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Data and Computer Communications

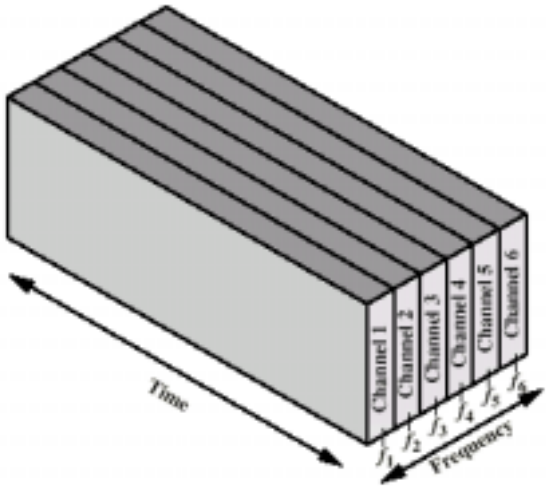
Chapter 8
Multiplexing

Multiplexing

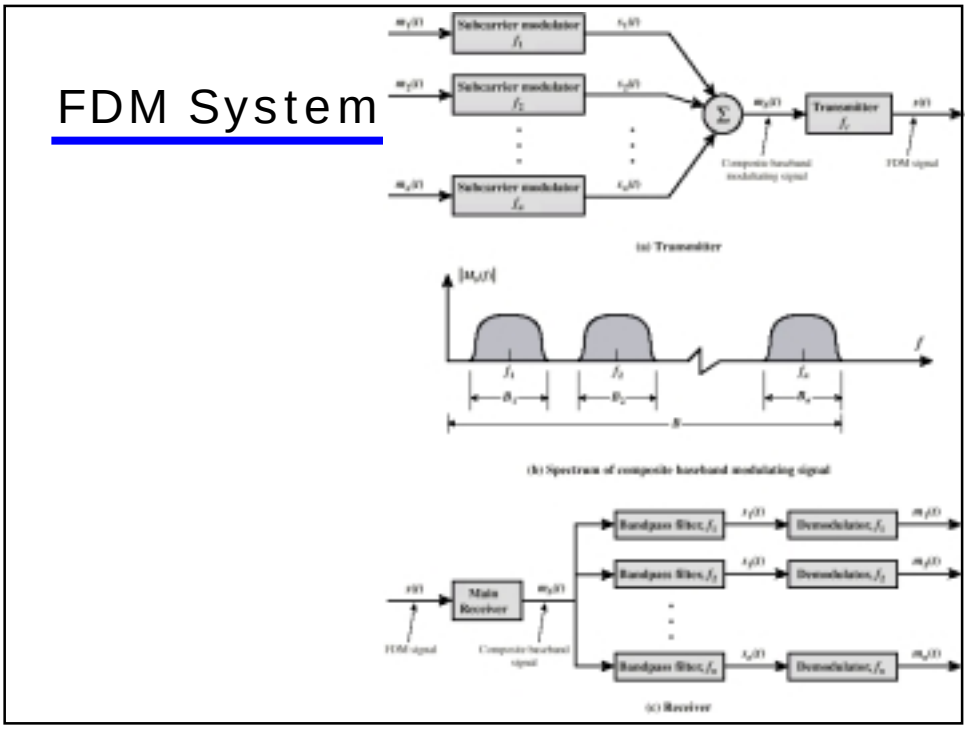
Frequency Division Multiplexing

- FDM
- Useful bandwidth of medium exceeds required bandwidth of channel
- Each signal is modulated to a different carrier frequency
- 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



