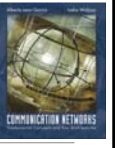
Chapter 4 Circuit-Switching Networks



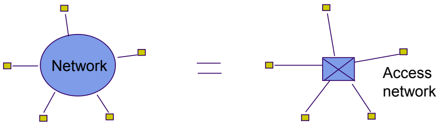
Multiplexing & SONET/SDH
Circuit Switches Architecture
The Telephone Network
Signaling in The Telephone Network
Wireless Cellular Networks
Blocking in Telephone Networks

Circuit Switching Networks

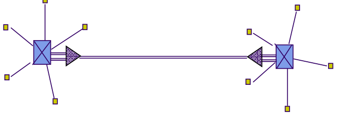
- End-to-end dedicated circuits between clients
  - Client can be a person or equipment (router or switch)
- Circuit can take different forms
  - Dedicated path for the transfer of electrical current
  - Dedicated time slots for transfer of voice samples
  - Dedicated frames for transfer of Nx51.84 Mbps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

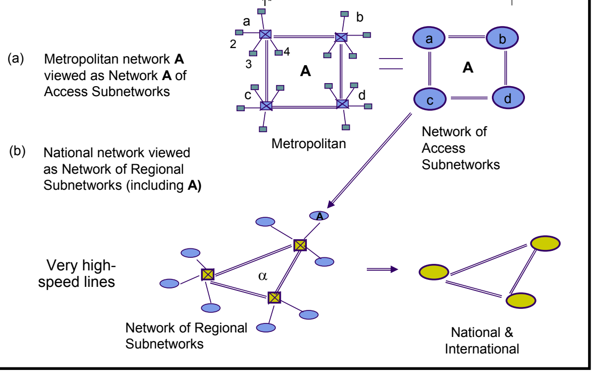
(a) A switch provides the network to a cluster of users, e.g. a telephone switch connects a local community



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

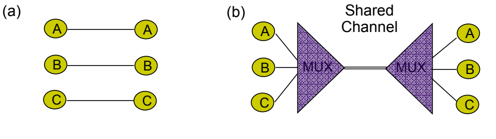


A Network Keeps Growing



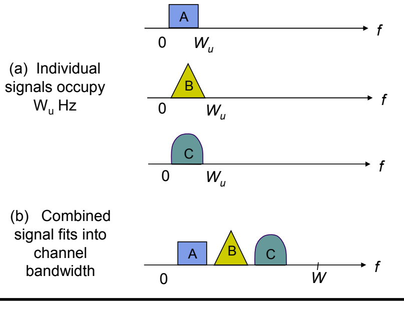
Multiplexing

- 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

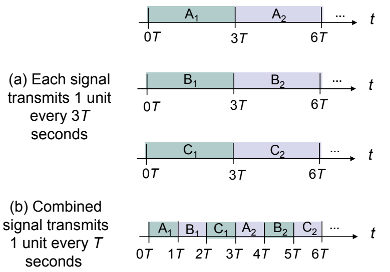
- Channel divided into frequency slots



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

Time-Division Multiplexing

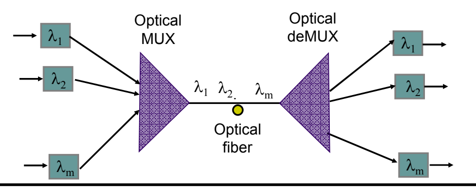
- High-speed digital channel divided into time slots



