DATA AND COMPUTER COMMUNICATIONS

Lecture 2 Physical Layer - Multiplexing

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Based on Lecture slides by William Stallings

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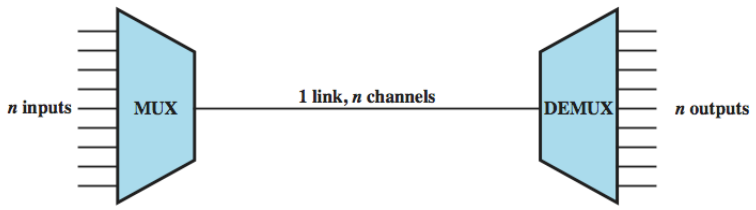
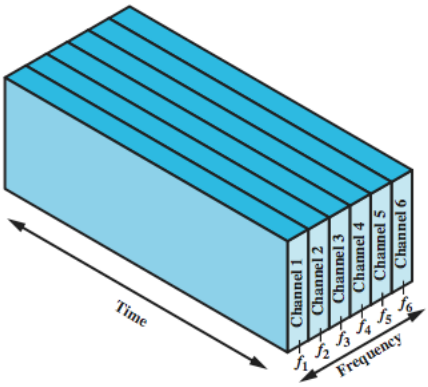
MULTIPLEXING

- multiple links on 1 physical line
- common on long-haul, high capacity, links
- have FDM, TDM, STDM alternatives

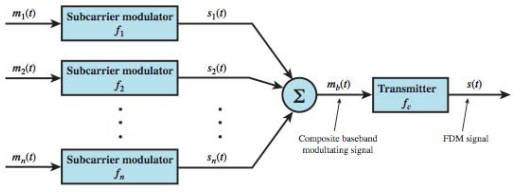


Frequency Division Multiplexing

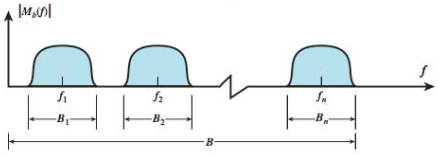


(a) Frequency division multiplexing

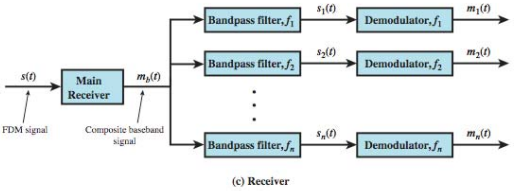
FDM System Overview



(a) Transmitter

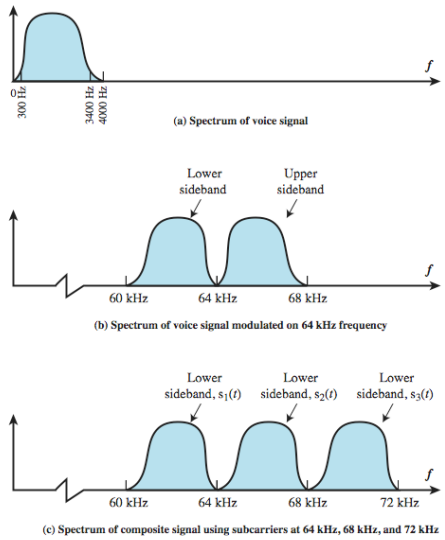


(b) Spectrum of composite baseband modulating signal



(c) Receiver

FDM Voiceband Example



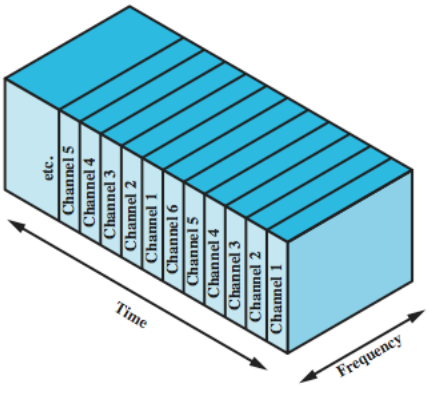
Analog Carrier Systems

- long-distance links use an FDM hierarchy
- AT&T (USA) and ITU-T (International) variants
- Group
  - 12 voice channels (4kHz each) = 48kHz
  - in range 60kHz to 108kHz
- Supergroup
  - FDM of 5 group signals supports 60 channels
  - on carriers between 420kHz and 612 kHz
- Mastergroup
  - FDM of 10 supergroups supports 600 channels
- so original signal can be modulated many times

