

# **Data Communications & Computer Networks**

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## **Chapter 8**

### **Multiplexing**

Fall 2008

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## **Agenda**

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- Preface
- FDM
- Synchronous TDM
- Statistical TDM
- ADSL
- Home Exercises

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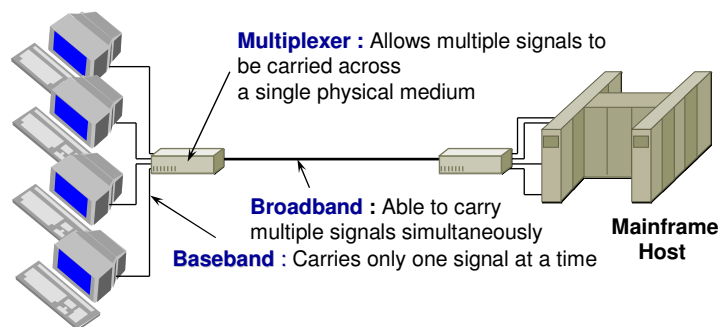
## Key points

- To make efficient use of high-speed communication lines, some form of multiplexing is used.
- Multiplexing allows several transmission sources to share a larger transmission capacity.
- Two common forms of multiplexing are:
  - **Frequency Division Multiplexing (FDM)**
  - **Time Division Multiplexing (TDM)**
    - Synchronous TDM
    - Statistical TDM

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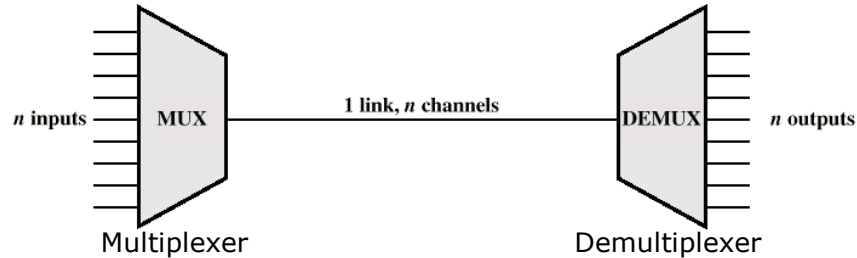
## Preface

- Another technology solution to connect multiple terminals to a single cable, apart from modems is **Multiplexing**
- What we can do with multiplexing is we can take multiple remote terminals, connect them back to our single central site, our single mainframe at the central site, but we can do it all over a single communications channel, a single line.



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## Multiplexing (MUX)



- Typically two communicating stations will not utilize the full capacity of a data link.
- For efficiency, it should be possible to share that capacity.
- A generic term for such sharing is **Multiplexing**
- Let's now look at the different ways to do our muxing.

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## Forms of Multiplexing (1)

- **FDM**
  - Can be used with analog signals
  - A number of signals are carried simultaneously on the same medium by allocating a **different frequency band to each signal**
  - Modulation equipment is needed to move each signal to the required frequency band
  - **Multiplexing** equipment is needed to combine the modulated signals
- **Synchronous TDM**
  - Can be used with digital signals or analog signals carrying digital data
  - Data from various sources are carried in **repetitive frames**
  - Each frame consists of a set of **timeslots** and each **source** is assigned one or more timeslots per frame
  - The effect is to **interleave** bits of data from the various sources

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## **Forms of Multiplexing (2)**

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- **Statistical TDM**

- Provides a generally **more efficient** service than synchronous TDM
- Timeslots are not pre-assigned to particular data sources
- User data are buffered and transmitted as rapidly as possible using available timeslots

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## **Frequency Division Multiplexing (FDM)**

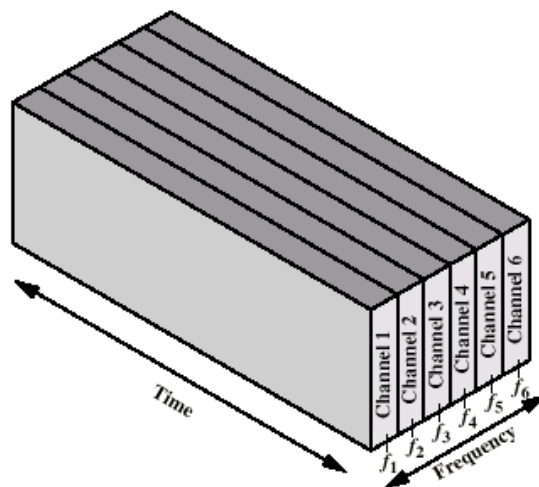
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## 1. Frequency Division Multiplexing (FDM)