FDM of Three Voice band Signals

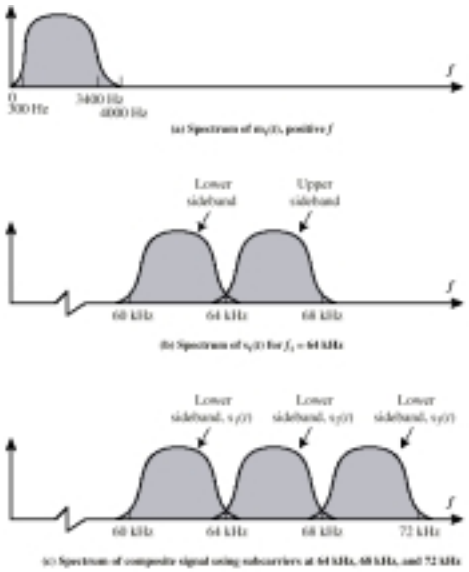


Table 8.1 Cable Television Channel Frequency Allocation

Channel Number	Band (MHz)	Channel Number	Band (MHz)	Channel Number	Band (MHz)
2	54-60	22	168-174	42	330-336
3	60-66	23	216-222	43	336-342
4	66-72	24	222-228	44	342-348
5	76-82	25	228-234	45	348-354
6	82-88	26	234-240	46	354-360
7	174-180	27	240-246	47	360-366
8	180-186	28	246-252	48	366-372
9	186-192	29	252-258	49	372-378
10	192-198	30	258-264	50	378-384
11	198-204	31	264-270	51	384-390
12	204-210	32	270-276	52	390-396
13	210-216	33	276-282	53	396-402
FM	88-108	34	282-288	54	402-408
14	120-126	35	288-294	55	408-414
15	126-132	36	294-300	56	414-420
16	132-138	37	300-306	57	420-426
17	138-144	38	306-312	58	426-432
18	144-150	39	312-318	59	432-438
19	150-156	40	318-324	60	438-444
20	156-162	41	324-330	61	444-450
21	162-168				

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

FDM Carrier Standards

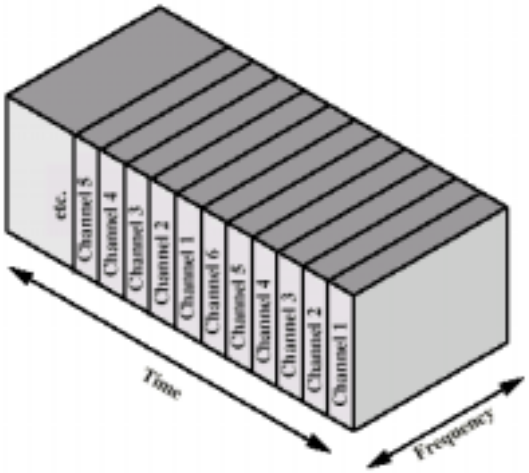
Table 8.2 North American and International FDM Carrier Standards

Number of voice channels	Bandwidth	Spectrum	AT&T	ITU-T
12	48 kHz	60–108 kHz	Group	Group
60	240 kHz	312–552 kHz	Supergroup	Supergroup
300	1.232 MHz	812–2044 kHz		Mastergroup
600	2.52 MHz	564–3084 kHz	Mastergroup	
900	3.872 MHz	8.516–12.388 MHz		Supermaster group
$N \times 600$			Mastergroup multiplex	
3,600	16.984 MHz	0.564–17.548 MHz	Jumbogroup	
10,800	57.442 MHz	3.124–60.566 MHz	Jumbogroup multiplex	