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

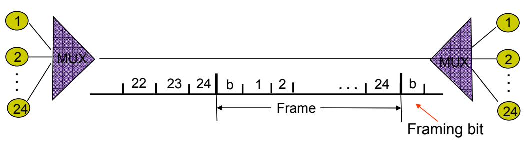
Wavelength-Division Multiplexing

- 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



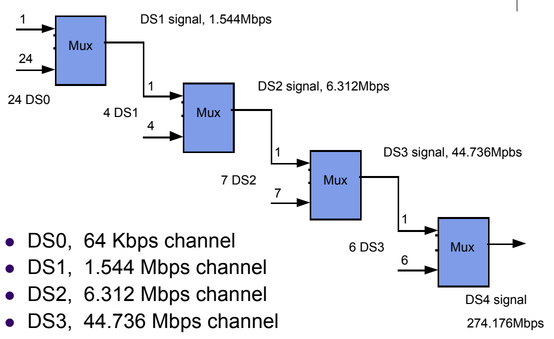
T-Carrier System

- 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

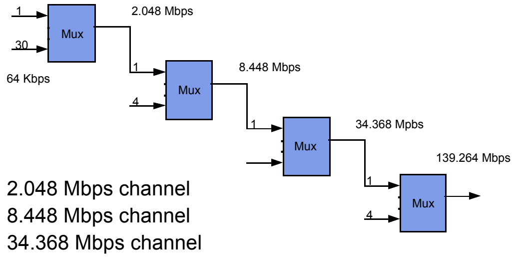
North American Digital Multiplexing Hierarchy



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

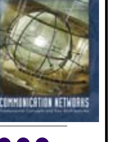
CCITT (ITU) Digital Hierarchy

- 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

Chapter 4
Circuit-Switching Networks



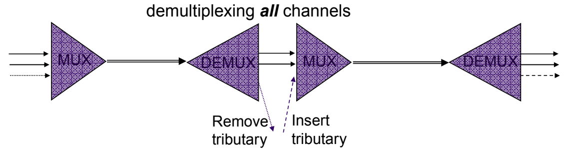
SONET & SDH

SONET: Overview

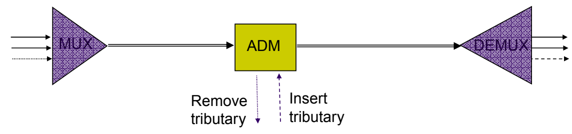
- TDM physical layer standard for optical fiber communications
- N.America: Synchronous Optical NETwork (SONET)
- 8000 frames/sec. (T_{frame} = 125 μsec)
  - compatible with North American digital hierarchy
- World: Synchronous Digital Hierarchy (SDH)
  - Needs to carry E1 and E3 signals
  - Compatible 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



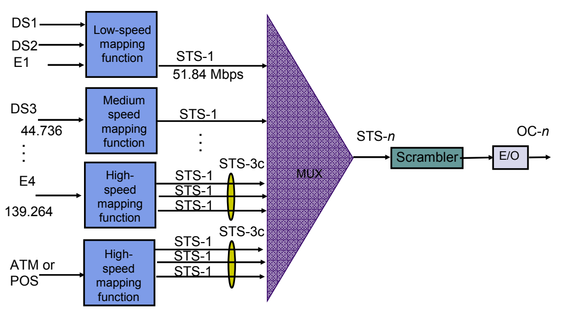
SONET Specifications

- 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

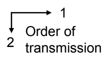


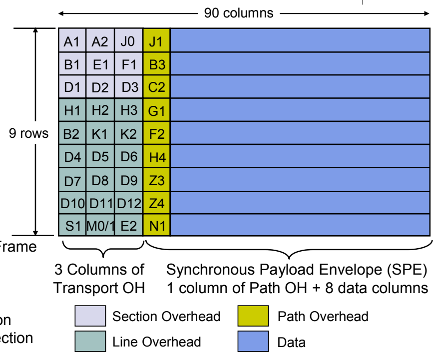
SONET Equipment

- 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

STS-1 Frame

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



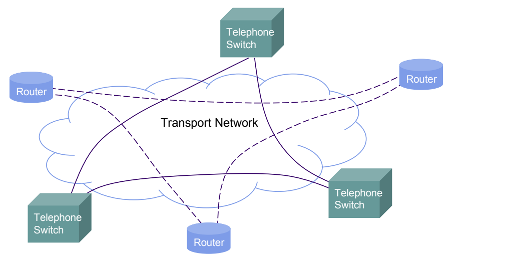


Special OH octets:

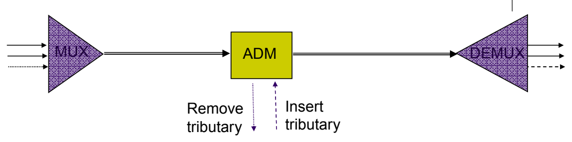
A1, A2 Frame Synch
B1 Parity on Previous Frame (BER monitoring)
J0 Section trace (Connection Alive?)
H1, H2, H3 Pointer Action
K1, K2 Automatic Protection Switching

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;



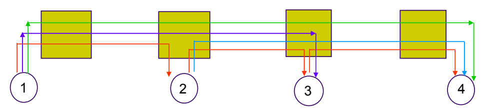
SONET ADM Networks



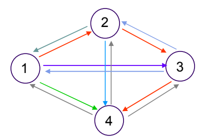
- SONET ADMs: the heart of existing transport networks
- ADMs interconnected in linear and ring topologies
- SONET signaling enables fast restoration (within 50 ms) of transport connections

Linear ADM Topology

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

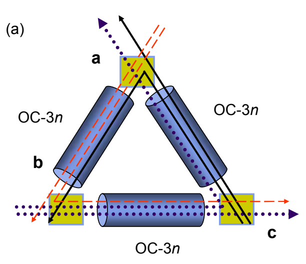


- Tributaries traverse ADMs transparently
- Connections create a *logical* topology seen by clients
- Tributaries from right to left are not shown

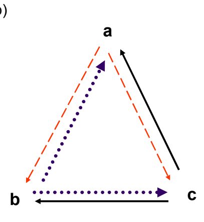


SONET Rings

- 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

From SONET to WDM

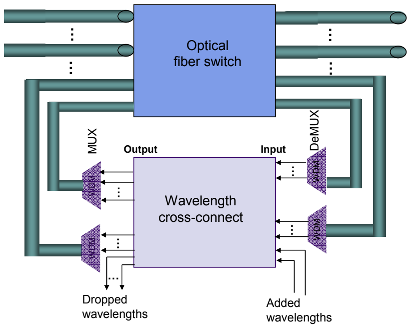
SONET

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

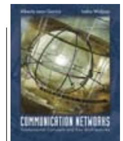
WDM

- 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



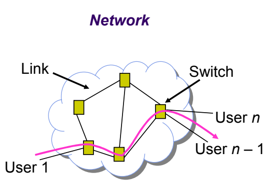
Chapter 4
Circuit-Switching Networks

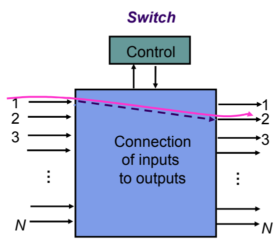


Circuit Switches Architecture

Network: Links & switches

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



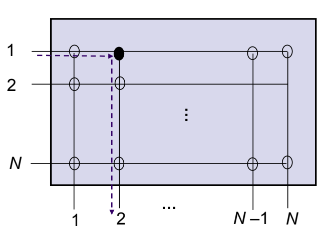


Circuit Switch Types

- 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

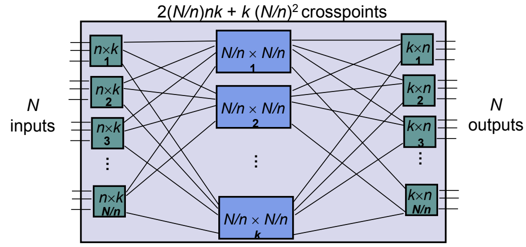
- *N* x *N* array of crosspoints
- Connect an input to an output by closing a crosspoint
- Nonblocking: Any input can connect to idle output
- Complexity: N^2 crosspoints



