CNL
Communications & Networking
Laboratory

ECE 462 – Data and Computer Communications

Lecture 13/14: Multiplexing

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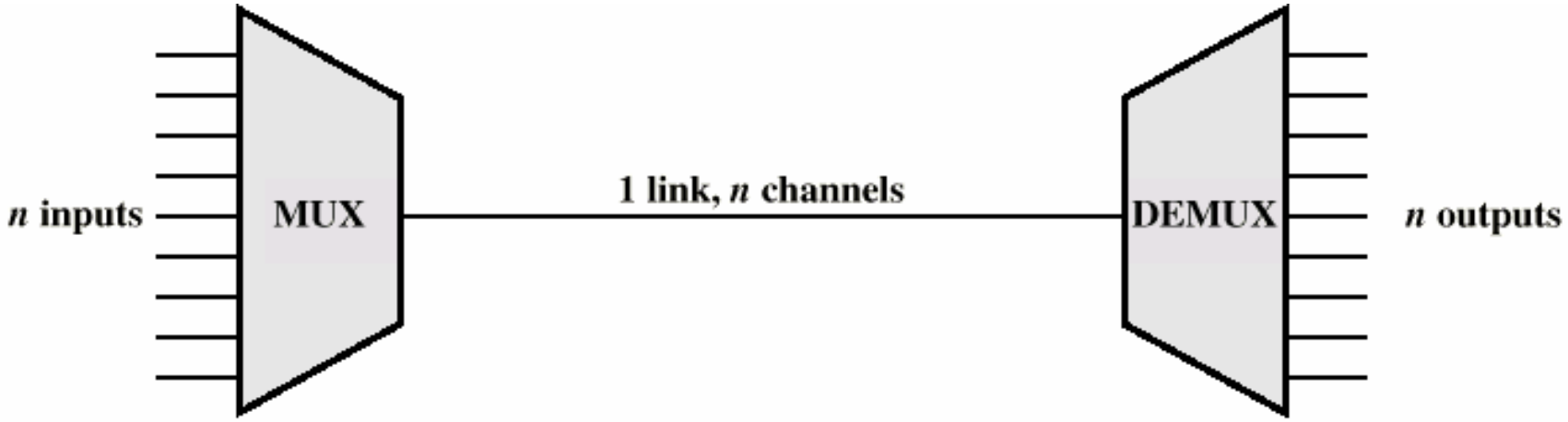
Outline

- Frequency Division Multiplexing – FDM
- Wavelength Division Multiplexing – WDM
- Synchronous Time Division Multiplexing - TDM
- Statistical Multiplexing
- Asymmetric Digital Subscriber Line ADSL
- XDSL

Note: Some material adapted from various textbook. In particular, the sequences of slides have been sorted to match closely that of the textbook Data and Computer Communications by W. Stallings, 7th Edition, Prentice Hall, 2007

Multiplexing

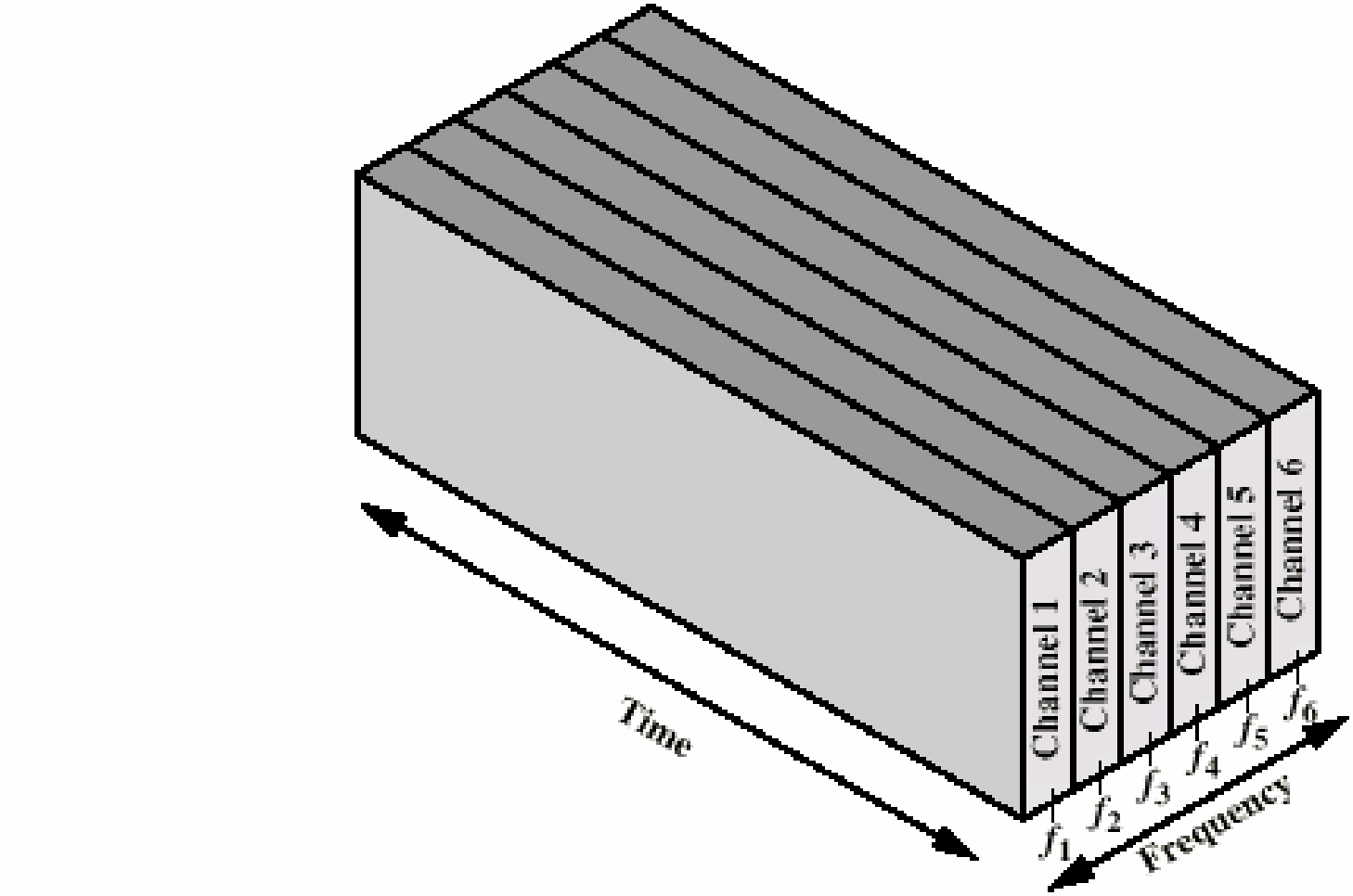
- Multiplexing allows several sources to share resources (e.g., BW)



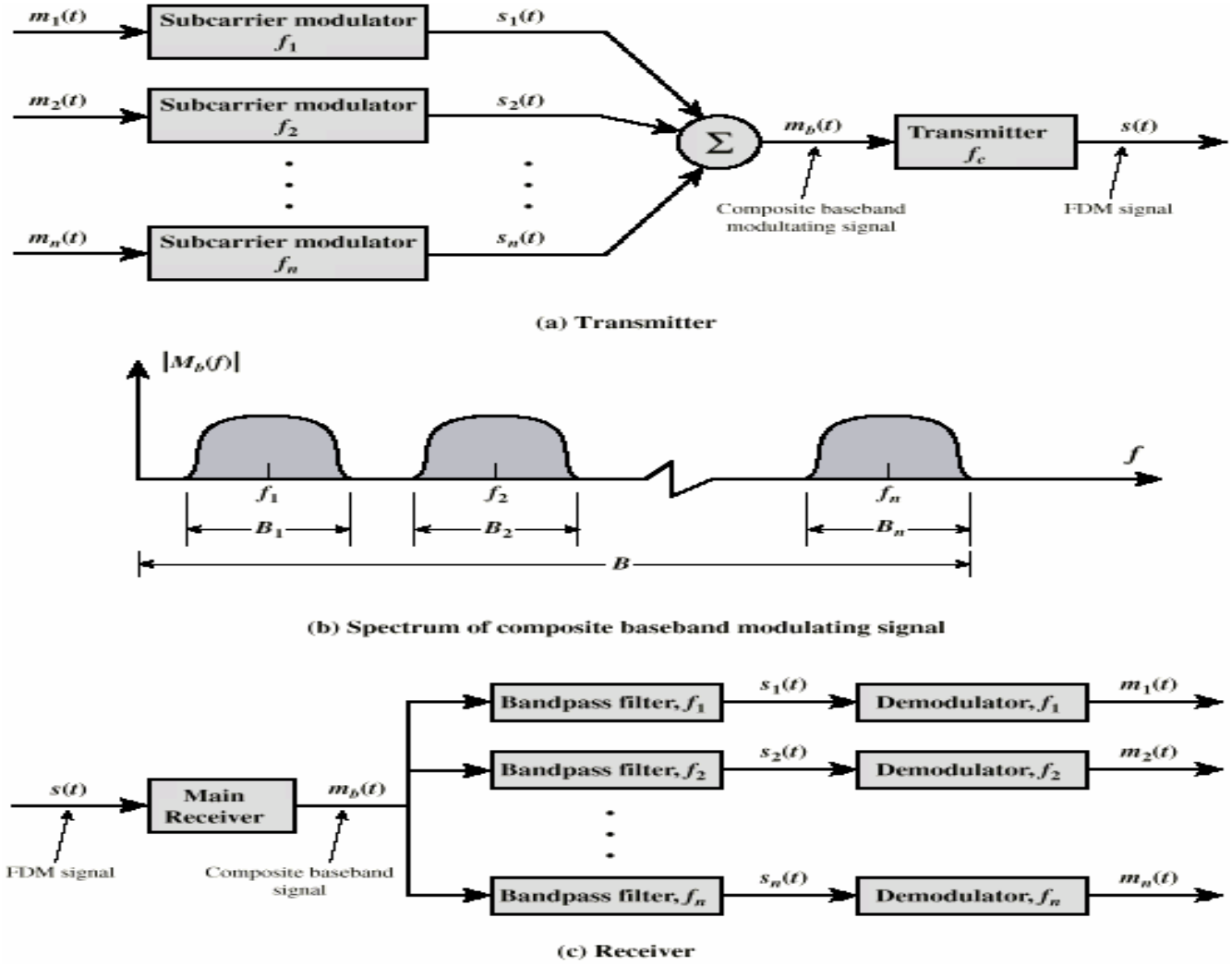
Frequency Division Multiplexing

- FDM
- Useful bandwidth of medium exceeds required bandwidth of channel
- Each signal is modulated to a different carrier frequency
  - TV signal: Luminance, color and audio components
- Carrier frequencies separated so signals do not overlap (guard bands)
  - e.g. broadcast radio
- Channel allocated even if no data