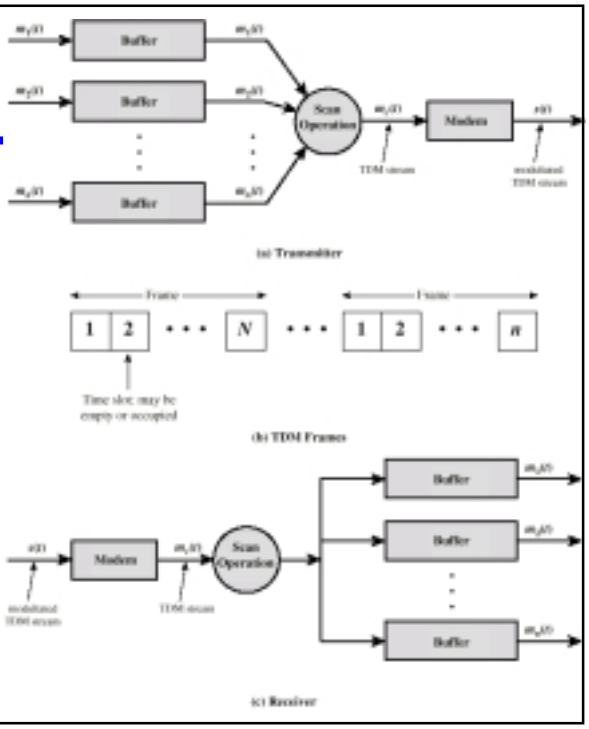
Synchronous Time Division Multiplexing

- 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



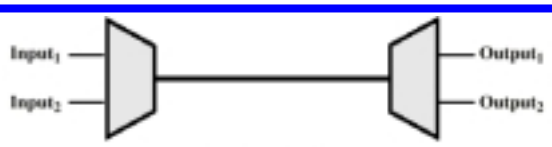
TDM System



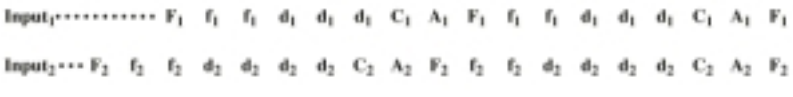
TDM Link Control

- No headers and tailers
- 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



(b) Input data streams

(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

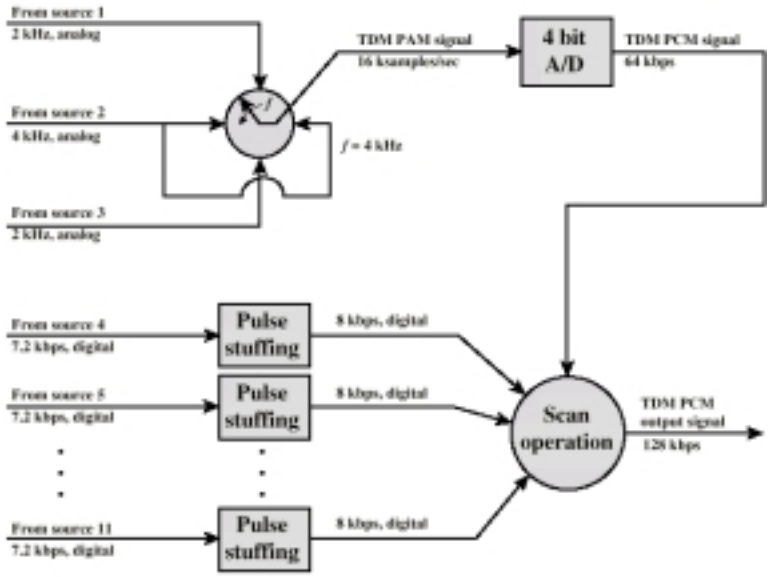
Framing

- 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



TDM Carrier Standards

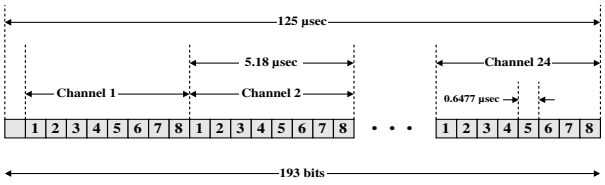
Table 8.3 North American and International TDM Carrier Standards

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

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

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.

Figure 8.9 DS-1 Transmission Format

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 information
- 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

Mixed Data

- DS-1 can carry mixed voice and data signals
- 24 channels used
- No sync byte
- Can also interleave DS-1 channels
  - Ds-2 is four DS-1 giving 6.312Mbps

ISDN User Network Interface

- ISDN allows multiplexing of devices over single ISDN line
- Two interfaces
  - Basic ISDN Interface
  - Primary ISDN Interface