Multistage Space Switch

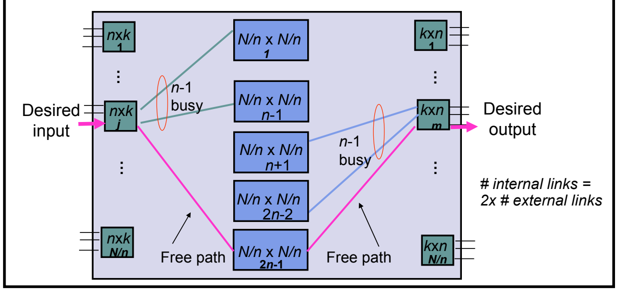
- Large switch built from multiple stages of small switches
- The n inputs to a first-stage switch share k paths through intermediate crossbar switches
- Larger k (more intermediate switches) means more paths to output
- In 1950s, Clos asked, “How many intermediate switches required to make switch nonblocking?”

$2(N/n)nk + k(N/n)^2$ 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



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*:

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

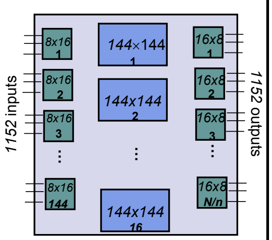
The minimized number of crosspoints is then:

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

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

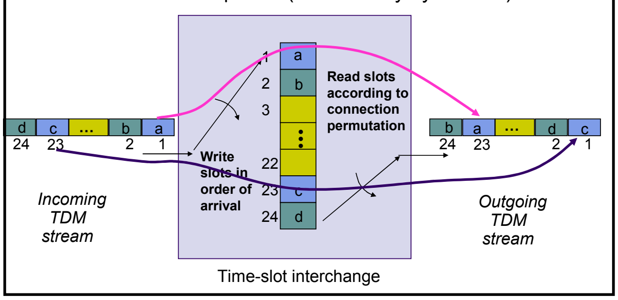
Example: Clos Switch Design

- Circa 2002, Mindspeed Co. 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



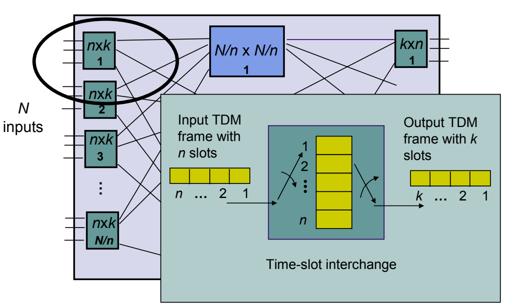
Time-Slot Interchange (TSI) Switching

- 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)