Wavelength Division Multiplexing

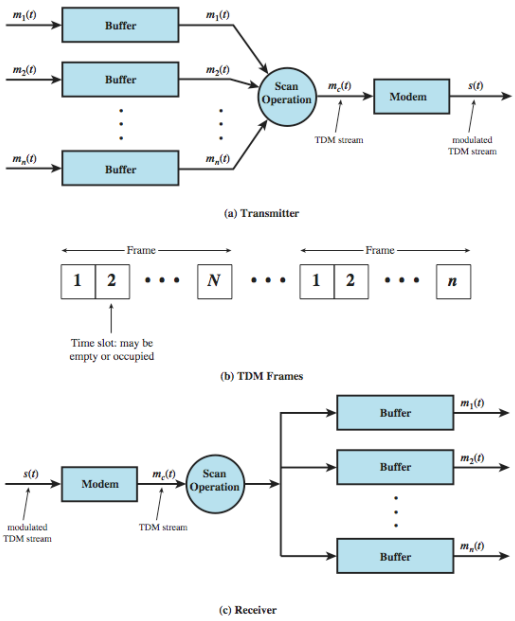
- FDM with multiple beams of light at different freq
- carried over optical fiber links
  - commercial systems with 160 channels of 10 Gbps
  - lab demo of 256 channels 39.8 Gbps
- architecture similar to other FDM systems
  - multiplexer consolidates laser sources (1550nm) for transmission over single fiber
  - Optical amplifiers amplify all wavelengths
  - Demux separates channels at the destination
- also have Dense Wavelength Division Multiplexing (DWDM)

Synchronous Time Division Multiplexing



(b) Time division multiplexing

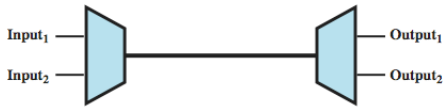
TDM System Overview



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
  - corresponding source must be quenched
  - leaving empty slots
- error control
  - errors detected & handled on individual channel

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

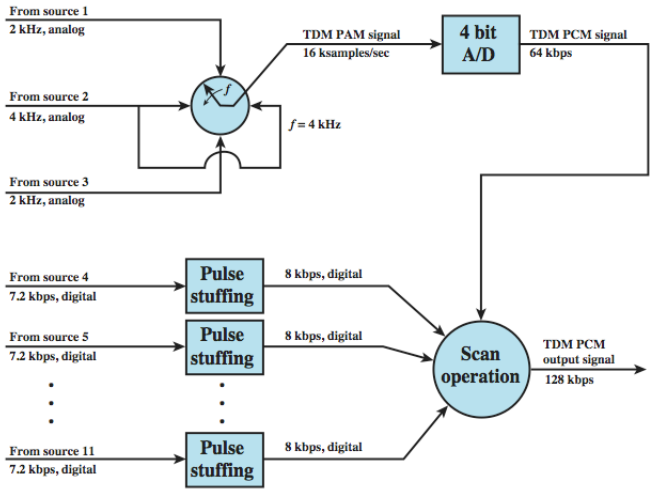
Framing

- no flag or SYNC chars bracketing TDM frames
- must still provide synchronizing mechanism between src and dest clocks
- added digit framing
  - one control bit added to each TDM frame
  - identifiable bit pattern used on control channel
  - eg. alternating 01010101…unlikely on a data channel
  - compare incoming bit patterns on each channel with known sync pattern

Pulse Stuffing

- have problem of synchronizing data sources
- with clocks in different sources drifting
- also issue of data rates from different sources not related by simple rational number
- Pulse Stuffing a common solution
  - have 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

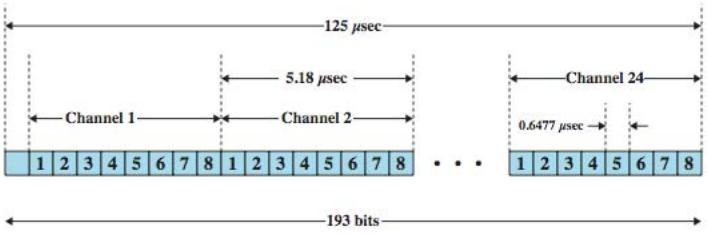
TDM Example



Digital Carrier Systems

- long-distance links use a TDM hierarchy
- AT&T (USA) and ITU-T (International) variants
- US system based on DS-1 format
- can carry mixed voice and data signals
- 24 channels used for total data rate 1.544Mbps
- each voice channel contains one word of digitized data (PCM, 8000 samples per sec)
- same format for 56kbps digital data
- can interleave DS-1 channels for higher rates
  - DS-2 is four DS-1 at 6.312Mbps

DS-1 Transmission Format



Notes:

1. The first bit is a framing bit, used for synchronization.
2. Voice channels:
   - 8-bit PCM used on five of six frames.
   - 7-bit PCM used on every sixth frame; bit 8 of each channel is a signaling bit.
3. Data channels:
   - Channel 24 is used for signaling only in some schemes.
   - Bits 1-7 used for 56 kbps service
   - Bits 2-7 used for 9.6, 4.8, and 2.4 kbps service.