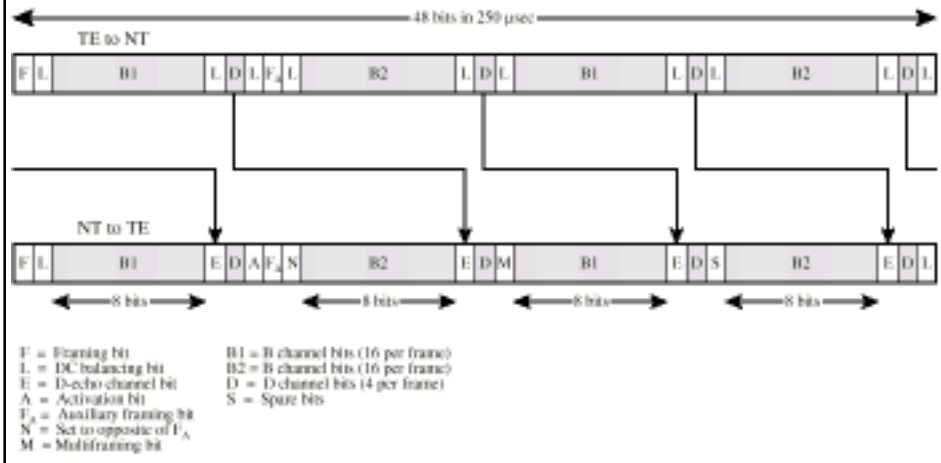
Basic ISDN Interface

- Digital data exchanged between subscriber and NTE - Full Duplex
- Separate physical line for each direction
- Pseudoternary coding scheme
  - 1=no voltage, 0=positive or negative 750mV +/- 10%
- Data rate 192kbps
- Basic access is two 64kbps B channels and one 16kbps D channel
- This gives 144kbps multiplexed over 192kbps
- Remaining capacity used for framing and sync

Basic ISDN Interface

- B channel is basic user channel
- Data
- PCM voice
- Separate logical 64kbps connections to different destinations
- D channel used for control or data
  - LAPD frames
- Each frame 48 bits long
- One frame every 250µs

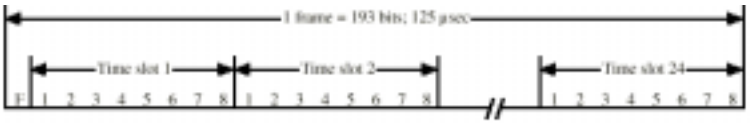
Frame Structure



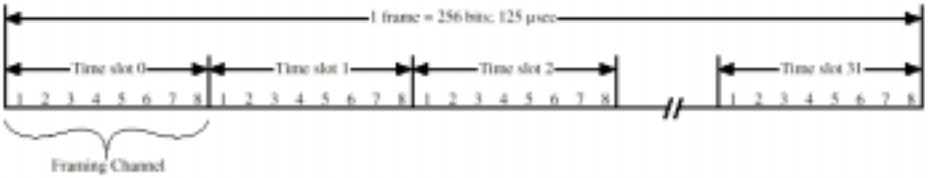
Primary ISDN

- Point to point
- Typically supporting PBX
- 1.544Mbps
  - Based on US DS-1
  - Used on T1 services
  - 23 B plus one D channel
- 2.048Mbps
  - Based on European standards
  - 30 B plus one D channel
  - Line coding is AMI usingHDB3