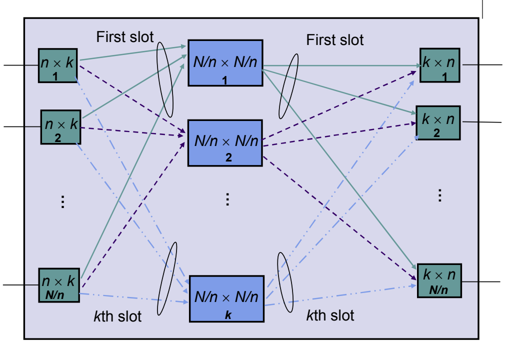


Time-Space-Time Hybrid Switch

- 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

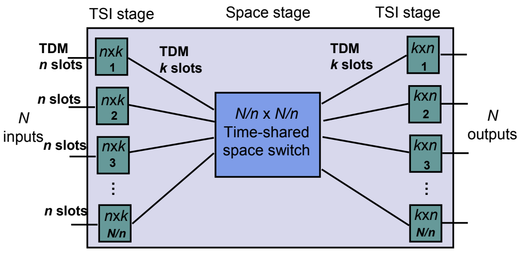


Flow of time slots between switches



- 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

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

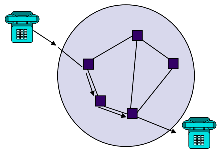
Pure Optical Switching

- 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

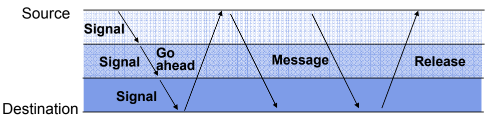
Chapter 4
Circuit-Switching Networks

The Telephone Network

Telephone Call



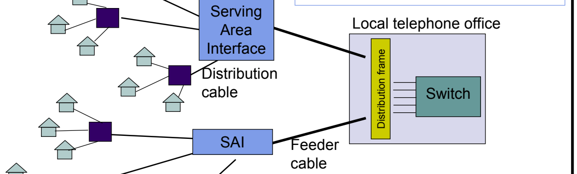
- User requests connection
- Network signaling establishes connection
- Speakers converse
- User(s) hang up
- Network releases connection resources



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?

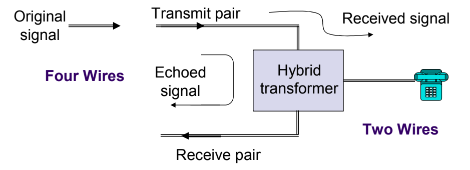
Data rates of 24-gauge twisted pair

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

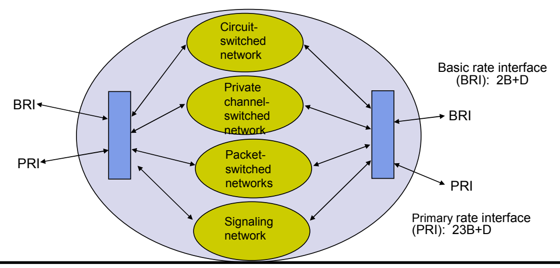
Two- & Four-wire connections

- 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

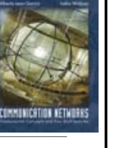


Integrated Services Digital Network (ISDN)

- 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 in Telephone Networks

Setting Up Connections

Manually

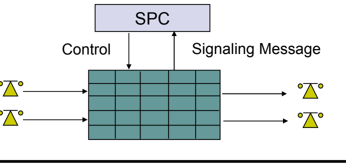
- Human Intervention
- Telephone
  - Voice commands & switchboard operators
- Transport Networks
  - Order forms & dispatching of craftpersons

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

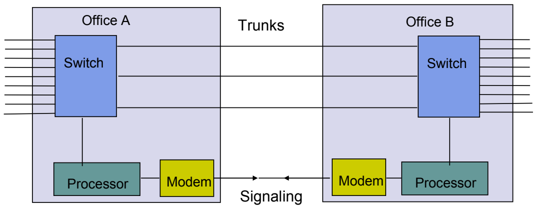
Stored-Program Control Switches

- 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



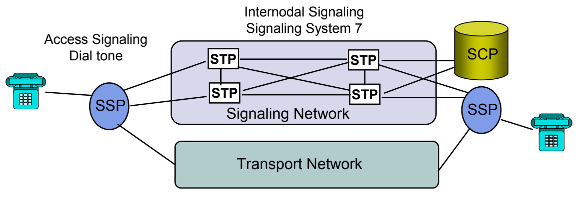
Message Signaling

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



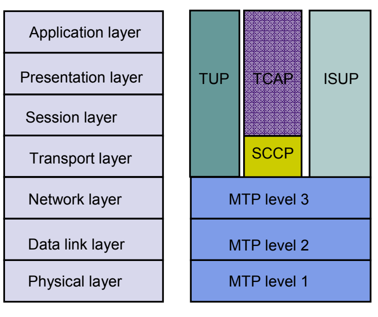
Signaling Network (SS7)

- 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)

SS7 Protocol Stack

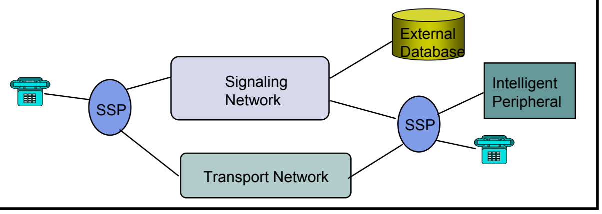


- Lower 3 layers ensure delivery of messages to signaling nodes
- SCCP allows messages to be directed to applications
- TCAP defines messages & protocols between applications
- ISUP performs basic call setup & release
- TUP instead of ISUP in some countries

