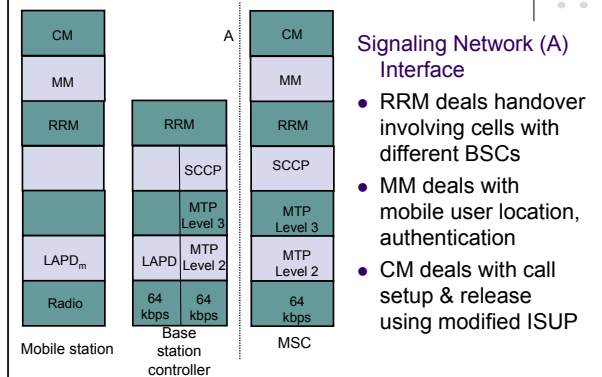


### A<sub>bis</sub> Interface

- 64 kbps link physical layer
- LAPD<sub>m</sub>
- BSC RRM can handle handover for cells within its control



## Cellular Network Protocol Stack



## What's Next for Cellular Networks?

- Mobility makes cellular phone compelling
  - Cell phone use increasing at expense of telephone
- Short Message Service (SMS) transfers text using signaling infrastructure
  - Growing very rapidly
- Multimedia cell phones
  - Digital camera to stimulate more usage
- Higher speed data capabilities
  - GPRS & EDGE for data transfer from laptops & PDAs
  - WiFi (802.11 wireless LAN) a major competitor