Primary ISDN Frame Formats



(a) Interface at 1.544 Mbps



(b) Interface at 2.048 Mbps

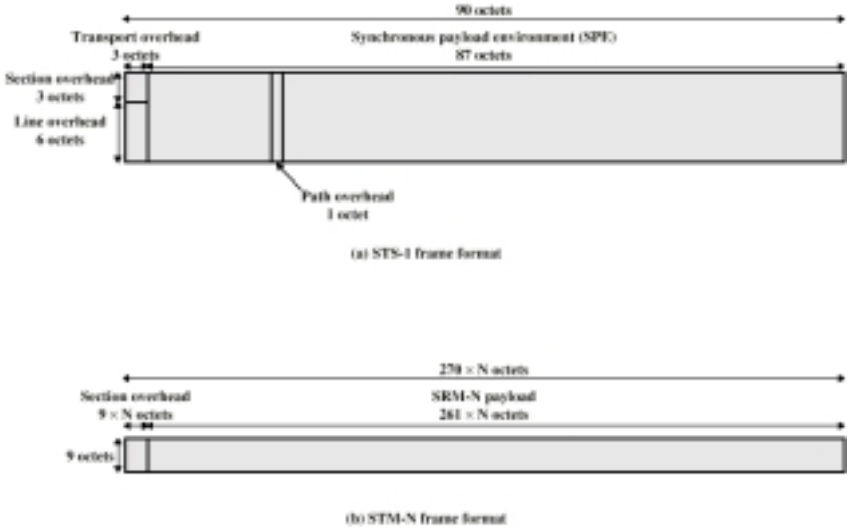
Sonet/SDH

- 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)

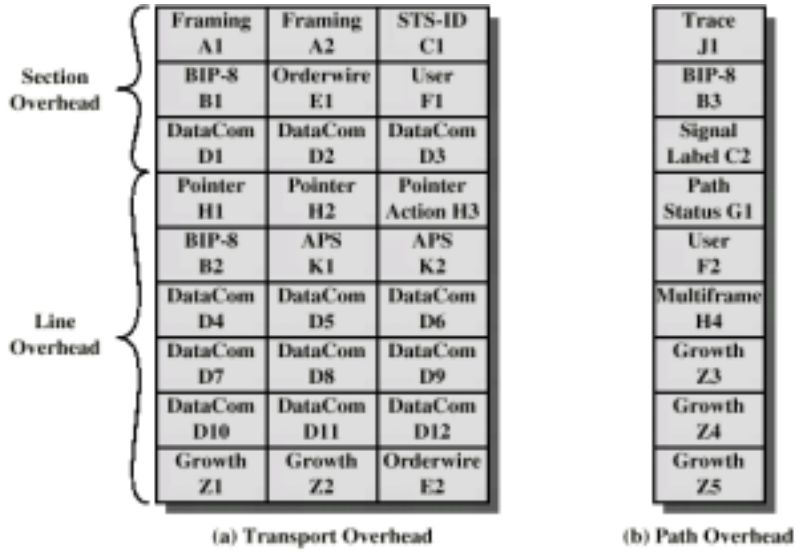
Table 8.4 SONET/SDH Signal Hierarchy

SONET Designation	ITU-T Designation	Data Rate (Mbps)	Payload Rate (Mbps)
STS-1/OC-1		51.84	50.112
STS-3/OC-3	STM-1	155.52	150.336
STS-9/OC-9		466.56	451.008
STS-12/OC-12	STM-4	622.08	601.344
STS-18/OC-18		933.12	902.016
STS-24/OC-24		1244.16	1202.688
STS-36/OC-36		1866.24	1804.032
STS-48/OC-48	STM-16	2488.32	2405.376
STS-96/OC-96		4876.64	4810.752
STS-192/OC-192	STM-64	9953.28	9621.504

SONET Frame Format



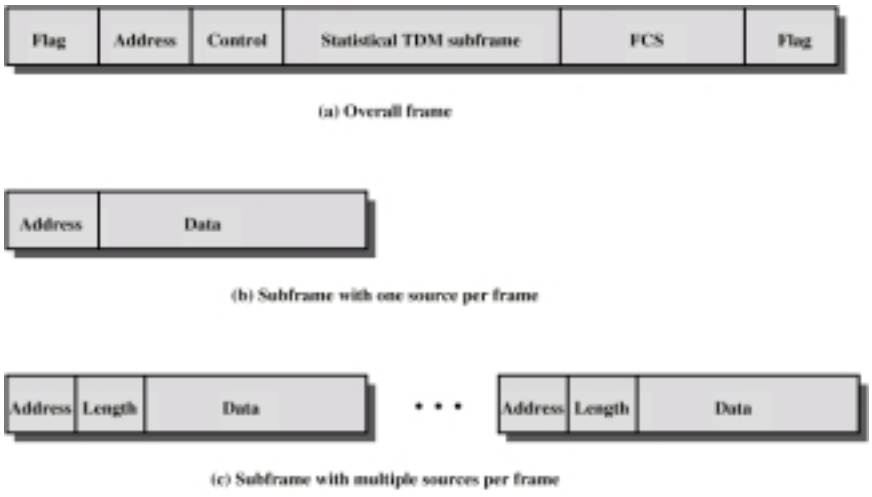
SONET STS-1 Overhead Octets



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



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

Table 8.6 Example of Statistical Multiplexer 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