- FDM is possible when the useful bandwidth of medium exceeds required channel bandwidth
- A number of signals can be carried simultaneously if each signal is modulated onto a different carrier frequency
- Carrier frequencies must be sufficiently separated so that signals do not overlap
- Each modulated signal requires a certain bandwidth centered on its carrier frequency, referred to as Channel
- To prevent interference, the channels must be separated by guard bands, which are unused portions of the spectrum
- Channel is allocated even if no data is to be sent

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### 1.1 FDM Diagram and characteristics

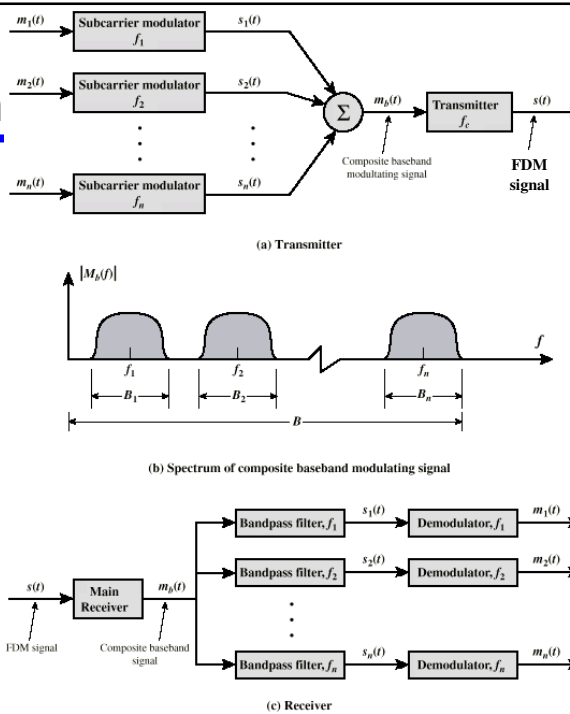


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# FDM System

## Block Diagram

- The composite signal transmitted across the medium is analog
- Input signals may be digital or analog, which are MUXed onto the same tx medium
- Each signal  $m_i(t)$  is modulated onto a carrier frequency  $f_i$
- Multiple carriers are used, each one is referred to as a subcarrier
- The resulting analog modulated signals are summed to produce composite baseband signal  $m_b(t)$

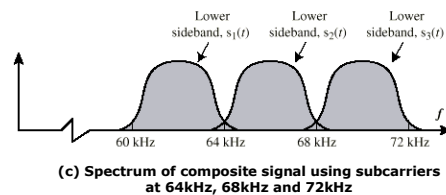
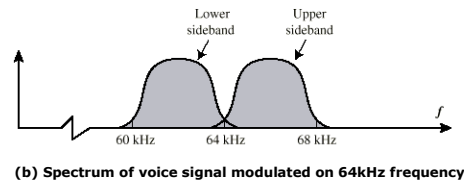
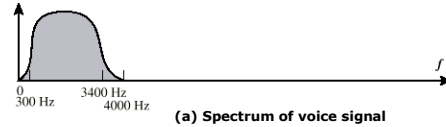


## FDM System (2)

- With reference to the previous slide...
  - The FDM signal has a total bandwidth of  $B$  Hz, where  $B > \sum B_i$  for  $i=1..n$
  - FDM signal is transmitted through the tx medium and received by the receiver, where it is demodulated to retrieve  $m_b(t)$
  - Signal  $m_b(t)$  is then passed through  $n$  bandpass filters, each filter centered on  $f_i$  and having a bandwidth  $B_i$
  - By this way, the signal is again split into its component parts
  - Each component is then demodulated to recover the original signal

## FDM of 3 Voiceband Signals

- This figure shows 3 voice channels transmitted simultaneously over a medium
- Bandwidth of a voice signal is about 4kHz with an effective spectrum from 300Hz to 3.4kHz
- If this signal is modulated with a 64kHz carrier, then the modulated signal has a bandwidth of 8kHz (from 60kHz-68kHz)
- To make efficient use of bandwidth only the lower sideband is transmitted
- If 3 voice signals are used to modulate carriers at 64kHz, 68kHz and 72kHz and only the lower sideband of each is taken, the spectrum of figure (c) results