Frequency Division Multiplexing Diagram

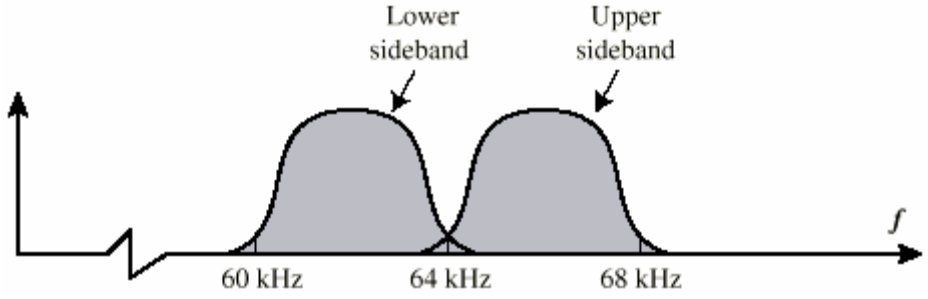


FDM System

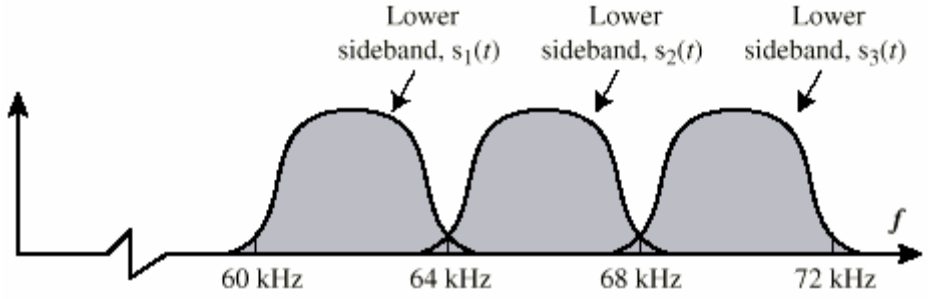

$m_1(t)$
Subcarrier modulator f_1
$s_1(t)$
$m_2(t)$
Subcarrier modulator f_2
$s_2(t)$
$m_n(t)$
Subcarrier modulator f_n
$s_n(t)$
Σ
$m_b(t)$
Transmitter f_c
$s(t)$
Composite baseband modulating signal
FDM signal
(a) Transmitter
$|M_b(f)|$
f_1
f_2
f_n
B_1
B_2
B_n
B
f
(b) Spectrum of composite baseband modulating signal
$s(t)$
Main Receiver
$m_b(t)$
FDM signal
Composite baseband signal
Bandpass filter, f_1
Bandpass filter, f_2
Bandpass filter, f_n
$s_1(t)$
$s_2(t)$
$s_n(t)$
Demodulator, f_1
Demodulator, f_2
Demodulator, f_n
$m_1(t)$
$m_2(t)$
$m_n(t)$
(c) Receiver

FDM of Three Voiceband Signals

(a) Spectrum of $m_1(t)$, positive f



(b) Spectrum of $s_1(t)$ for $f_1 = 64$ kHz



(c) Spectrum of composite signal using subcarriers at 64 kHz, 68 kHz, and 72 kHz

Analog Carrier Systems

- AT&T (USA)
- Hierarchy of FDM schemes
- Group
  - 12 voice channels (4kHz each) = 48kHz
  - Range 60kHz to 108kHz
- Supergroup
  - 60 channel
  - FDM of 5 group signals on carriers between 420kHz and 612 kHz
- Mastergroup
  - 10 supergroups

Wavelength Division Multiplexing

- Multiple beams of light at different frequency
- Carried by optical fiber
- A form of FDM
- Each color of light (wavelength) carries separate data channel
- 1997 Bell Labs
  - 100 beams
  - Each at 10 Gbps
  - Giving 1 terabit per second (Tbps)
- Commercial systems of 160 channels of 10 Gbps now available
- Lab systems (Alcatel) 256 channels at 39.8 Gbps each
  - 10.1 Tbps
  - Over 100km

WDM Operation

- Same general architecture as other FDM
- Number of sources generating laser beams at different frequencies
- Multiplexer consolidates sources for transmission over single fiber
- Optical amplifiers amplify all wavelengths
  - Typically tens of km apart
- Demux separates channels at the destination
- Mostly 1550nm wavelength range
- Was 200MHz per channel
- Now 50GHz

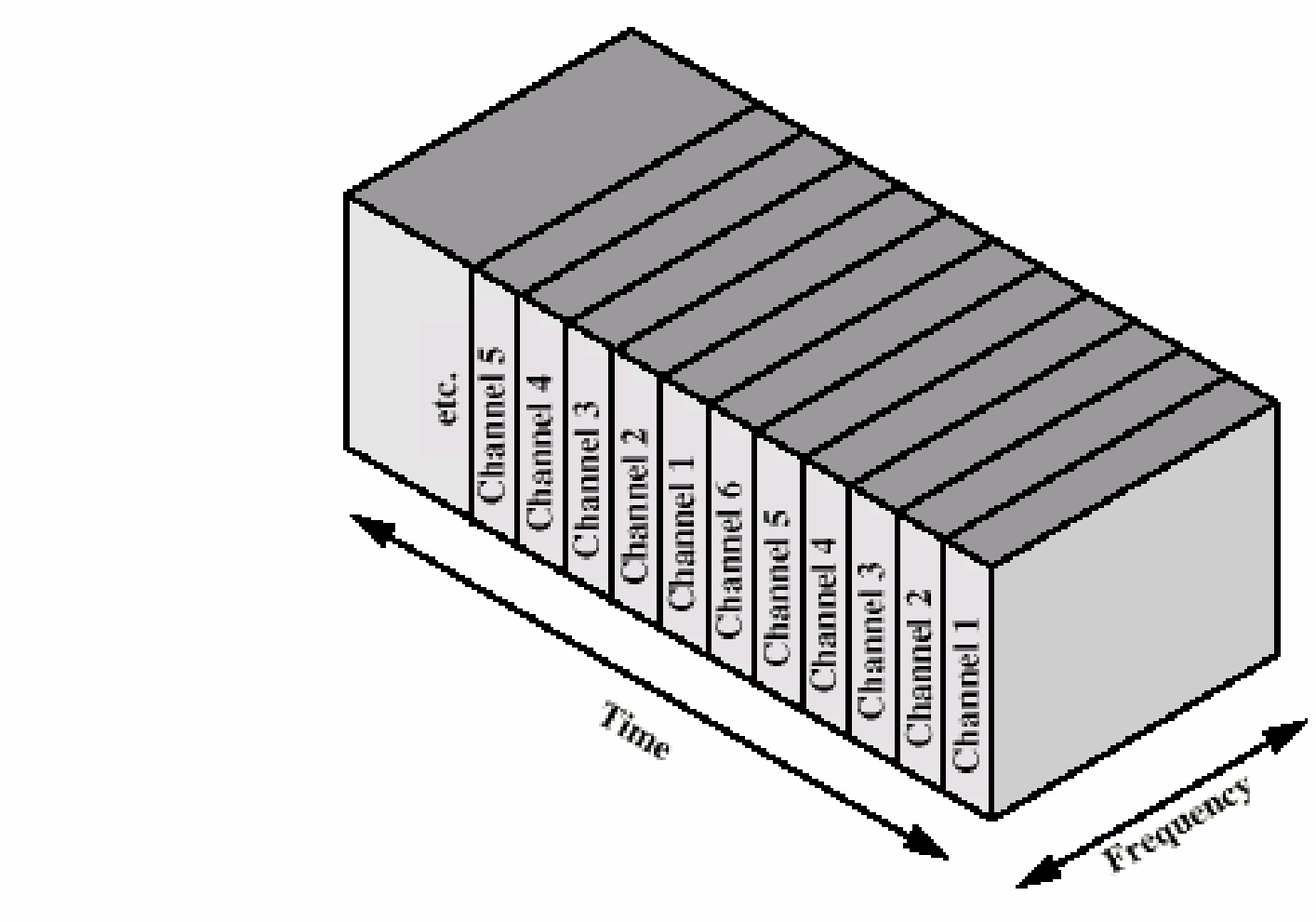
Dense Wavelength Division Multiplexing

- DWDM
- No official or standard definition
- Implies more channels more closely spaced that WDM
- Channel spacing of 200GHz or less is dense!

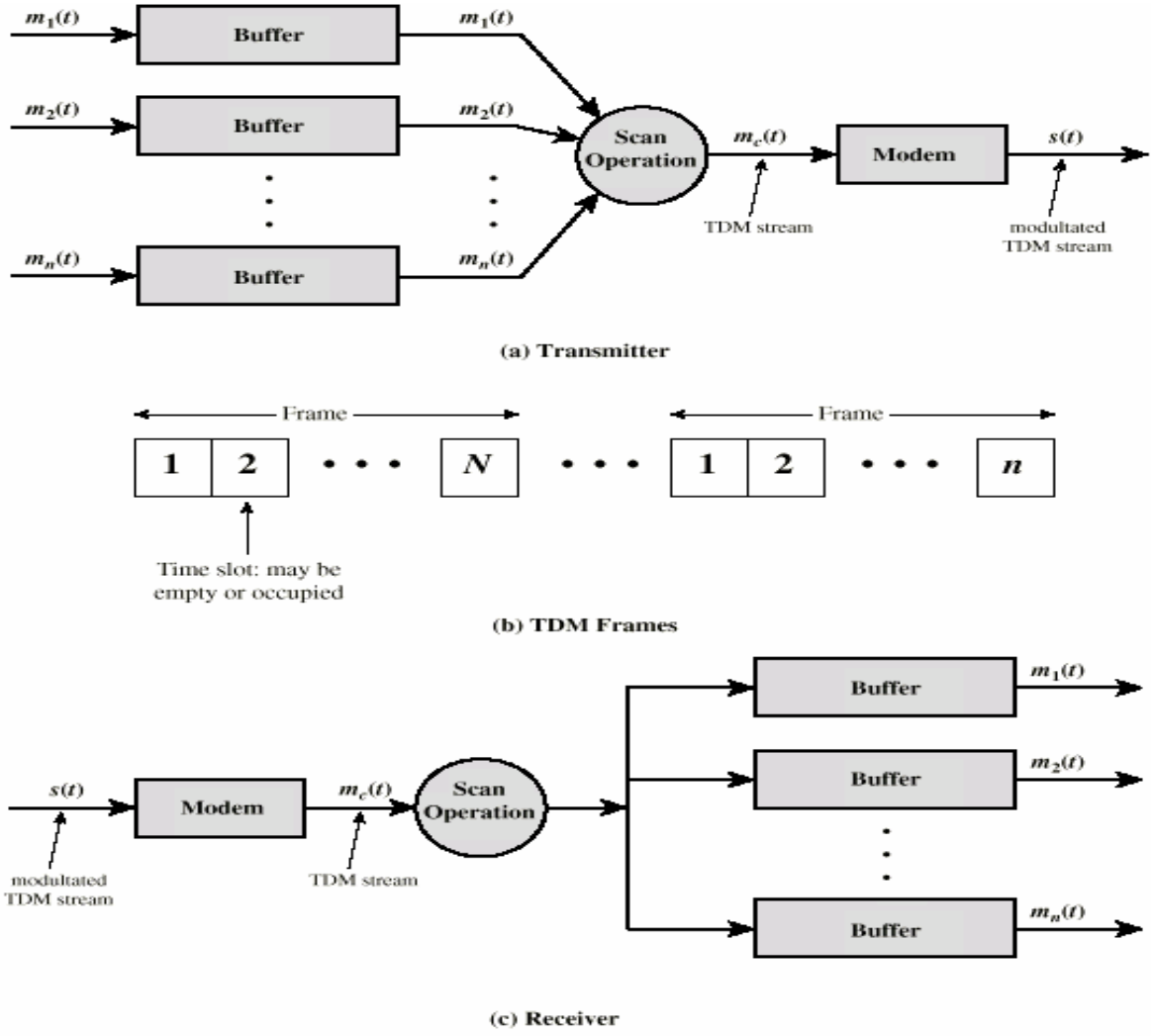
Synchronous Time Division Multiplexing

- Data rate of medium exceeds data rate of digital signal to be transmitted
- Multiple digital signals interleaved in time
- May be at bit level of blocks
- Time slots preassigned to sources and fixed
- Time slots allocated even if no data
- Time slots do not have to be evenly distributed amongst sources

Time Division Multiplexing



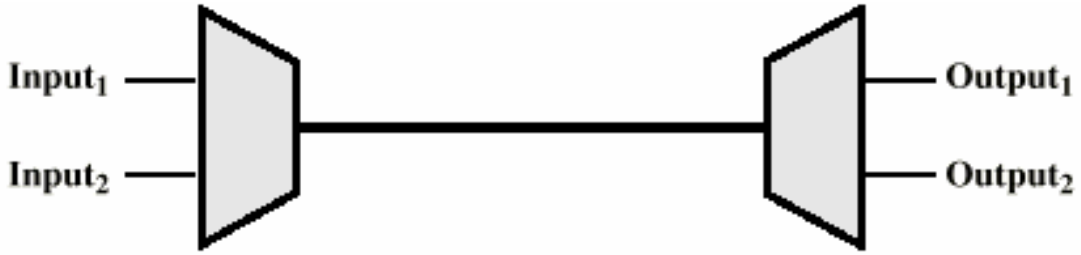
TDM System


$m_1(t)$
Buffer
$m_1(t)$
$m_2(t)$
Buffer
$m_2(t)$
Scan Operation
$m_c(t)$
Modem
$s(t)$
$m_n(t)$
Buffer
$m_n(t)$
TDM stream
modultated TDM stream
(a) Transmitter
Frame
Frame
1
2
N
1
2
n
Time slot: may be empty or occupied
(b) TDM Frames
$s(t)$
Modem
$m_c(t)$
Scan Operation
Buffer
$m_1(t)$
Buffer
$m_2(t)$
Buffer
$m_n(t)$
modultated TDM stream
TDM stream
(c) Receiver