- 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=M/(IR)=ratio of multiplexed line capacity to total maximum input; $\alpha < K < 1$
  - If $K < \alpha$, input will exceed multiplexer's capacity

Table 8.7 Single-Server Queues with Constant Service Times and Poisson (Random) Arrivals

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)
σ_r	= standard deviation of T_r

Formulas

$$\rho = \lambda T_s$$

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

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

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

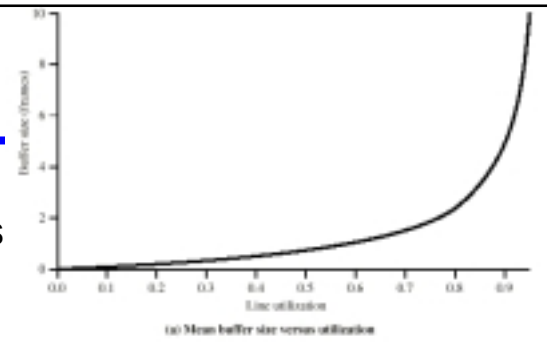
Performance

- Assume random (Poisson) arrivals and constant service time
- Average arrival rate λ $\lambda = \alpha IR$
- Service time T_s $T_s = \frac{1}{M}$
- Utilization or fraction of total line capacity used

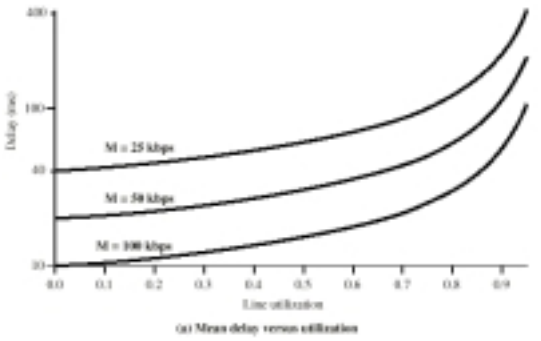
$$\rho = \lambda T_s = \frac{\alpha IR}{M} = \frac{\alpha}{K} = \frac{\lambda}{M}$$

Buffer Size and Delay

- Increasing utilization increases
  - Buffer size
  - delay
- Utilization >0.8 is undesirable



(a) Mean buffer size versus utilization



(a) Mean delay versus utilization

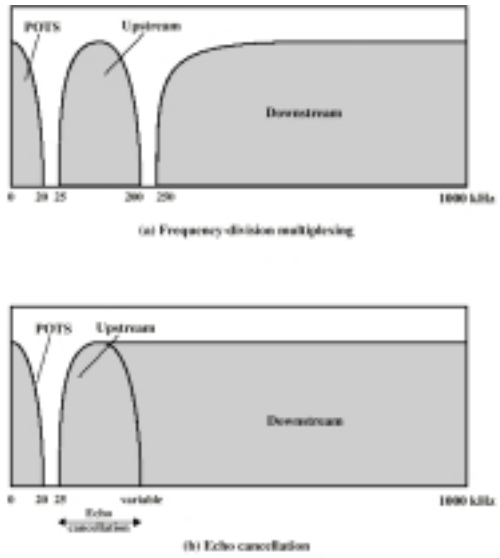
Asymmetrical Digital Subscriber Line (ADSL)

- In high-speed wide area digital network, challenging part is digital subscriber line
- Link between subscriber and network
  - Local loop
- Exploits currently installed twisted pair cable
  - Can carry broader spectrum
  - 1 MHz or more
- Provides high speed digital data transmission over ordinary telephone wires