## Problem that FDM may face

- Previous figure points 2 problems that an FDM system must cope with
  - **Crosstalk**
    - May occur if the spectra of adjacent component signals overlap significantly
    - If voice signals with effective bandwidth of 3.1kHz (300-3400Hz), then a 4kHz bandwidth is adequate
  - **Intermodulation noise**
    - Discussed in lecture 3
    - On a long link, the non-linear effects of amplifiers on a signal in one channel could produce frequency components in other signals

## 1.2 Analog Carrier Systems

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- Hierarchy of FDM schemes
  - **Group**
    - 12 voice channels (4kHz each) = 48kHz
    - Frequency Range from 60kHz to 108kHz with subcarriers in increments of 4kHz
  - **Supergroup**
    - 60 voice channels
    - FDM of 5 group signals on carriers between 420kHz and 612 kHz, with subcarriers in increments of 48kHz
  - **Mastergroup**
    - 10 supergroups, 600 voice channels
    - Total bandwidth of 2.52MHz

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## 1.3 Wavelength Division Multiplexing (WDM)

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- Multiple beams of light at different frequencies
- Carried by optical fiber
- A form of FDM but commonly called WDM
- With WDM light streaming through the fiber consists of many colors, each color of light (wavelength) carries separate data channel
- 1997 Bell Labs
  - 100 beams
  - Each at 10 Gbps
  - Giving a total of 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

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## **WDM Operation**

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- Same general architecture as other FDM systems
- Number of sources generating laser beams at different frequencies
- Multiplexer consolidates sources for transmission over single fiber
- Optical amplifiers amplify all wavelengths
  - Typically 10s of km apart
- Composite signal arrives at Demux, which separates the channels at the destination
- Most WDM operate in 1550nm wavelength range
- Was 200MHz per channel
- Now 50GHz spacing

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## **Dense Wavelength Division Multiplexing**

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- DWDM
- No official or standard definition
- Implies more channels more closely spaced than WDM
- In general, channel spacing of 200GHz or less

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## **Synchronous Time Division Multiplexing**

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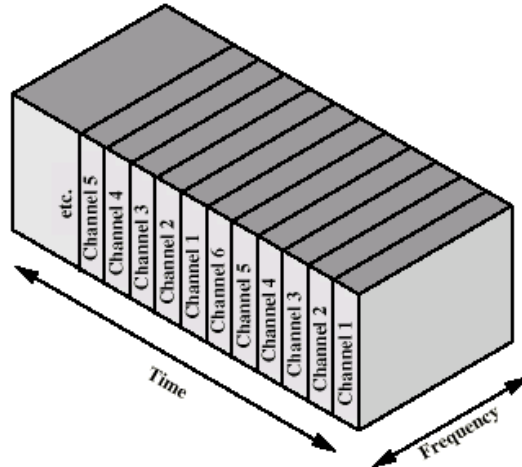
### **2. Synchronous Time Division Multiplexing**

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- Synchronous TDM is possible when the data rate of medium exceeds the data rate of digital signals to be transmitted
- Multiple digital signals are interleaved in time
- Interleaving may be at bit level or in blocks of bytes or larger quantities
- Time slots pre-assigned to sources and fixed
- Time slots allocated even if no data
- Time slots do not have to be evenly distributed amongst sources

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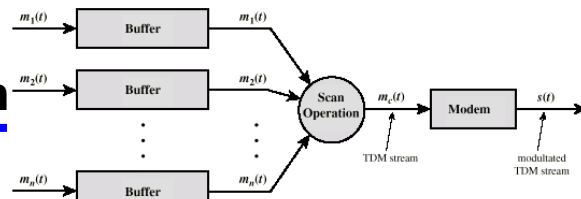
## 2.1 Time Division Multiplexing



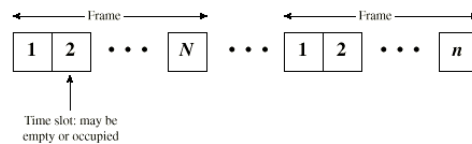
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### TDM System Block Diagram