TDM Link Control

- No headers and trailers
- Data link control protocols not needed
- Flow control
  - Data rate of multiplexed line is fixed
  - If one channel receiver can not receive data, the others must carry on
  - The corresponding source must be quenched
  - This leaves empty slots
- Error control
  - Errors are detected and handled by individual channel systems

Data Link Control on TDM



(a) Configuration

$Input_1$ ····· F_1 f_1 f_1 d_1 d_1 d_1 C_1 A_1 F_1 f_1 f_1 d_1 d_1 d_1 C_1 A_1 F_1

$Input_2$ ··· F_2 f_2 f_2 d_2 d_2 d_2 d_2 C_2 A_2 F_2 f_2 f_2 d_2 d_2 d_2 d_2 C_2 A_2 F_2

(b) Input data streams

··· f_2 F_1 d_2 f_1 d_2 f_1 d_2 d_1 d_2 d_1 C_2 d_1 A_2 C_1 F_2 A_1 f_2 F_1 f_2 f_1 d_2 f_1 d_2 d_1 d_2 d_1 d_2 d_1 C_2 C_1 A_2 A_1 F_2 F_1

(c) Multiplexed data stream

Legend: F = flag field; d = one octet of data field; A = address field; f = one octet of FCS field; C = control field

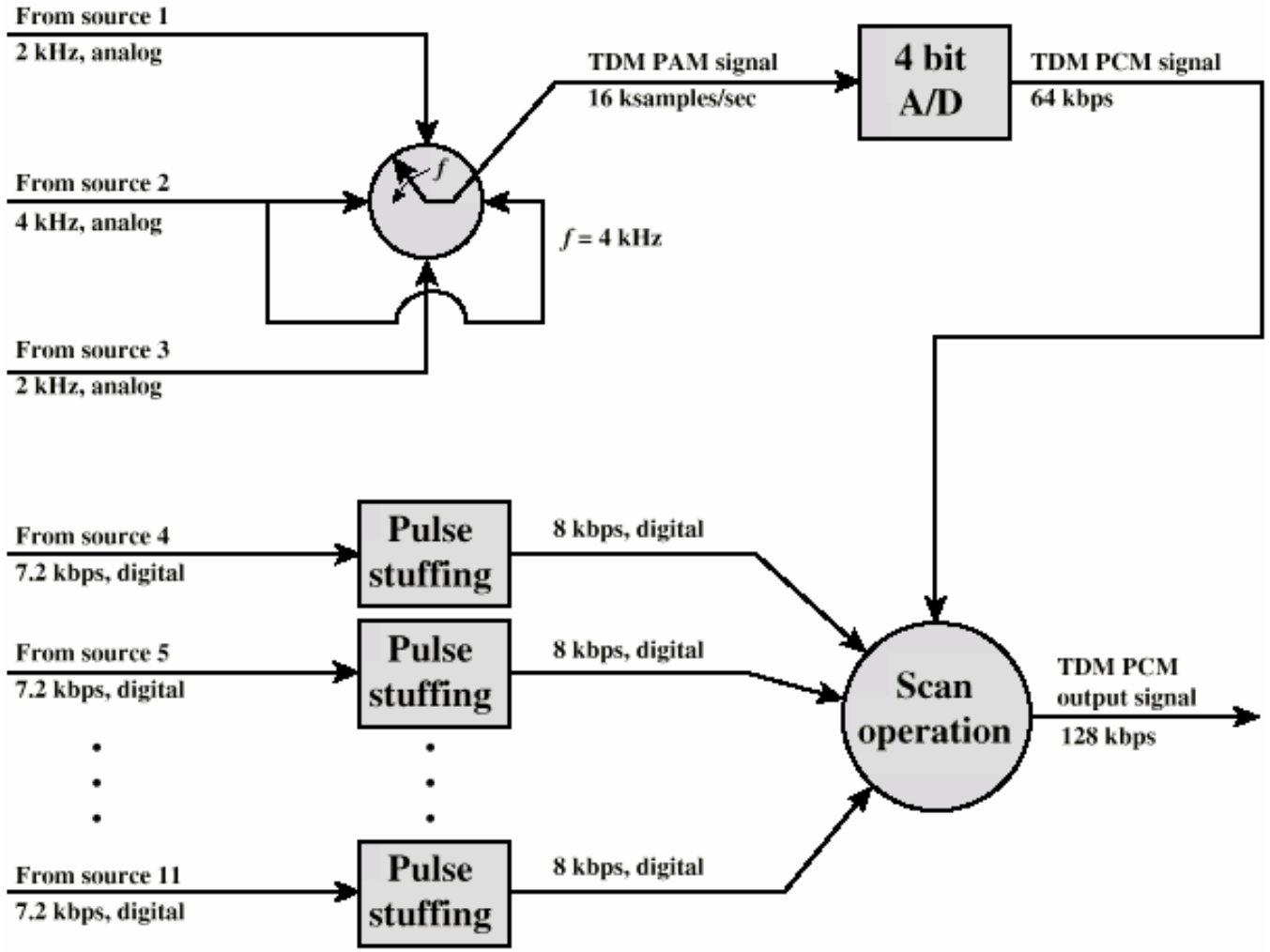
Framing

- No flag or SYNC characters bracketing TDM frames
- Must provide synchronizing mechanism
- Added digit framing
  - One control bit added to each TDM frame
    - Looks like another channel - "control channel"
  - Identifiable bit pattern used on control channel
  - e.g. alternating 01010101…unlikely on a data channel
  - Can compare incoming bit patterns on each channel with sync pattern

Pulse Stuffing

- Problem - Synchronizing data sources
- Clocks in different sources drifting
- Data rates from different sources not related by simple rational number
- Solution - Pulse Stuffing
  - Outgoing data rate (excluding framing bits) higher than sum of incoming rates
  - Stuff extra dummy bits or pulses into each incoming signal until it matches local clock
  - Stuffed pulses inserted at fixed locations in frame and removed at demultiplexer

TDM of Analog and Digital Sources



Digital Carrier Systems

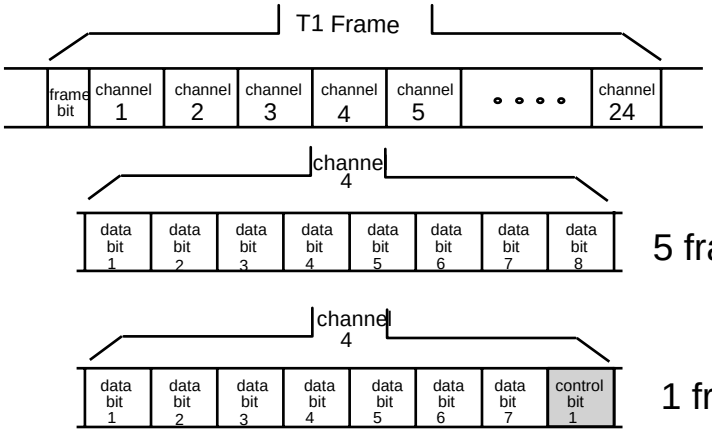
- Hierarchy of TDM
- USA/Canada/Japan use one system
- ITU-T use a similar (but different) system
- US system based on DS-1 format
- Multiplexes 24 channels
- Each frame has 8 bits per channel plus one framing bit
- 193 bits per frame

Digital Signal Levels

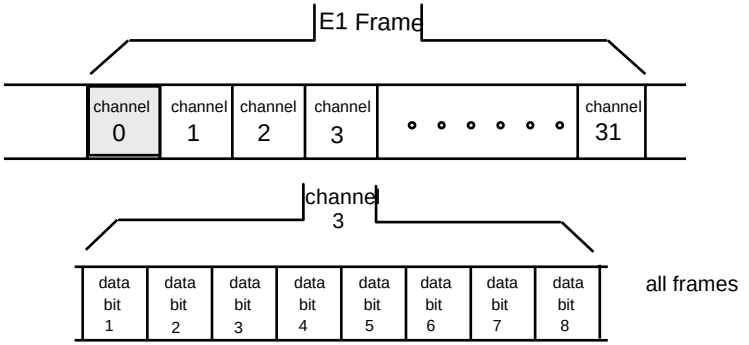
- DS0 1 Channel 64 Kbps
- DS1 24 Channels 1.544 Mbps
- DS2 96 Channels (4T1) 6.312 Mbps
- DS3 672 Channels (7T2=28T1) 44.7 Mbps
- DS4 4032 Channels (6T3) 274.17 Mbps

T1 and E1 Carriers

T1 multiplexed line



E1 multiplexed line



Digital Carrier Systems

- For voice each channel contains one word of digitized data (PCM, 8000 samples per sec)
  - Data rate 8000x193 = 1.544Mbps
  - Five out of six frames have 8 bit PCM samples
  - Sixth frame is 7 bit PCM word plus signaling bit
  - Signaling bits form stream for each channel containing control and routing info
- Same format for digital data
  - 23 channels of data
    - 7 bits per frame plus indicator bit for data or systems control
  - 24th channel is sync

SONET/SDH

- Synchronous Optical Network (ANSI)
- Synchronous Digital Hierarchy (ITU-T)
- Compatible
- Signal Hierarchy
  - Synchronous Transport Signal level 1 (STS-1) or Optical Carrier level 1 (OC-1)
  - 51.84Mbps
  - Carry DS-3 or group of lower rate signals (DS1 DS1C DS2) plus ITU-T rates (e.g. 2.048Mbps)
  - Multiple STS-1 combined into STS-N signal
  - ITU-T lowest rate is 155.52Mbps (STM-1)

Optical Carrier Levels

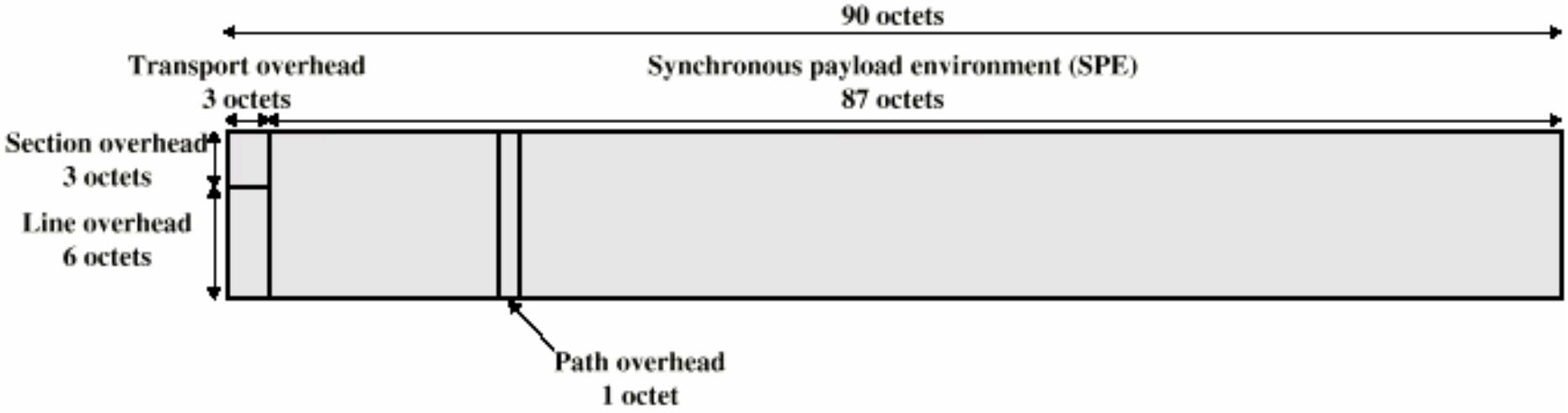
OC Level	Mbps	Number of 64-Kbps (DS-0) Channels
OC-1	52	627
OC-3	155	2016
OC-9	466	6048
OC-12	622	8064
OC-18	933	12,096
OC-24	1244	16,128
OC-36	1866	24,192
OC-48	2488	32,256
OC-96	4976	64,512
OC-192	10,000	129,024
OC-256	13,271	172,032
OC-768	39,812	516,096

The number of channels in each optical carrier level is a multiple of the 627 channels in the OC-1 speed. An OC-3 line has 3X627=2016.