ADSL Design

- Asymmetric
  - Greater capacity downstream than upstream
- Perfect fit for internet requirement
- Frequency division multiplexing
  - Lowest 25kHz for voice
    - Plain old telephone service (POTS)
  - Use echo cancellation or FDM to give two bands
  - Use FDM within bands
- Range 5.5km

ADSL Channel Configuration



ADSL Design

- Advantages of echo cancellation
  - More of downstream bandwidth is in good part of spectrum
  - Upstream bandwidth can be easily extended
- Disadvantages of echo cancellation
  - Need for echo cancellation logic at both ends

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

DMT Bits per Channel Allocation

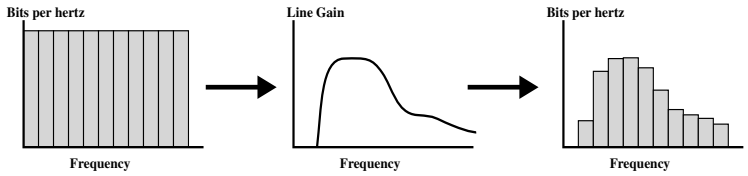
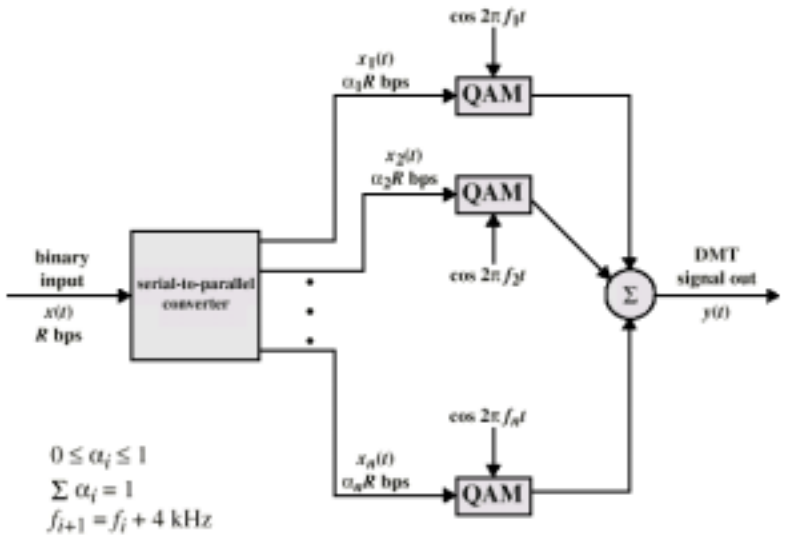


Figure 8.19 DMT Bits per Channel Allocation

DMT Transmitter



xDSL

- High data rate DSL (HDSL)
  - Cost effective T1 data rate (1.544 Mbps)
  - Two twisted pair lines
- Single line DSL (SDSL)
  - Single twisted pair
  - Echo cancellation
- Very high data rate DSL (VDSL)
  - Much higher data rate sacrificing distance
  - Does not use echo cancellation
  - Provides separate bands for different services

Table 8.8 Comparison of xDSL Alternatives

	ADSL	HDSL	SDSL	VDSL
Bits/second	1.5 to 9 Mbps downstream 16 to 640 kbps upstream	1.544 or 2.048 Mbps	1.544 or 2.048 Mbps	13 to 52 Mbps downstream 1.5 to 2.3 Mbps upstream
Mode	Asymmetric	Symmetric	Symmetric	Asymmetric
Copper Pairs	1	2	1	1
Range (24-gauge UTP)	3.7 to 5.5 km	3.7 km	3.0 km	1.4 km
Signaling	Analog	Digital	Digital	Analog
Line Code	CAP/DMT	2B1Q	2B1Q	DMT
Frequency	1 to 5 MHz	196 kHz	196 kHz	≥ 10 MHz
Bits/cycle	Varies	4	4	Varies

UTP = unshielded twisted pair