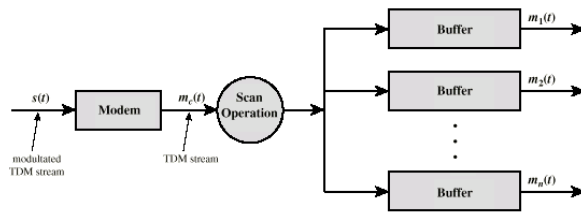
- A number of signals  $m_i(t)$ ,  $i=1..n$  are to be MUXed onto the same tx medium
- The signals carry digital data and are generally digital signals
- The incoming data from each source are buffered
- Each buffer is typically 1 bit or 1 character in length
- The buffers are scanned sequentially to form a composite digital data stream  $m_c(t)$
- Scan operation is sufficiently rapid so that each buffer is emptied before more data can arrive
- Data rate of  $m_c(t) = \sum \text{data rates of } m_i(t)$
- Digital signal  $m_c(t)$  is passed through a modem so that an analog signal is transmitted



(a) Transmitter



(b) TDM Frames



(c) Receiver

## **TDM system**

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- Data are organized into frames
- Each frame contains a cycle of timeslots
- In each frame, one or more slots are dedicated to each data source
- The sequence of slots dedicated to one source, from frame to frame is called a **channel**
- The slot length = tx buffer length

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## **Byte interleaving**

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- Byte interleaving technique is used with asynchronous and synchronous sources
- Each timeslot contains 1 character of data
- Typically start and stop bits of each character are eliminated before transmission and reinserted by the receiver, thus improving efficiency
- Bit-interleaving is used with synchronous sources and may also be used with asynchronous sources
  - Each timeslot contains just one bit
- At the receiver, the interleaved data are DeMUXed and routed to the appropriate destination buffer
  - For each input source  $m_i(t)$ , there is an identical output destination that will receive the output data at the same rate at which it was generated

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## **Why called synchronous TDM**

- Called synchronous not because synchronous transmission is used, but because the timeslots are preassigned to sources
- The timeslots for each source are transmitted whether or not the source has data to send
  - Same as in FDM
  - Capacity is wasted to achieve simplicity of implementation

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## **2.2 TDM Link Control**

- No headers and trailers in the frame of previous slide
  - Data link control protocols are not needed to manage the overall TDM link
- **Flow control**
  - Data rate of multiplexed line is fixed
  - If one channel receiver can not receive data, the others must carry on
  - Solution: Apply Flow control on a per channel basis.
    - The corresponding source must be signaled to stop the transmission of data
    - However, this leaves empty slots
- **Error control**
  - Errors are detected and handled by individual channel systems
  - Solution: Apply Error control on a per channel basis

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## 2.2.1 Framing

- No link control protocol is needed to manage the TDM link
  - No flag or SYNC characters bracketing TDM frames
  - Must provide a synchronizing mechanism
- **Mechanism is the 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
  - To synchronize, the receiver compares incoming bit patterns on each channel with the sync pattern
    - If pattern does not match, successive bit positions are searched until the pattern persists over multiple frames
    - Once framing sync is established, the receiver continues to monitor the framing bit channel
    - If the pattern breaks down, the receiver must again enter a framing search mode

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## 2.2.2 Pulse Stuffing

- The most difficult problem in the design of synchronous TDM is that of synchronizing the various data sources
- Clocks in different sources could be drifting which causes loss of synchronization
- Data rates from different sources are not related by a simple rational number
- Solution is **Pulse Stuffing**
  - Outgoing data rate of MUX (excluding framing bits) is higher than the sum of incoming rates
  - The extra capacity is used by stuffing extra dummy bits or pulses into each incoming signal until it matches local clock
  - Stuffed pulses are inserted at fixed locations in frame and removed at demultiplexer

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## 2.3 Digital Carrier Systems

- Based on TDM Hierarchy
- 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 1 framing bit
  - Total of  $24 \times 8 + 1 = 193$  bits per frame

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## Digital Carrier Systems (2)

- For **voice** transmission, each channel contains one word of digitized data (PCM, 8000 samples per second)
  - Data rate  $8000 \times 193 = 1.544\text{Mbps}$
  - 5 out of 6 frames have 8 bit PCM samples
  - 6<sup>th</sup> frame is 7 bit PCM word + signaling bit
  - Signaling bits form a stream for each voice channel containing control and routing info, eg establish a connection or terminate a call
- Same DS-1 format is used for digital **data**
  - Same data rate of 1.544Mbps is used
  - 23 channels of data
    - 7 bits per frame plus indicator bit for data or systems control
  - 24th channel is sync, which allows faster and more reliable reframing following a framing error