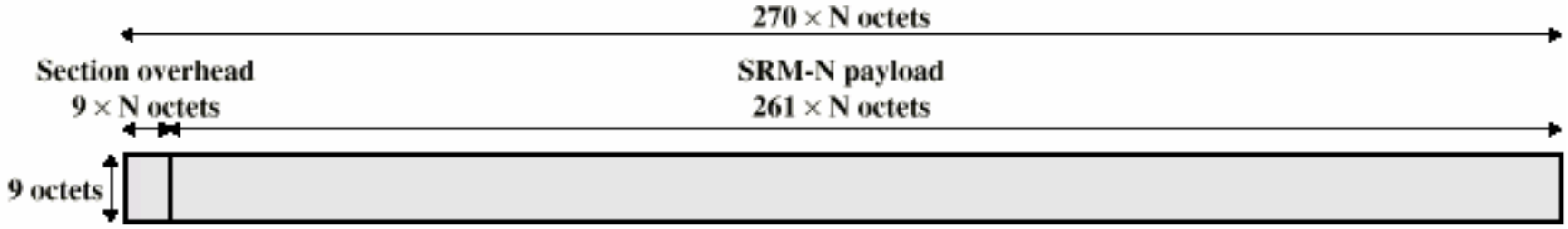
SONET/SDH Capacity

Speed	North American Synchronous Transport Signals (STS) Levels	SONET Channels	European Synchronous Transfer Mode (STM) Levels	Synchronous Digital Hierarchy (SDH) Channels
52 Megabits/s	OC-1	28 DS-1s or 1 DS3	STM-0	21 E1s
155 Megabits/s	OC-3	84 DS-1s or 3 DS3s	STM-1	63 E1s or 1E4
622 Megabits/s	OC-12	336 DS-1s or 12 DS3s	STM-4	252 E1s or 4 E4s
2488 Megabits/s	OC-48	1344 DS-1s or 48 DS3s	STM-16	1008 E1s or 16 E4s
9953 Megabits/s	OC-192	5376 DS-1s or 192 DS3s	STM-64	4032 E1s or 64 E4s
39.812 Gigabits/s	OC-768	21,504 DS-1s or 768 DS3s	STM-256	16,128 E1s or 256 E4s

SONET Frame Format



(a) STS-1 frame format

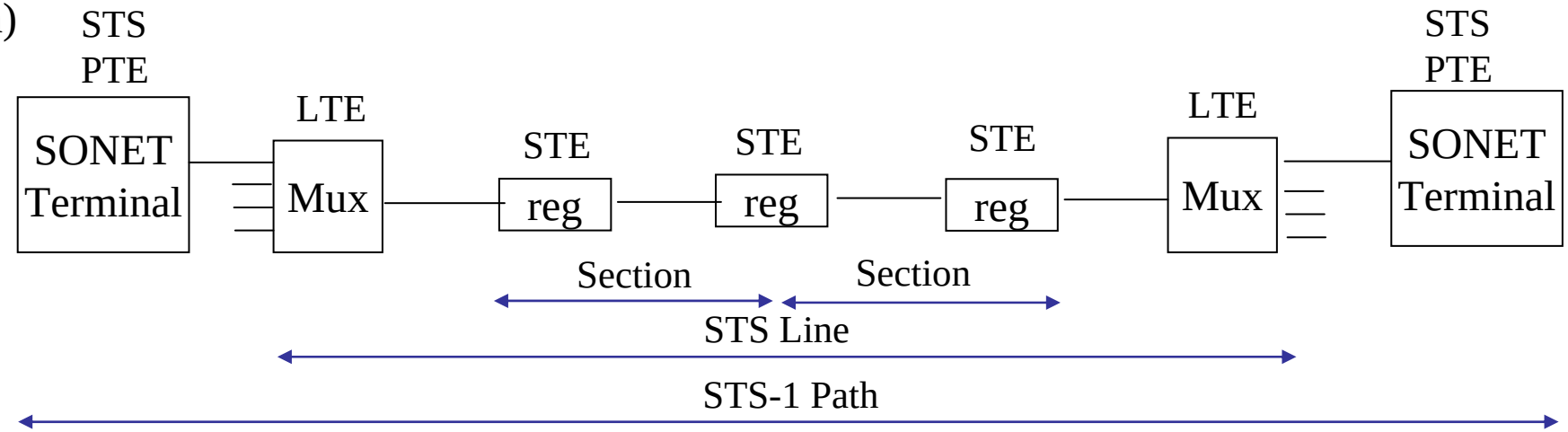


(b) STM-N frame format

SONET Functions

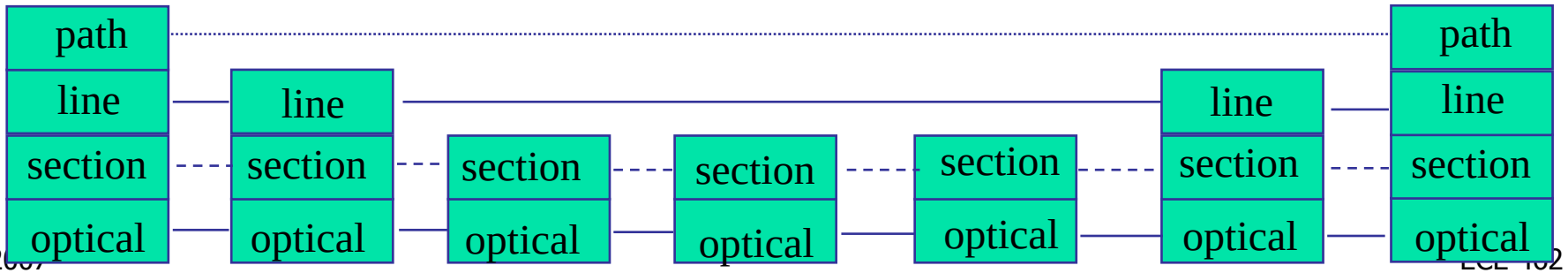
- Four functions or layers –
  - The 'photonic' layer converts electrical signals to optical signals and vice versa
  - The 'section' layer monitors the condition of the transmission between the SONET equipment and optical amplifiers
  - The 'line' layer synchronizes and multiplexes multiple streams into one stream or 'pipe' of traffic. Also provides monitoring and administration of SONET multiplexers
  - The 'path' layer assembles and disassembles voice and data carried on SONET into frames

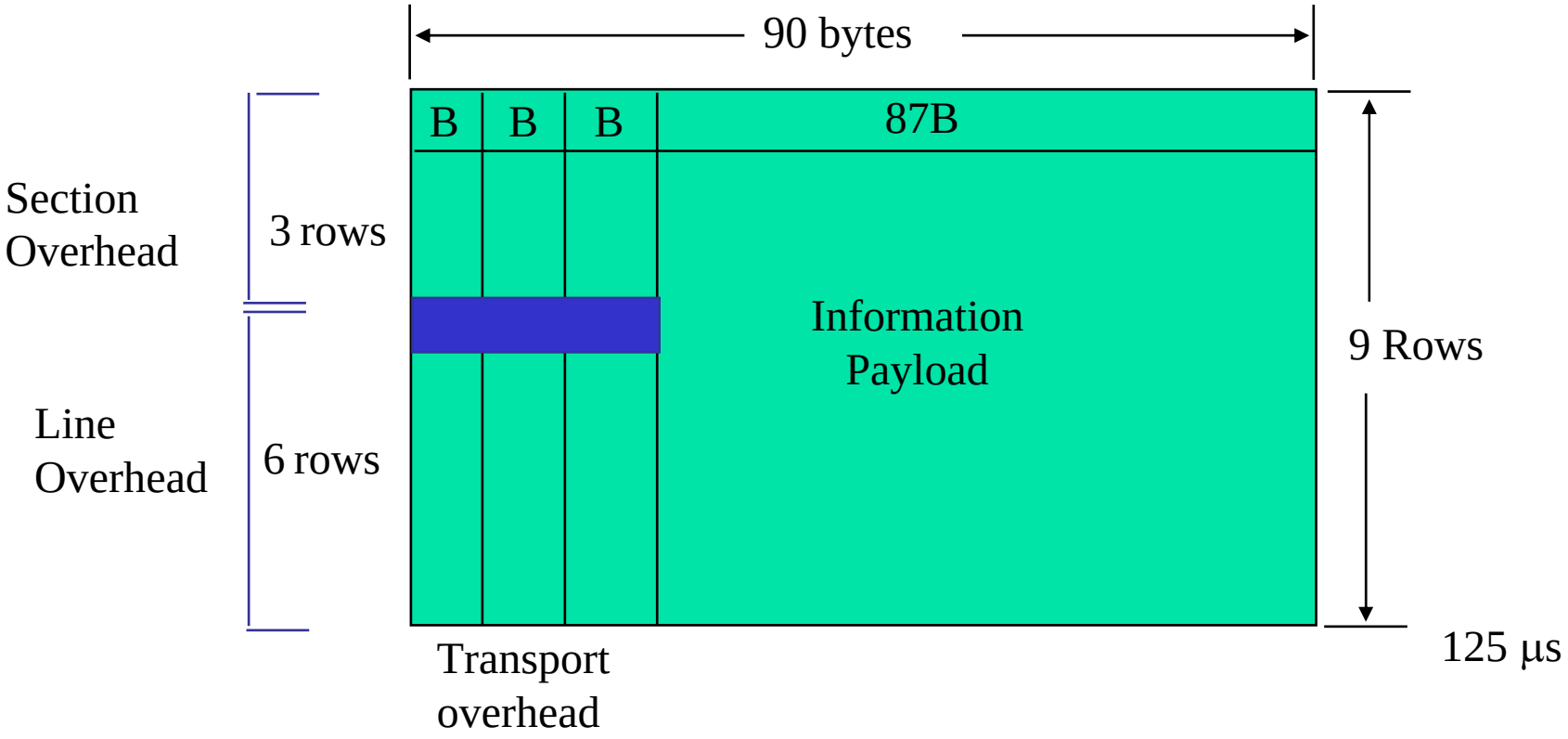
(a)



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

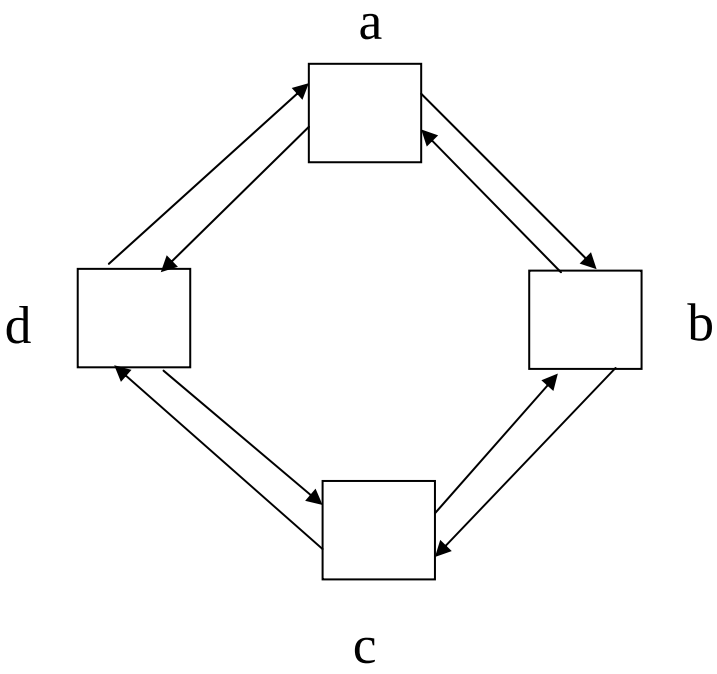
(b)