North American and International TDM Carrier Standards

North American			International (ITU-T)		
Designation	Number of Voice Channels	Data Rate (Mbps)	Level	Number of Voice Channels	Data Rate (Mbps)
DS-1	24	1.544	1	30	2.048
DS-1C	48	3.152	2	120	8.448
DS-2	96	6.312	3	480	34.368
DS-3	672	44.736	4	1920	139.264
DS-4	4032	274.176	5	7680	565.148

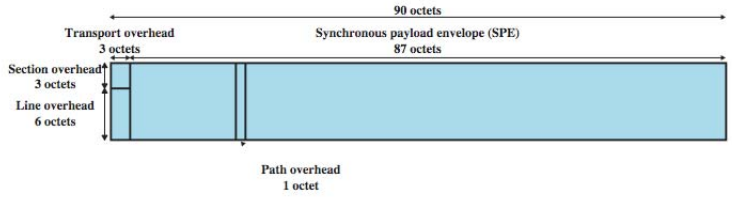
SONET/SDH

- Synchronous Optical Network (ANSI)
- Synchronous Digital Hierarchy (ITU-T)
- have hierarchy of signal rates
  - Synchronous Transport Signal level 1 (STS-1) or Optical Carrier level 1 (OC-1) is 51.84Mbps
  - carries one DS-3 or multiple (DS1 DS1C DS2) plus ITU-T rates (eg. 2.048Mbps)
  - multiple STS-1 combine into STS-N signal
  - ITU-T lowest rate is 155.52Mbps (STM-1)

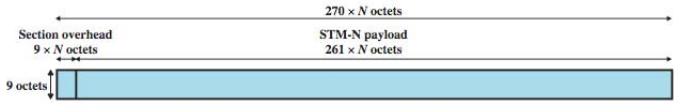
SONET/SDH Signal Hierarchy

SONET Designation	ITU-T Designation	Data Rate	Payload Rate (Mbps)
STS-1/OC-1		51.84 Mbps	50.112 Mbps
STS-3/OC-3	STM-1	155.52 Mbps	150.336 Mbps
STS-9/OC-9		466.56 Mbps	451.008 Mbps
STS-12/OC-12	STM-4	622.08 Mbps	601.344 Mbps
STS-18/OC-18		933.12 Mbps	902.016 Mbps
STS-24/OC-24		1.24416 Gbps	1.202688 Gbps
STS-36/OC-36		1.86624 Gbps	1.804032 Gbps
STS-48/OC-48	STM-16	2.48832 Gbps	2.405376 Gbps
STS-96/OC-96		4.87664 Gbps	4.810752 Gbps
STS-192/OC-192	STM-64	9.95328 Gbps	9.621504 Gbps
STS-768	STM-256	39.81312 Gbps	38.486016 Gbps
STS-3072		159.25248 Gbps	153.944064 Gbps

SONET Frame Format



(a) STS-1 frame format

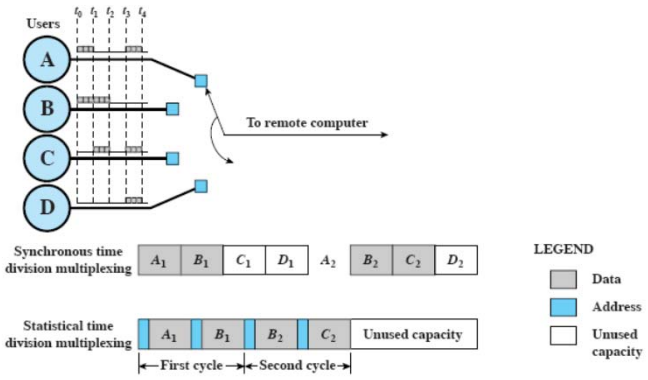


(b) STM-N frame format

STATISTICAL TDM

- in Synch TDM many slots are wasted
- Statistical TDM allocates time slots dynamically based on demand
- multiplexer scans input lines and collects data until frame full
- line data rate lower than aggregate input line rates
- may have problems during peak periods
  - must buffer inputs