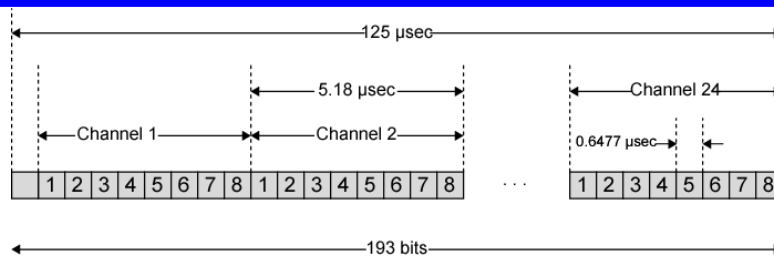
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## Mixed Data

- DS-1 can carry mixed voice and data signals
- In this case, all 24 channels are used
- No sync byte

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## 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.

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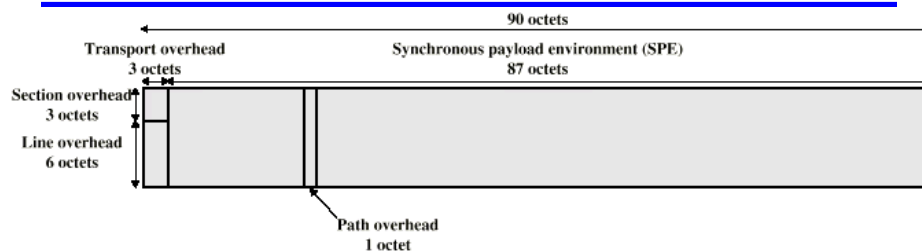


## 2.4 SONET/SDH

- 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 to form an STS-N signal
  - ITU-T lowest rate is 155.52Mbps (STM-1)

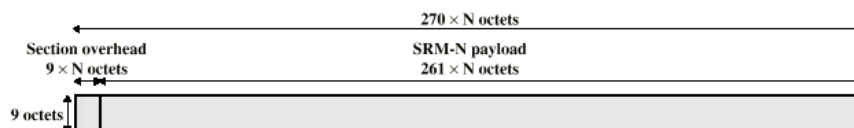
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## SONET Frame Format



(a) STS-1 frame format

- **STS-1 frame consists of 810 octets**
- **Transmitted once every 125μs**
- **Overall data rate 51.84Mbps**



(b) STM-N frame format

## SONET STS-1 Overhead Octets

- The frame can be logically be viewed as a matrix of 9 rows of 90 octets each, with transmission being one row at a time, from left to right and top to bottom
- The first 3 columns (3 octets x 9 rows) of the frame are overhead octets
- The remainder of the frame is payload

Section Overhead	Framing A1	Framing A2	STS-ID C1
	BIP-8 B1	Orderwire E1	User F1
	DataCom D1	DataCom D2	DataCom D3
Line Overhead	Pointer H1	Pointer H2	Pointer Action H3
	BIP-8 B2	APS K1	APS K2
	DataCom D4	DataCom D5	DataCom D6
	DataCom D7	DataCom D8	DataCom D9
	DataCom D10	DataCom D11	DataCom D12
	Growth Z1	Growth Z2	Orderwire E2

(a) Transport Overhead

Trace J1
BIP-8 B3
Signal Label C2
Path Status G1
User F2
Multiframe H4
Growth Z3
Growth Z4
Growth Z5

(b) Path Overhead

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## Statistical Time Division Multiplexing

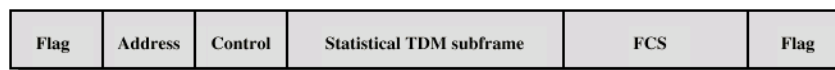
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### 3. Statistical TDM

- 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 is full
- Data rate on multiplexed line is less than the aggregate data rates of input lines
  - This is because statistical TDM takes advantage of the fact that the attached devices are not all transmitting all the time

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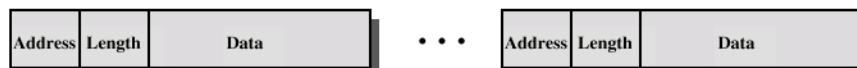
### 3.1 Statistical TDM Frame Formats