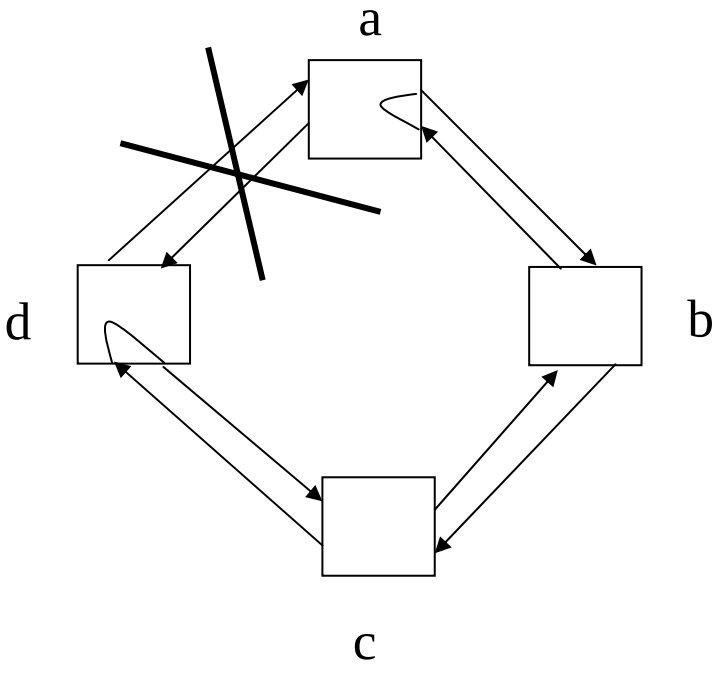

90 bytes
B
B
B
87B
Section
Overhead
3 rows
Information
Payload
9 Rows
Line
Overhead
6 rows
Transport
overhead
125 µs

SONET Rings – For Greater Reliability

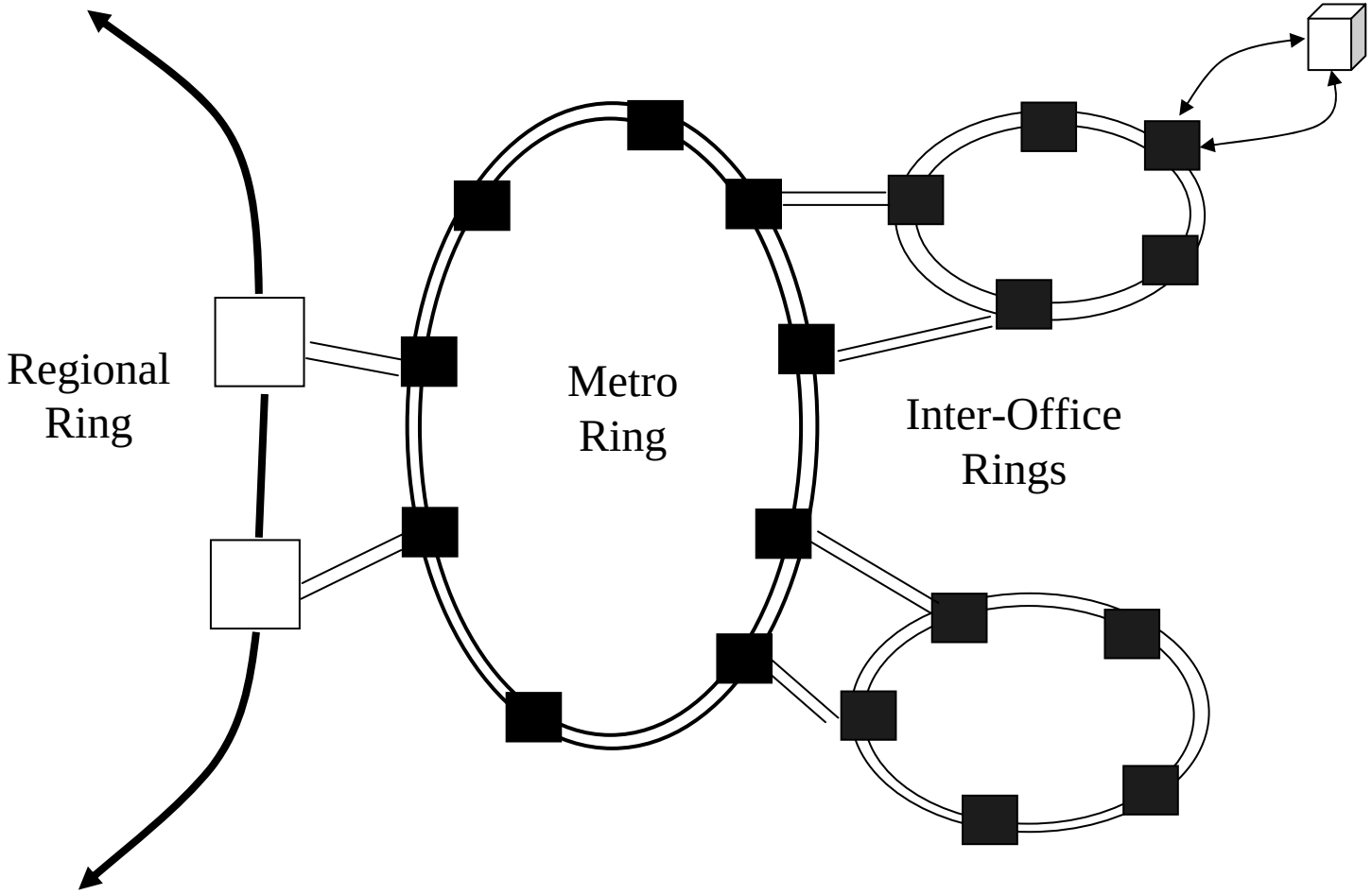
- The higher speeds attainable on fiber make reliability extremely important
- OC-192 can carry 129,000 64 Kbps transmissions
- Nearly 5% of the total SONET bandwidth is devoted to network management and maintenance
- To ensure reliability, SONET deployments often use bidirectional ring topology



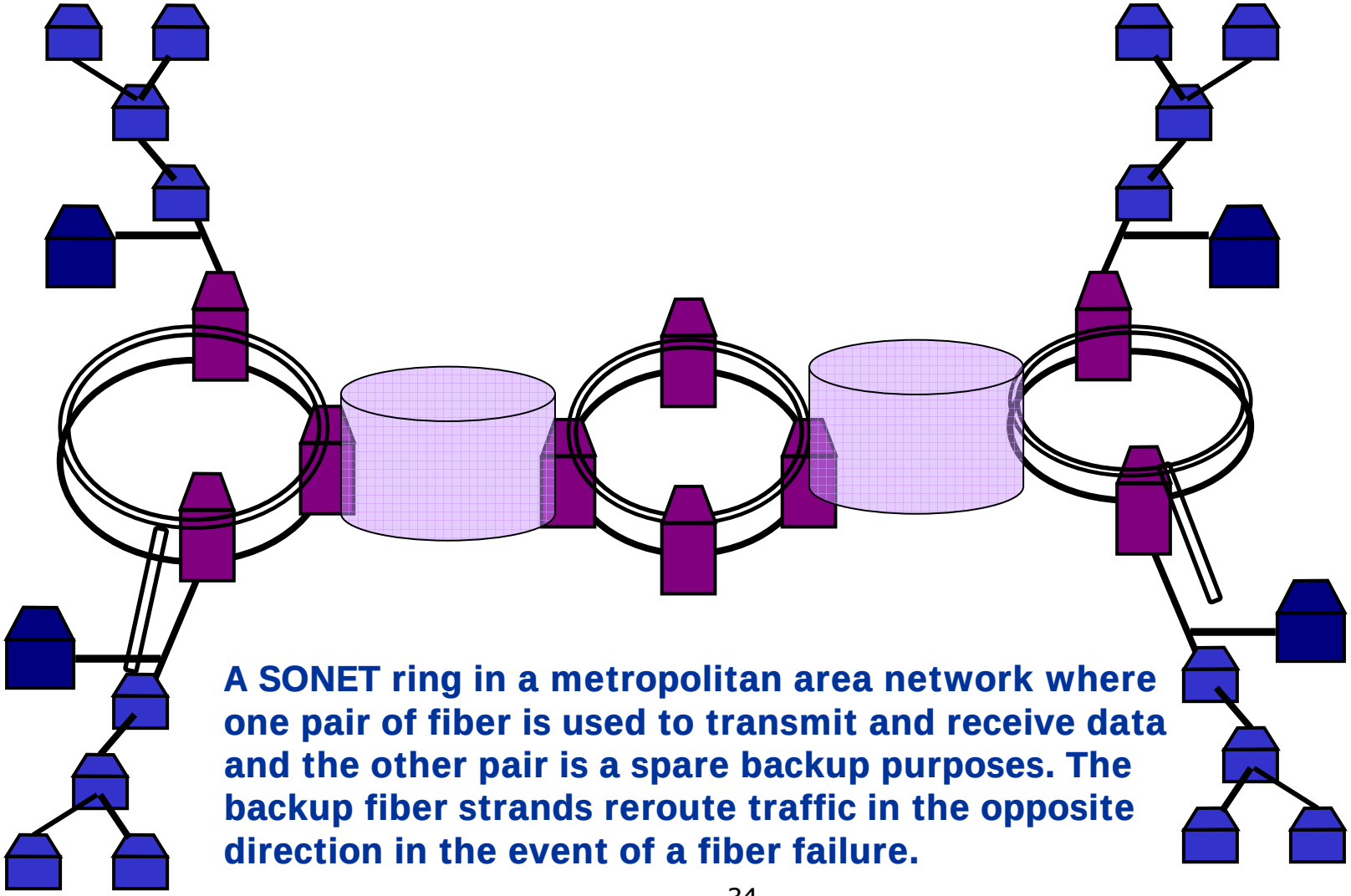
(a) Dual ring



(b) Loop-around in response to fault


Regional
Ring
Metro
Ring
Inter-Office
Rings

SONET Rings

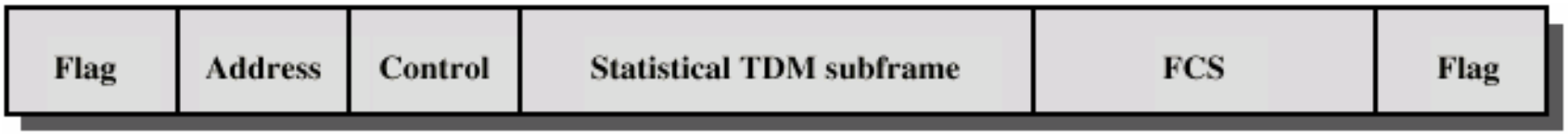


A SONET ring in a metropolitan area network where one pair of fiber is used to transmit and receive data and the other pair is a spare backup purposes. The backup fiber strands reroute traffic in the opposite direction in the event of a fiber failure.