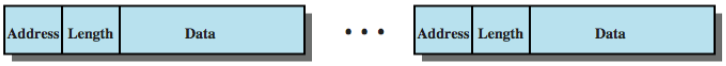
STATISTICAL TDM VS. SYNCHRONOUS TDM



STATISTICAL TDM FRAME FORMAT

(a) Overall frame

(b) Subframe with one source per frame



(c) Subframe with multiple sources per frame

PERFORMANCE

	Capacity = 5000 bps		Capacity = 7000 bps	
Input[a]	Output	Backlog	Output	Backlog
6	5	1	6	0
9	5	5	7	2
3	5	3	5	0
7	5	5	7	0
2	5	2	2	0
2	4	0	2	0
2	2	0	2	0
3	3	0	3	0
4	4	0	4	0
6	5	1	6	0
1	2	0	1	0
10	5	5	7	3
7	5	7	7	3
5	5	7	7	1
8	5	10	7	2
3	5	8	5	0
6	5	9	6	0
2	5	6	2	0
9	5	10	7	2
5	5	10	7	0

[a]Input = 10 sources, 1000 bps/source; average input rate = 50% of maximum.

Performance

- Tradeoff between system response time and the speed of the speed of multiplexed line

  I = number of input resources

  R = data rate of each source

  M = effective capacity of multiplexed line

  α = mean fraction of time each source is transmitting, $0<\alpha<1$

  $K = M/IR$ = ratio of multiplexed line capacity to total maximum input, $\alpha<K<1$

Single-Server Queue Model

- Parameters

  λ = mean number of arrivals per second, $\lambda=\alpha IR$

  Ts = service time for each arrival, $Ts=1/M$

  ρ = utilization; fraction of time server is busy

  N = mean number of items in system (waiting and being served)

  Tr = residence time; mean time an item spends in system (waiting and being served)

  σr = standard deviation of Tr

Single-Server Queue Model

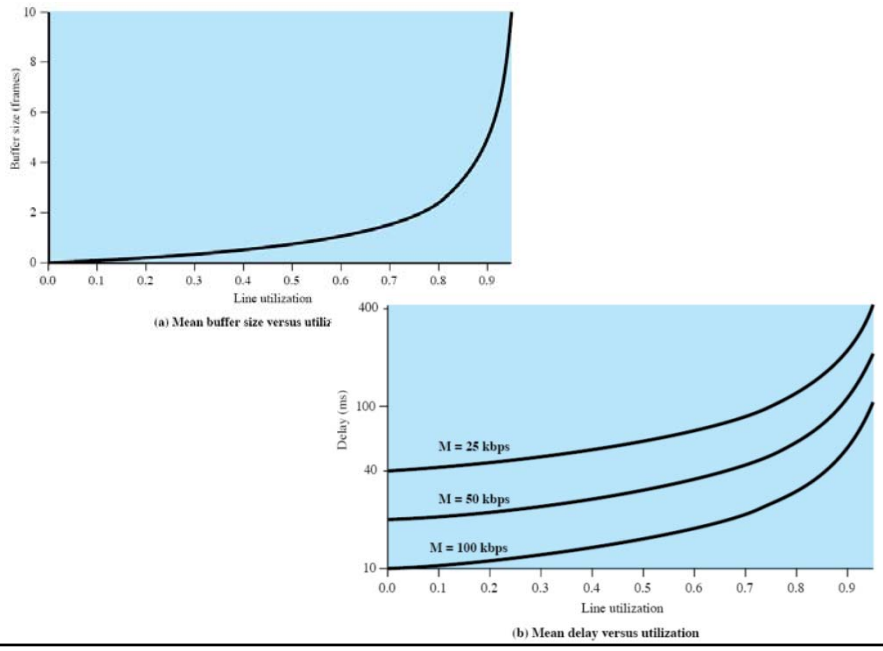
$$\rho = \lambda Ts = \alpha IR/M = \alpha/K = \lambda/\mathrm{M}$$

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

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

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

Single-Server Queue Model



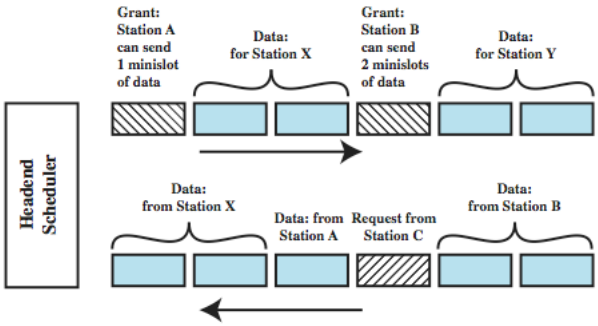
Cable Modems

- dedicate two cable TV channels to data transfer
- each channel shared by number of subscribers, using statistical TDM
- Downstream
  - cable scheduler delivers data in small packets
  - active subscribers share downstream capacity
  - also allocates upstream time slots to subscribers
- Upstream
  - user requests timeslots on shared upstream channel
  - Headend scheduler notifies subscriber of slots to use