(a) Overall frame



(b) Subframe with one source per frame



(c) Subframe with multiple sources per frame

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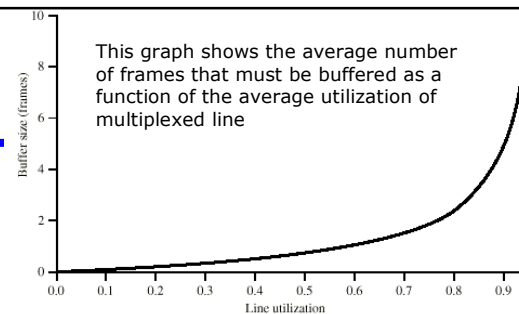
## 3.2 Performance

- Output data rate is less than aggregate input rates
  - This is allowable because it is expected that the average amount of input is less than the capacity of the multiplexed line
- However, may cause problems during peak periods when input exceeds capacity
  - Solution is to include a buffer in the MUX to hold temporary excess inputs
  - Keep buffer size to minimum to reduce delay

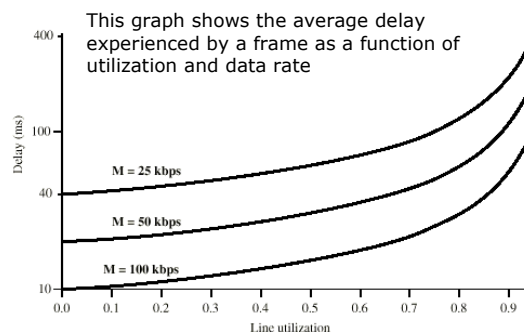
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### Buffer Size and Delay

- These graphs show the trade-off between system response time and speed of multiplexed line
- Note that as the utilization rises, so do the buffer requirements and the delay.
- Utilization above 80% is undesirable.



(a) Mean buffer size versus utilization



(a) Mean delay versus utilization

### 3.3 Cable Modem Outline

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

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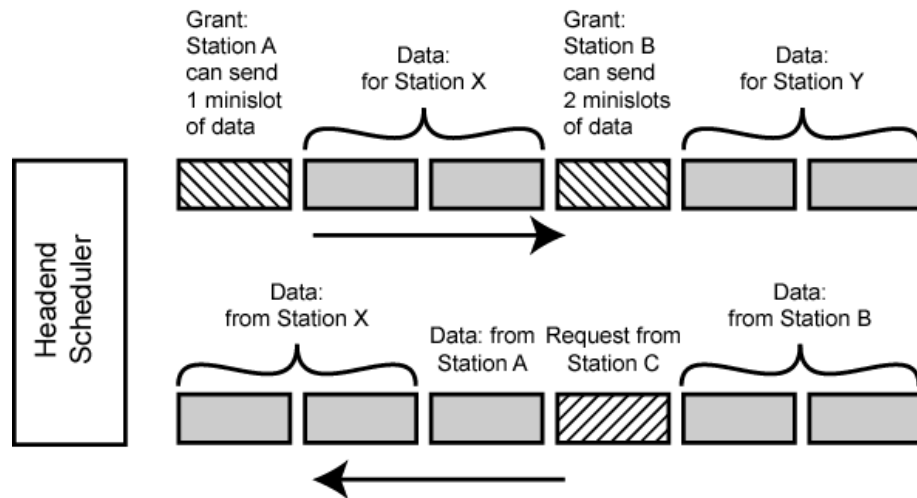
### Cable Modem Operation

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- **Downstream**
  - Cable scheduler delivers data in small packets
  - If more than one subscriber active, each gets a fraction of downstream capacity
    - May get 500kbps to 1.5Mbps or more
  - 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 time slots to subscriber

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## Cable Modem Scheme



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## Asymmetrical Digital Subscriber Line (ADSL)

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## 4. Asymmetrical Digital Subscriber Line (ADSL)

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- Link between subscriber and network
  - Local loop
- Uses currently installed twisted pair cable
  - Can carry broader spectrum
  - 1 MHz or more
- Provides high-speed digital data transmission over ordinary telephone wire

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### 4.1 ADSL Design

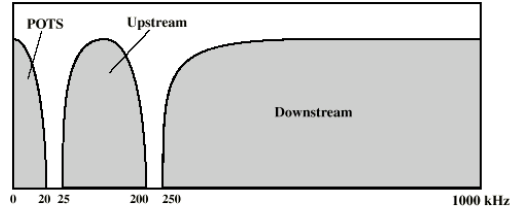
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- **Asymmetric**
  - Greater capacity downstream than upstream
  - Perfectly fitted for access to the Internet
    - Users require far higher capacity for downstream than for upstream transmission
- **Frequency Division Multiplexing**
  - Lowest 25kHz for voice
    - Plain old telephone service (POTS)
  - Use **echo cancellation** or **FDM** to give two bands
    - Echo-cancellation is a technique that allows transmission of digital signals in both directions on a single transmission line simultaneously
  - Use FDM within bands
- Range of up to 6km for PSTN, lower range for ISDN depending on the diameter of the cable and its quality