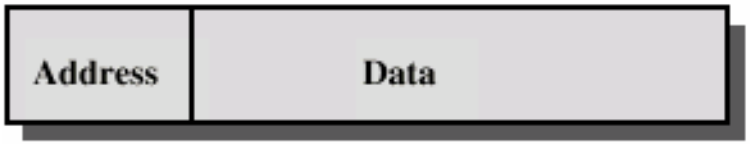
Statistical TDM

- In Synchronous TDM many slots are wasted
- Statistical TDM allocates time slots dynamically based on demand
- Multiplexer scans input lines and collects data until frame full
- Data rate on line lower than aggregate rates of input lines

Statistical TDM Frame Formats



(a) Overall frame



(b) Subframe with one source per frame

(c) Subframe with multiple sources per frame

Stat Mux utilization

Parameters:

I = number of input sources

R= data rate of each source in bit per second

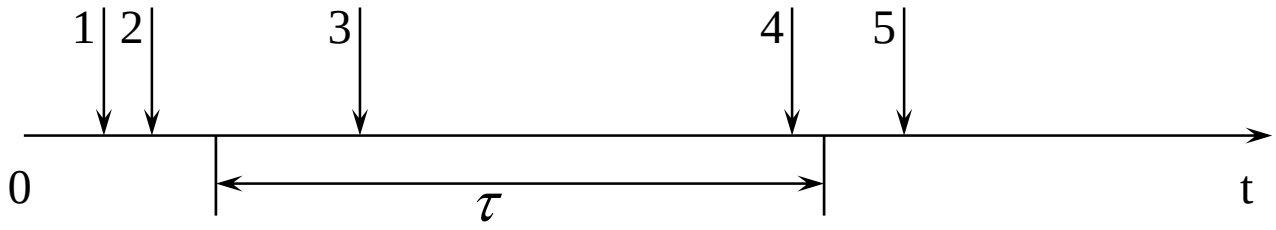
M= Effective capacity of Multiplexed line

α (i.e, alpha) = Fraction of time each source is transmitting

$K = M/IR$

Note: $\alpha \leq K < 1$

Poisson Process With Rate λ

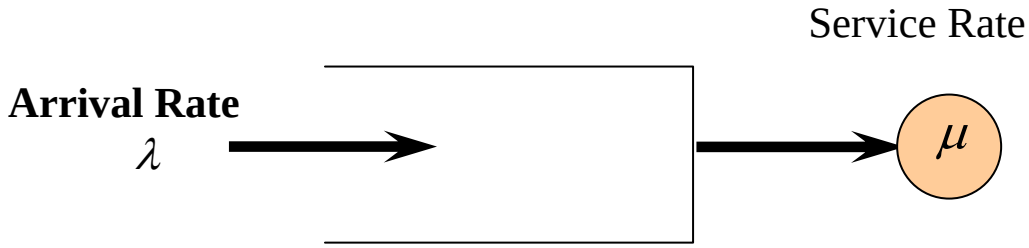


Poisson Arrivals

A(t) = number of arrivals from 0 to t

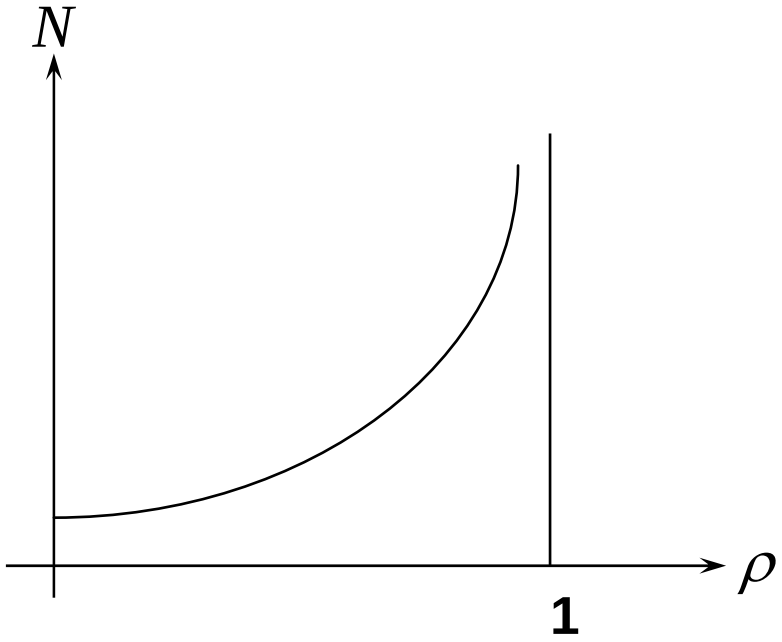
- **Number of arrivals in any interval of length τ has Poisson distribution with parameter $\lambda\tau$**

M/D/1 Queue



- Single Server
- Poisson arrivals with rate λ
- Service time with parameter for each arrival Ts
- Independent interarrival and service times

Single Server Queues with Constant Service Times and Poisson (Random) Arrivals



Statistical time division multiplexer

- Parameters:
  - I = number of input sources
  - R = data rate of each source, bps
  - M = effective capacity of multiplexed line, bps
  - α = mean fraction of time each source is transmitting, $0 < \alpha < 1$
  - $K = \frac{M}{IR}$ = ratio of multiplexed line capacity to total maximum input
  - The value of K is a measure of the compression achieved by the multiplexer, and can be bounded as: $\alpha < K < 1$

A single-server queue model (1)

- Parameters
  - λ = mean number of arrivals per second
  - T_s = service time for each arrival
  - ρ = utilization; fraction of time server is busy
  - N = mean number of items in system (waiting and being served)
  - T_r = residence time; mean time an item spends in system (waiting and being served) = delay
  - σ_r = standard deviation of T_r

A single-server queue model (2)

- Formulas

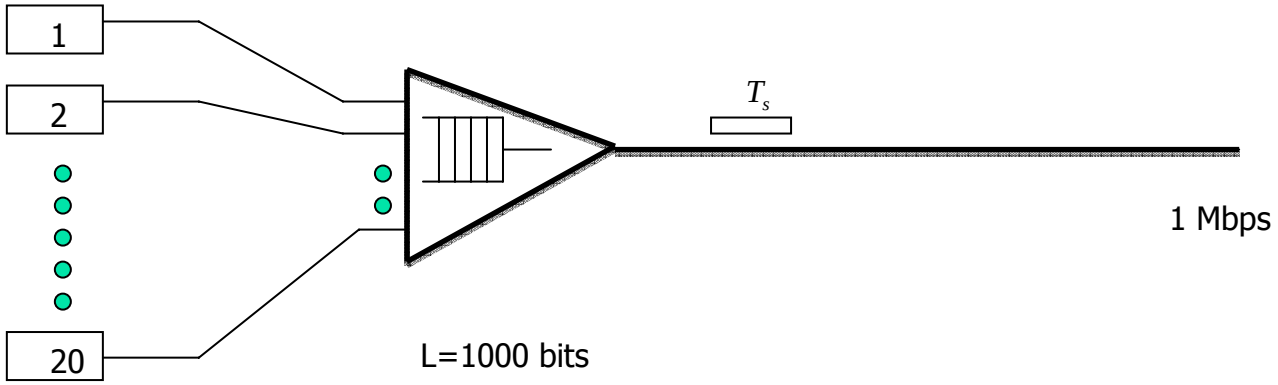
$$\rho = \lambda T_s$$

$$N = \frac{\rho^2}{2(1-\rho)} + \rho$$

$$T_r = \frac{T_s(2-p)}{2(1-p)}$$

$$\sigma_r = \frac{1}{1-\rho}\sqrt{\rho - \frac{3\rho^2}{2} + \frac{5\rho^3}{6} - \frac{\rho^4}{12}}$$

Example



$$T_s = \frac{1000}{1000{,}000} = 1 m\sec$$

$$\lambda_1 = \frac{5000}{1000} = 5\ frames/\sec$$ per station

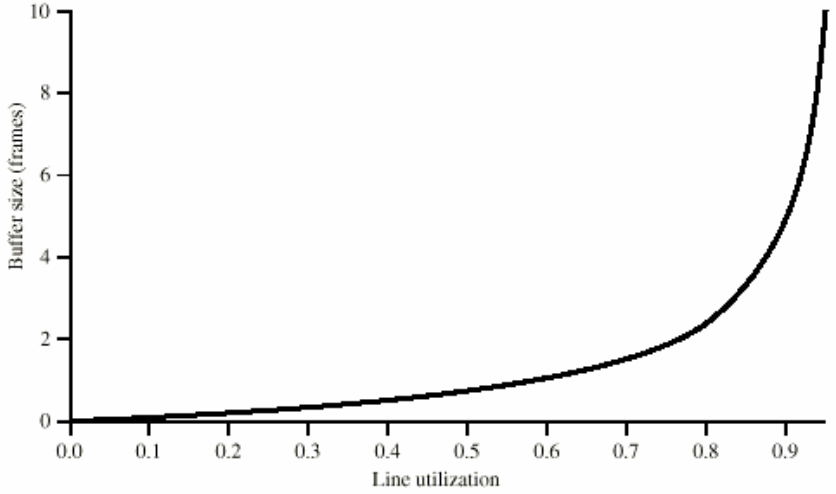
$$\lambda = 5*20 = 100\ frames/\sec$$ From all stations

$$\rho = \lambda T_s = 100*0.001 = 0.1$$

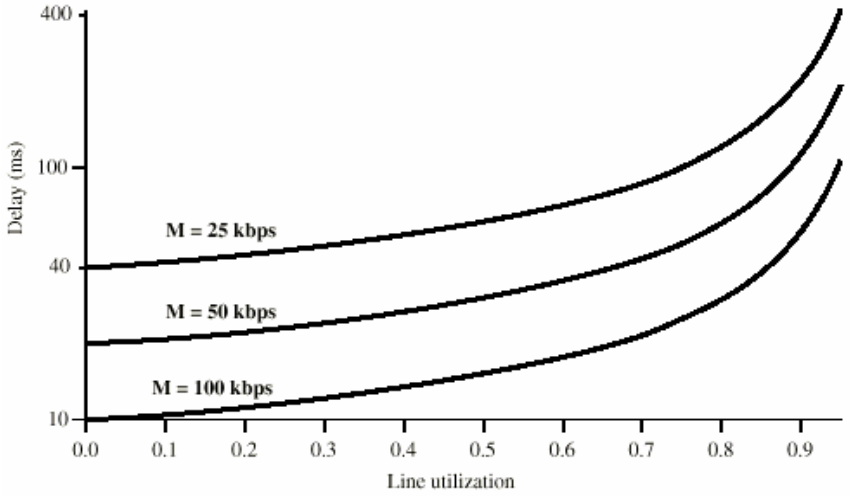
Performance

- Output data rate less than aggregate input rates
- May cause problems during peak periods
  - Buffer inputs
  - Keep buffer size to minimum to reduce delay