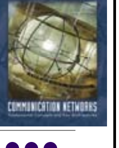
ISUP = ISDN user part
SSCP = signaling connection control part
TUP = telephone user part
MTP = message transfer part
TCAP = transaction capabilities part

Intelligent Networks

- 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

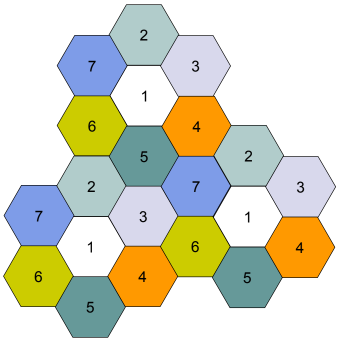


Cellular Telephone Networks

Mobile Cellular Networks

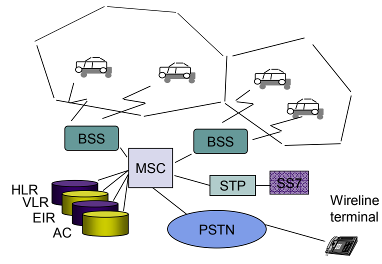
- Radio communication using TDMA/FDMA/CDMA
- Full duplex (two-way) using FDD (sometimes TDD)
- Two critical functions are required:
  - Frequency Reuse
    - A region is partitioned into *cells*
    - Each cell is covered by a *base station*
    - Power transmission levels controlled to minimize inter-cell interference
    - Spectrum can be reused in other cells
- Handover
  - Procedure 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 (Reuse factor = 1)

Cellular Network Architecture



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

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

Examples of Signaling & Connection Control

- *Special setup channels* reserved for call setup & handover
- Mobile unit selects setup channel with strongest signal & monitors this channel
- **Example: 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 switch to the new channels
  - Mobile phone rings

Signaling & Control cont'd

- Mobile-originated call:
  - Mobile sends request in reverse setup channel
  - Message from mobile includes serial # and 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

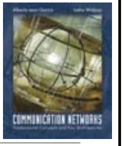
Handover

- Base station monitors signal levels from its mobiles
- If signal level drops below threshold, MSC is notified & mobile is instructed to transmit on special channel
- Other base stations in vicinity of mobile also monitor signal from mobile on special channel
- Results are sent to MSC, which selects new cell
- Current BSS & mobile prepare for handover
- MSC releases connection to first BSS and sets up connection to new BSS
- Mobile changes to new channel 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

Chapter 4
Circuit-Switching Networks

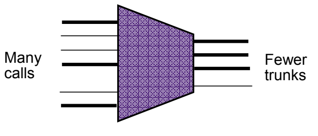


Traffic Modeling & Blocking in Telephone Networks

Telephony Traffic (Tele-Traffic)

- Telephone calls come and go !
- People activity follow patterns
  - Mid-morning & mid-afternoon at office
  - Evening at home
  - Vacation & week-ends
- Special events cause surge in Tele-traffic
- Need good traffic modeling in order to design and manage telephone networks

Traffic Trunking



- Tele-Traffic fluctuates as calls are initiated & terminated
- To provide guaranteed service for every call would be too expensive
- Typically, economical design to provide service most of the time
- Switches concentrate many lines onto few *shared* trunks
- Blocking of requests will occur from time to time
- Traffic engineering estimates required resources to meet blocking performance targets (typically less than 1 to 2%)