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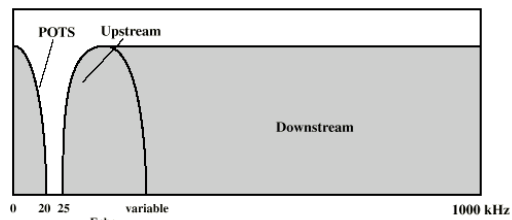
## ADSL Channel Configuration

- When echo-cancellation is used, the entire frequency band for the spectrum channel overlaps the lower portion of the downstream channel. This has 2 advantages compared to the use of distinct frequency bands for upstream and downstream
  - the higher the frequency, the greater the attenuation
  - echo cancellation design is more flexible for changing upstream capacity



(a) Frequency-division multiplexing

- Disadvantage of echo-cancellation
  - need for echo-cancellation logic on both ends of the line



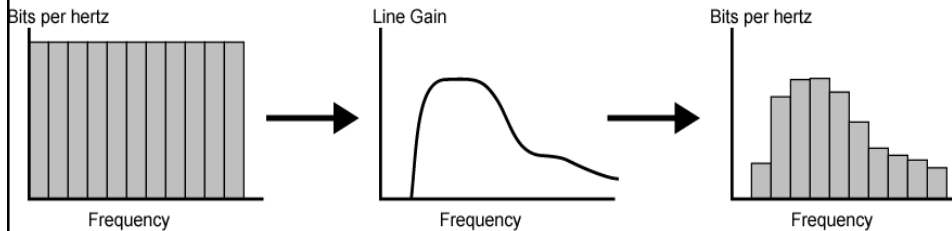
(b) Echo cancellation

## 4.2 Discrete Multitone (DMT)

- Uses multiple carrier signals at different frequencies
- Some bits are sent on each channel
- Transmission band is divided into a number of 4kHz subchannels
- On initialization, DMT modem sends test signals on each subchannel to determine the signal-to-noise ratio
  - Modem assigns more bits to channels with poorer signal quality
- Present ADSL/DMT designs employ 256 downstream subchannels
  - With each 4kHz subchannel carrying 60kbps, it would be possible to transmit at a rate of 15.36MHz
  - In practice, transmission impairments bring this down to 1.5Mbps - 9Mbps depending on line distance and quality



## DTM Bits Per Channel Allocation



- Each subchannel can carry a data rate from 0 – 60kbps.
- The figure shows a typical situation in which there is increasing attenuation and hence decreasing signal-to-noise ratio at higher frequencies
- As a result, the higher-frequency subchannels carry less of the load

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## xDSL

- **High data rate DSL (HDSL)**
  - Developed to provide a more cost-effective means of delivering a T1 data rate (1.544Mbps)
  - Provides data rates up to 2Mbps over two twisted pair lines within bandwidth up to about 200kHz
    - A range of about 3.7km can be achieved
- **Single line DSL (SDSL)**
  - HDSL uses 2 twisted pair lines, whereas typical residential subscriber has a single twisted pair, so SDSL is used
  - Uses echo cancellation to achieve full-duplex transmission
- **Very high data rate DSL (VDSL)**
  - The objective is to provide a scheme similar to ADSL at much higher data rate by sacrificing distance (up to 1.4km)
  - Does not use echo cancellation but provides separate bands for different services with the following allocation
    - POTS: 0 - 4kHz
    - ISDN: 4 - 80kHz
    - Upstream: 300 – 700kHz
    - Downstream: > 1MHz

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## **Required Reading**

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- Stallings chapter 8
- Web sites on
  - ADSL
  - SONET

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## **Home Exercises**

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## **Review questions**

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- Why is multiplexing so cost effective?
- How is interference avoided by using FDM
- What is echo-cancellation?
- Define upstream and downstream with respect to subscriber lines.
- Explain how synchronous TDM works.
- Why is statistical TDM more efficient than a synchronous TDM multiplexer?
- Draw the block diagrams of an FDM and TDM communication system
- Why is ADSL best suited for residential customers for accessing the Internet?

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