Buffer Size and Delay



(a) Mean buffer size versus utilization



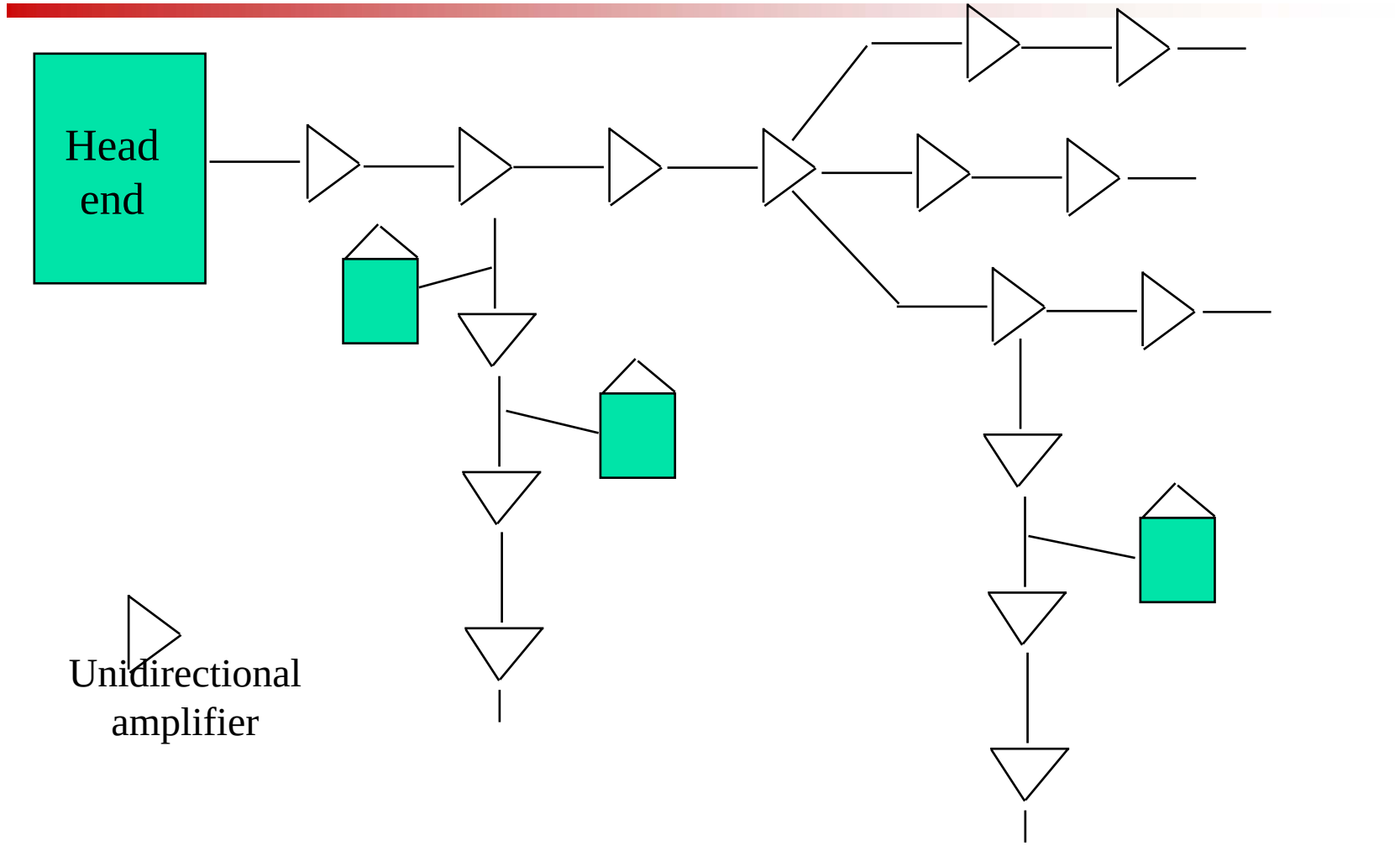
(a) Mean delay versus utilization

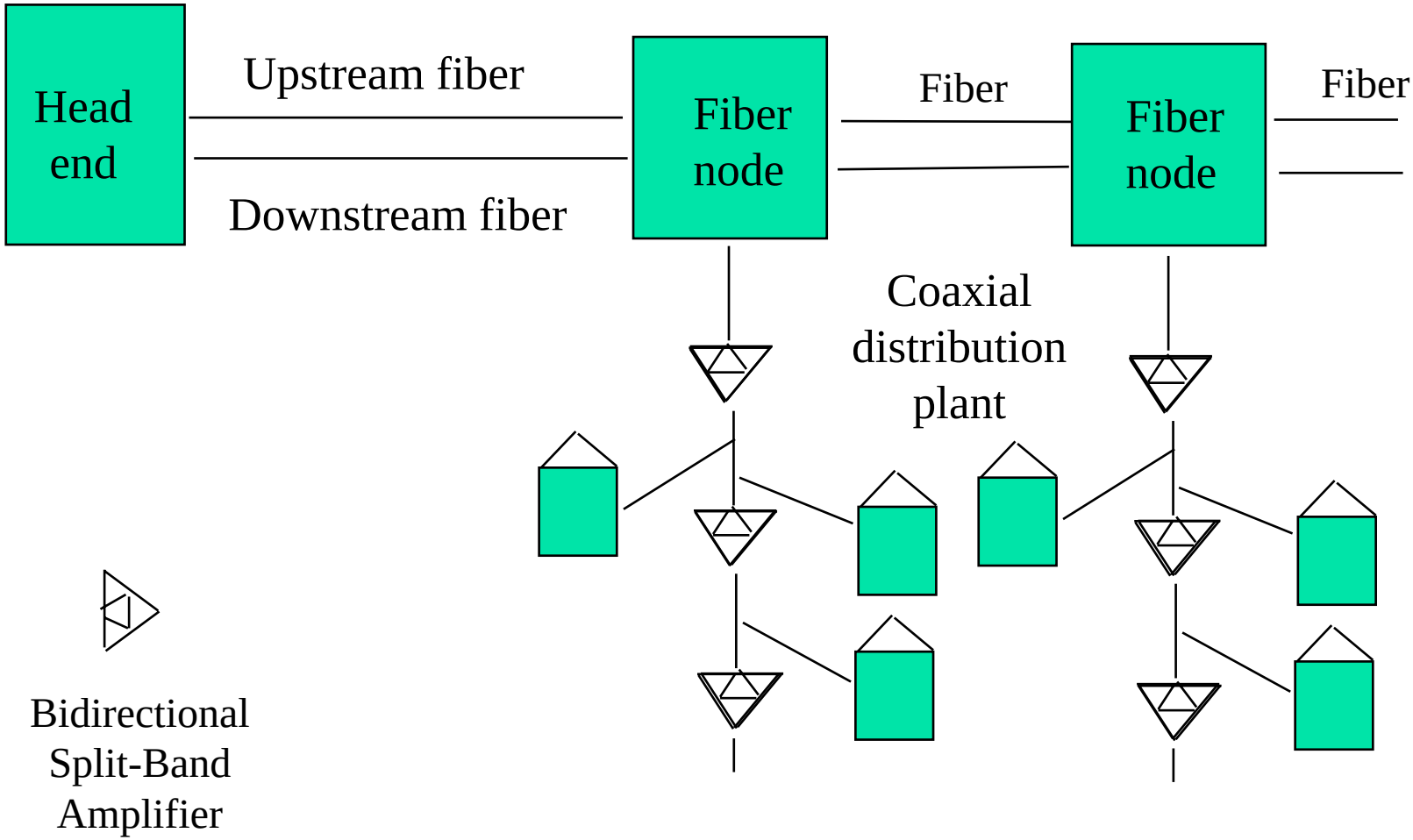
Cable Modem Outline

- Two channels from cable TV provider dedicated to data transfer
  - One in each direction
- Each channel shared by number of subscribers
  - Scheme needed to allocate capacity
  - Statistical TDM

Cable Modem Operation

- Downstream
  - Cable scheduler delivers data in small packets
  - If more than one subscriber active, each gets fraction of downstream capacity
    - May get 500kbps to 1.5Mbps
  - Also used to allocate upstream time slots to subscribers
- Upstream
  - User requests timeslots on shared upstream channel
    - Dedicated slots for this
  - Headend scheduler sends back assignment of future tme slots to subscriber


Head
end
Unidirectional
amplifier


Head end
Upstream fiber
Downstream fiber
Fiber node
Fiber
Fiber node
Fiber
Coaxial distribution plant
Bidirectional Split-Band Amplifier

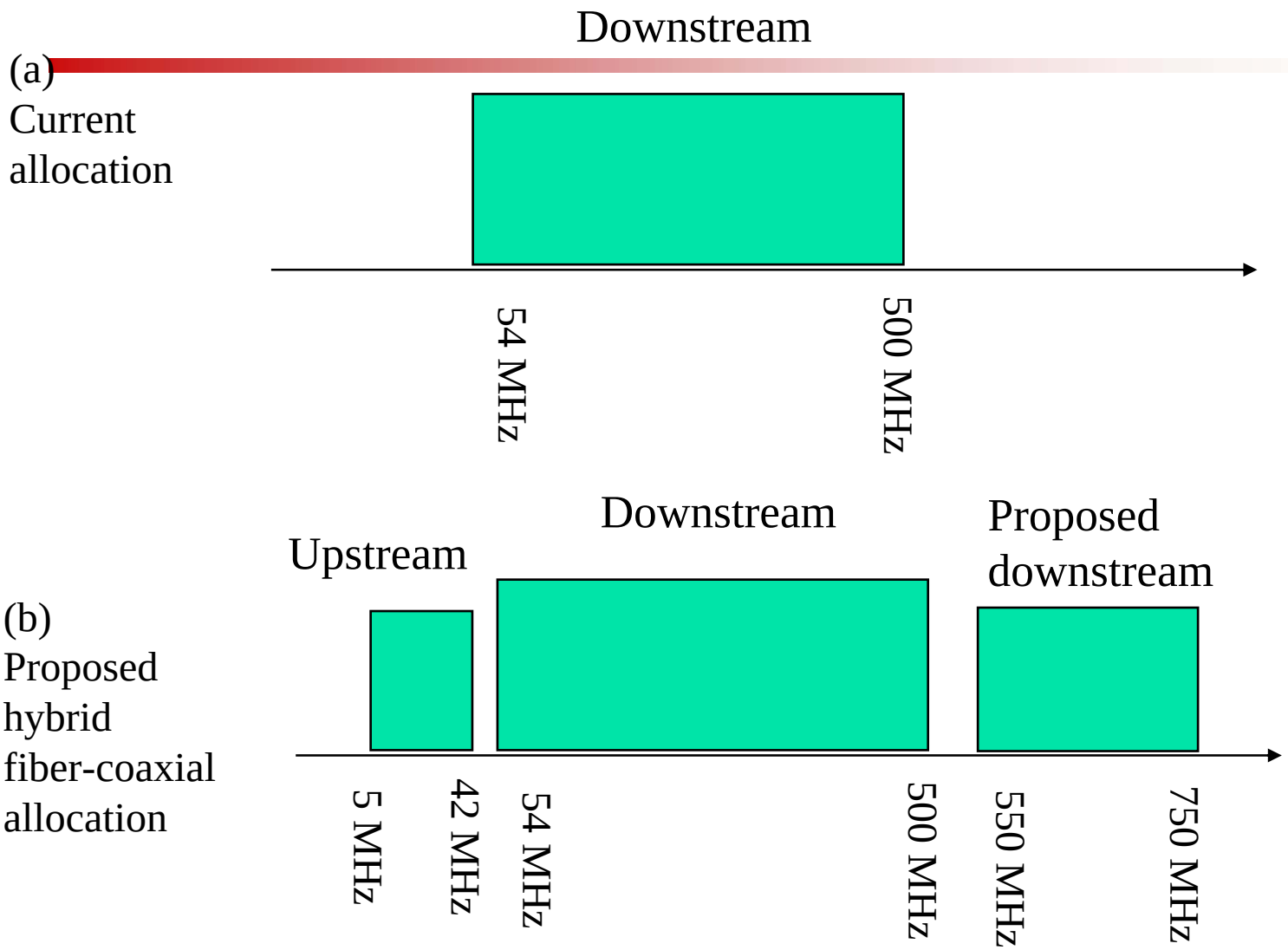
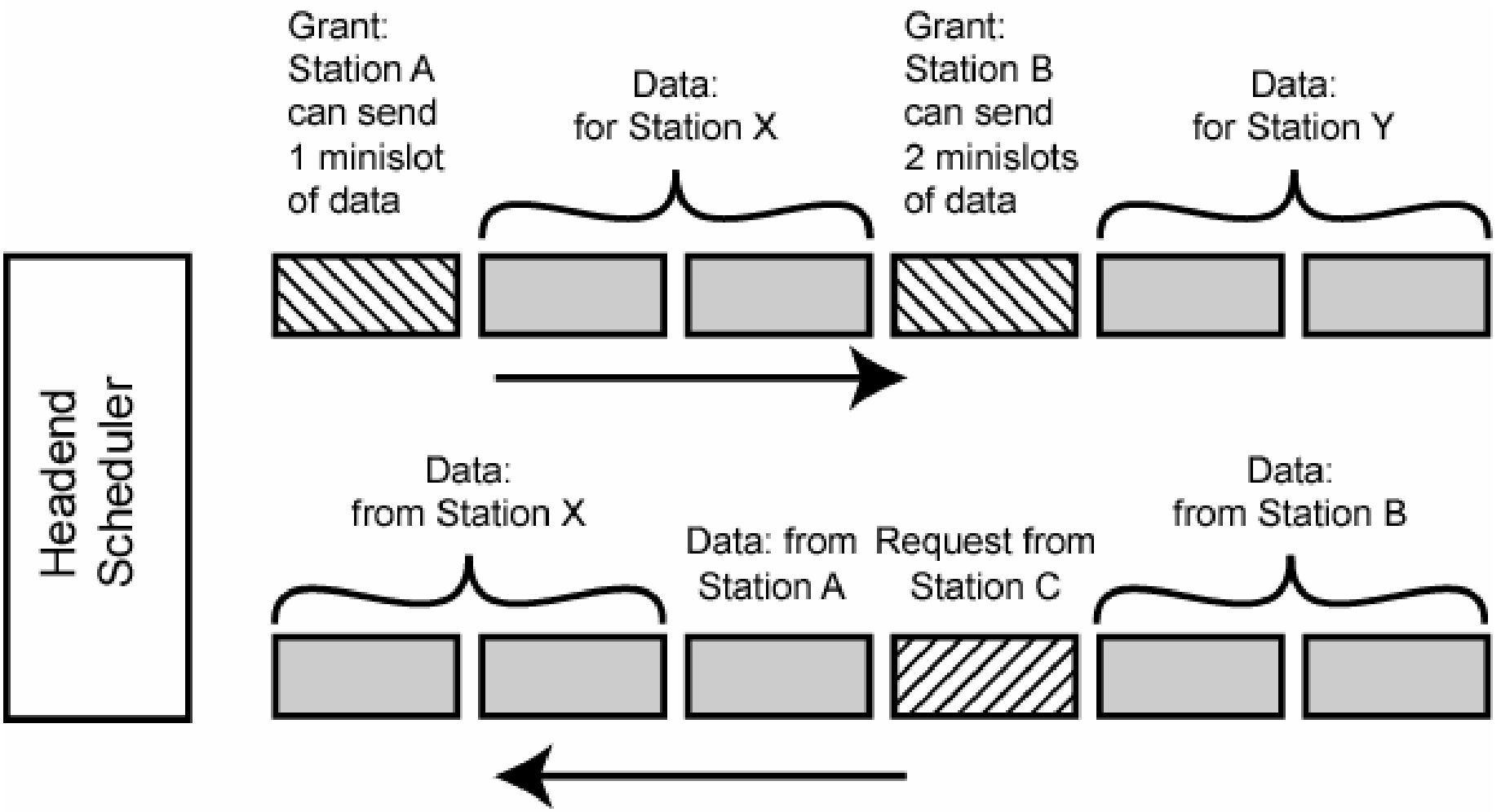