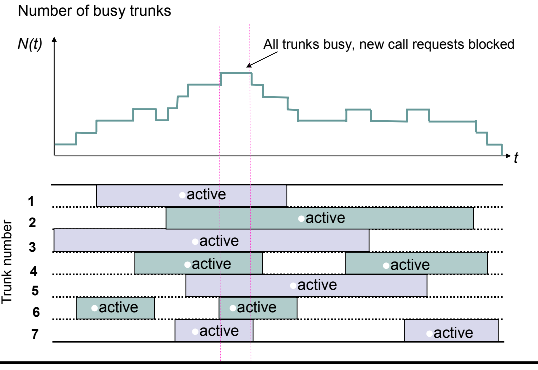
Trunking Explained

- The concept of ***Trunking*** allows a large number of users to share few available channels.
- Trunking exploits the statistical behavior of users
  - A fixed number of circuits accommodates a large number of users who most likely will not try to access the system at the same time although many of them will try during the ***busy hour***.

Grade of Service (GoS)

- Because the number of available channels is always less than the number of users in the system (otherwise system would not be cost effective), there will always be a probability of blocking some calls from accessing the system.
- Grade of Service –**GoS**– is defined as the probability of blocking incoming calls during the "Busy Time".
- GoS depends on:
  - Traffic intensity
  - Available channels (or trunks)
  - Subscriber behavior & System queuing rules

Fluctuation in Trunk Occupancy



Traffic Modeling

- Find the statistics of *N(t):* the number of calls in the system
- Use Queuing Theory to model system
- ***Call Arrival Rate***: λ requests per second
- The resulting random arrivals are modeled as a Poisson process:

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

- In a very small time interval Δ,
  - Prob[new request] = $\lambda\Delta$
  - Prob[no new request] = 1 - $\lambda\Delta$
- ***Call Holding Time X***: time a user maintains a connection
  - *X* modeled as random variable with mean *E(X)*
- ***Offered Load***: traffic intensity offered by users
  - $a = \lambda$ calls/sec * E(*X*) seconds/call (measured in Erlangs)

Erlang Calculations

- Example: Total 1000 subscribers

200 make One 5min call/hour	200 x 1 x 5/60	=16.67
100 make Two 2min call/hour	100 x 2 x 2/60	=6.67
500 make Five 1min call/hour	500 x 5 x 1/60	=41.67
200 make Three 0.5min call/hour	200 x 3 x 0.5/60	=5
1000 Users		**70 Erlang**

On average each user generates 70mE

Blocking Probability & Utilization

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

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

- ***System Utilization*** is the average # of trunks in use

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

Erlang B Formula

- C is the number of trunked channels
- A is the total offered traffic intensity

$$\Pr[\text{blocking}] = \text{GoS} = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}}$$

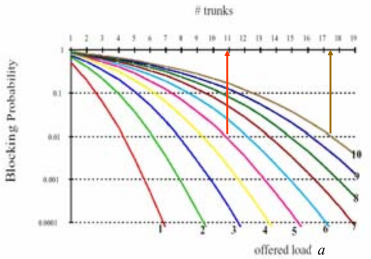
Blocking Probability GoS

Number of Channels *C*	Capacity (Erlangs) for GOS = 0.01	= 0.005	= 0.002	= 0.001
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

Trunked Channels

Erlang Capacity

Erlang-B Plot



Example: to achieve 1% blocking probability:
a = 5 Erlangs requires 11 trunks
a = 10 Erlangs requires 18 trunks

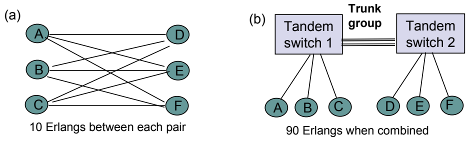
Multiplexing Gain

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
- Combining traffic flows to share centrally allocated resources is more efficient
- This effect is called *Multiplexing Gain*

Example:

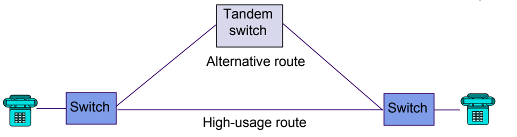
- Useful to combine smaller flows to share resources
- Example: 3 nearby Central Office (CO) switches in one region and 3 other close COs in another region
- Assume 10 Erlangs of traffic between each pair of COs



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