Cable Spectrum Division

- to support both cable television programming and data channels, the cable spectrum is divided in to three ranges:
  - user-to-network data (upstream): 5 - 40 MHz
  - television delivery (downstream): 50 - 550 MHz
  - network to user data (downstream): 550 - 750 MHz

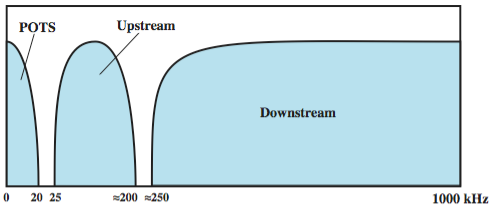
Cable Modem Scheme



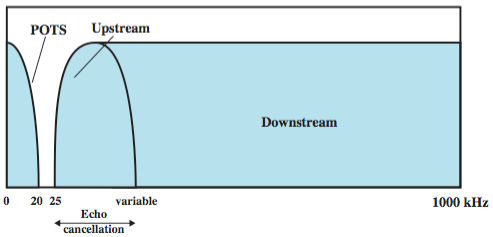
Asymmetrical Digital Subscriber Line (ADSL)

- link between subscriber and network
- uses currently installed twisted pair cable
- is Asymmetric - bigger downstream than up
- uses Frequency division multiplexing
  - reserve lowest 25kHz for voice (POTS)
  - uses echo cancellation or FDM to give two bands
- has a range of up to 5.5km

ADSL Channel Configuration



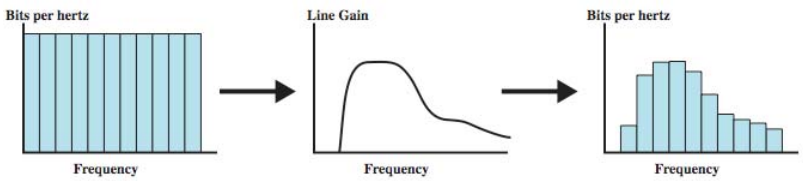
(a) Frequency-division multiplexing



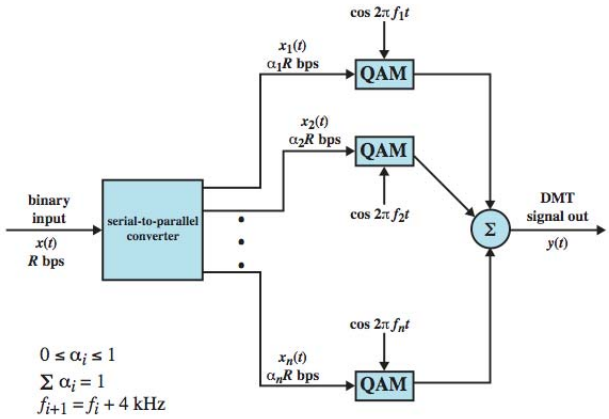
(b) Echo cancellation

Discrete Multitone (DMT)

- multiple carrier signals at different frequencies
- divide into 4kHz subchannels
- test and use subchannels with better SNR
- 256 downstream subchannels at 4kHz



DMT Transmitter



Broadband – Customer Side

- DSL link is between provider and customer
- a splitter allows simultaneous telephone and data service
- data services use a DSL modem
  - sometimes referred to as G.DMT modem
- DSL data signal can be divided into a video stream and a data stream
  - the data stream connects the modem to a router which enables a customer to support a wireless local area network

Broadband – Provider Side

- a splitter separates telephone from Internet
- voice traffic is connected to public switched telephone network (PSTN)
- data traffic connects to a DSL multiplexer (DSLAM) which multiplexes multiple customer DSL connections to a single high-speed ATM line.
- ATM line connects ATM switches to a router which provides entry to the Internet

xDSL

- High data rate DSL (HDSL)
  - 2B1Q coding on dual twisted pairs
  - up to 2Mbps over 3.7km
- Single line DSL
  - 2B1Q coding on single twisted pair (residential) with echo cancelling
  - up to 2Mbps over 3.7km
- Very high data rate DSL
  - DMT/QAM for very high data rates
  - over separate bands for separate services

SUMMARY

- multiplexing multiple channels on a single link
- FDM
  - analog carrier systems
  - wavelength division multiplexing
- TDM
  - TDM link control
  - pulse stuffing
- Statistical TDM
- broadband
- ADSL and xDSL