Downstream
(a)
Current
allocation
54 MHz
500 MHz
Upstream
Downstream
Proposed
downstream
(b)
Proposed
hybrid
fiber-coaxial
allocation
5 MHz
42 MHz
54 MHz
500 MHz
550 MHz
750 MHz

Figure 3.43

Cable Modem Scheme



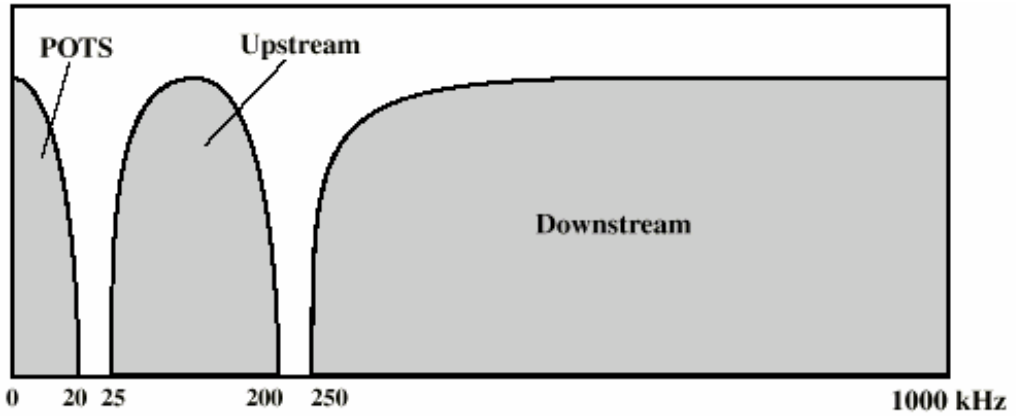
Asymmetrical Digital Subscriber Line (ADSL)

- ADSL: Deploying broadband
- Challenge is the Link between subscriber and network
  - AKA Local loop (Digital Subscriber Line)
- Uses currently installed twisted pair cable
  - Can carry broader spectrum
    - 1 MHz or more

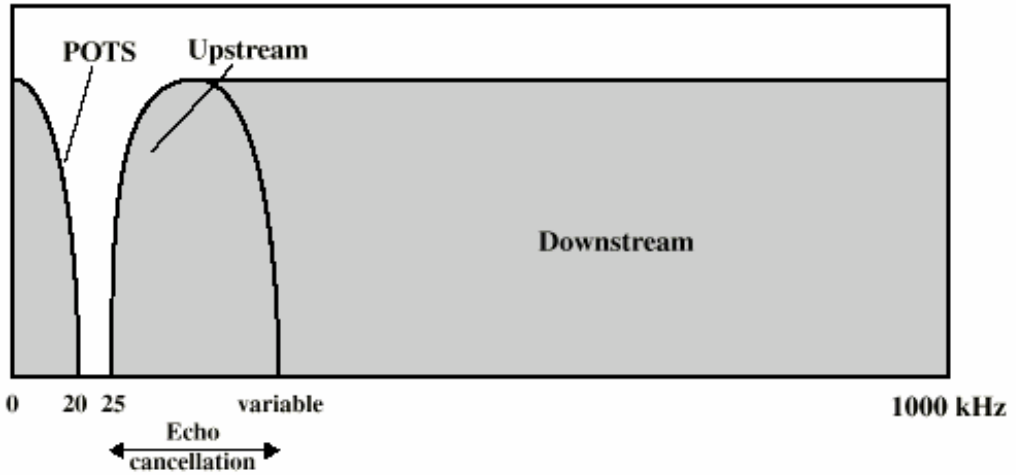
ADSL Design

- Asymmetric
  - Greater capacity downstream than upstream
- Frequency division multiplexing
  - Lowest 25kHz for voice
    - Plain old telephone service (POTS)
  - Use echo cancellation or FDM to give two bands
    - Smaller Upstream and larger Downstream
  - Use FDM within bands
- Range 5.5km

ADSL Channel Configuration



(a) Frequency-division multiplexing

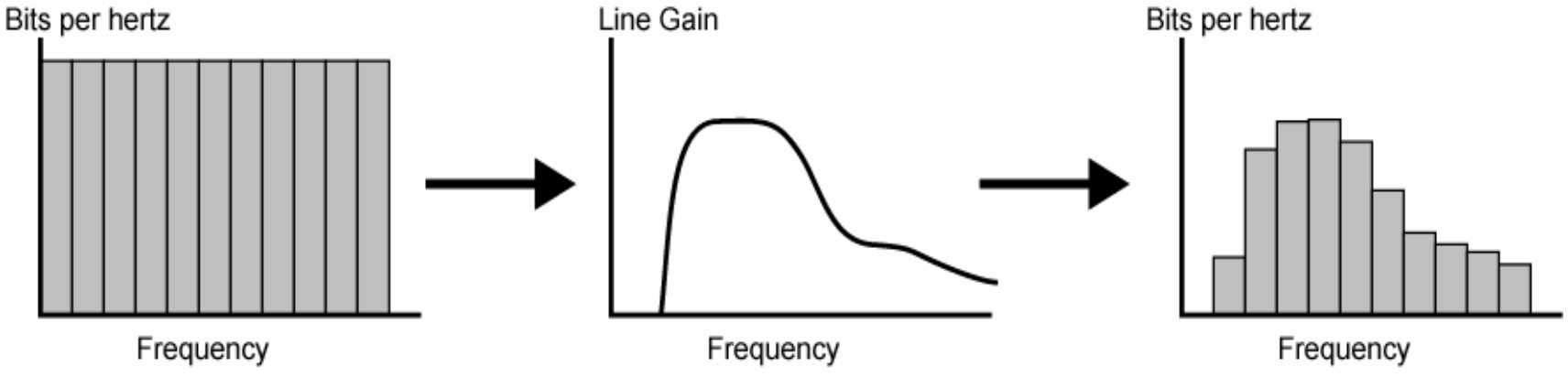


(b) Echo cancellation

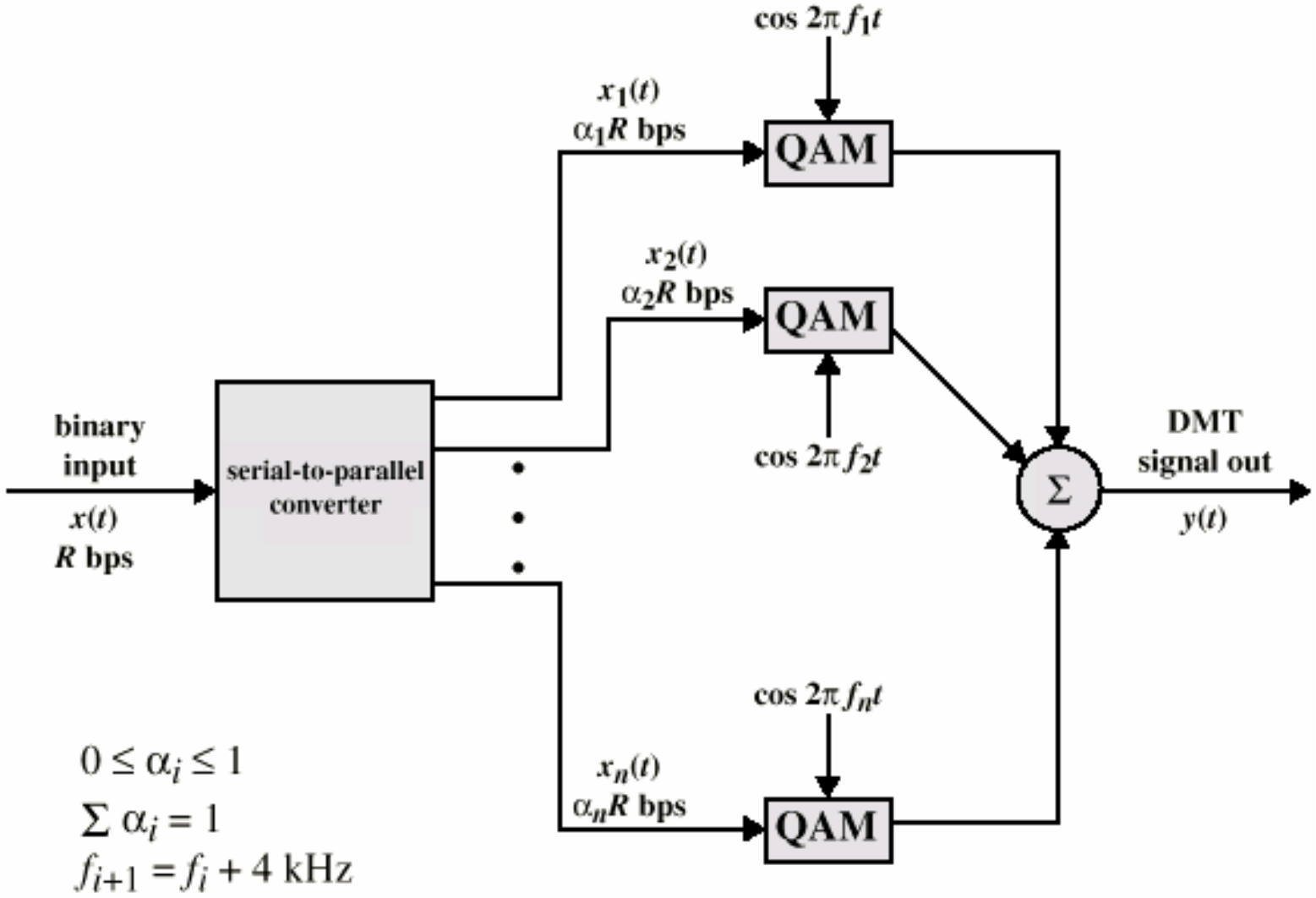
Discrete Multitone

- DMT
- Multiple carrier signals at different frequencies
- Some bits on each channel
- 4kHz subchannels
- Send test signal and use subchannels with better signal to noise ratio
- 256 downstream subchannels at 4kHz (60kbps)
  - 15.36MHz
  - Impairments bring this down to 1.5Mbps to 9Mbps

DTM Bits Per Channel Allocation



DMT Transmitter



xDSL

- High data rate DSL
- Single line DSL
- Very high data rate DSL