Computer Networks 1

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MULTIPLEXING

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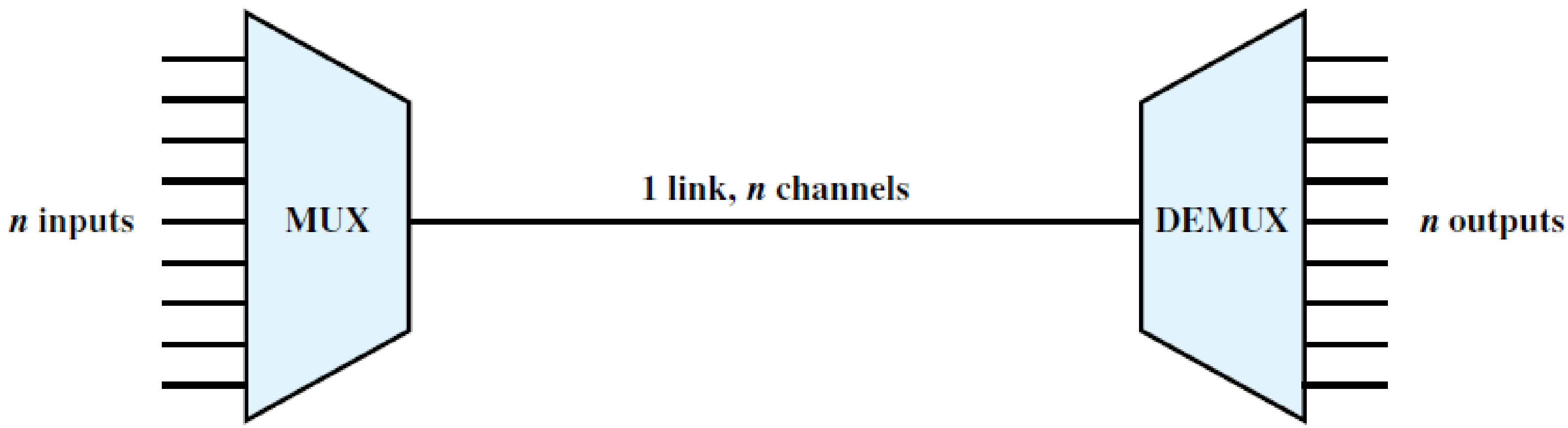
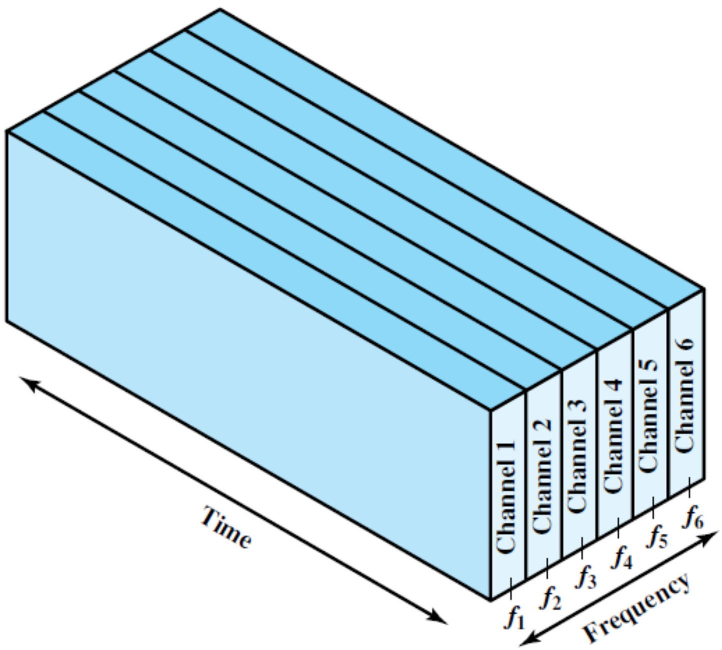
MULTIPLEXING

- To make efficient use of high-speed telecommunications lines
- Allowing several transmission sources to share a transmission capacity
- Two common forms
  - Frequency division multiplexing (FDM)
  - Time division multiplexing (TDM)

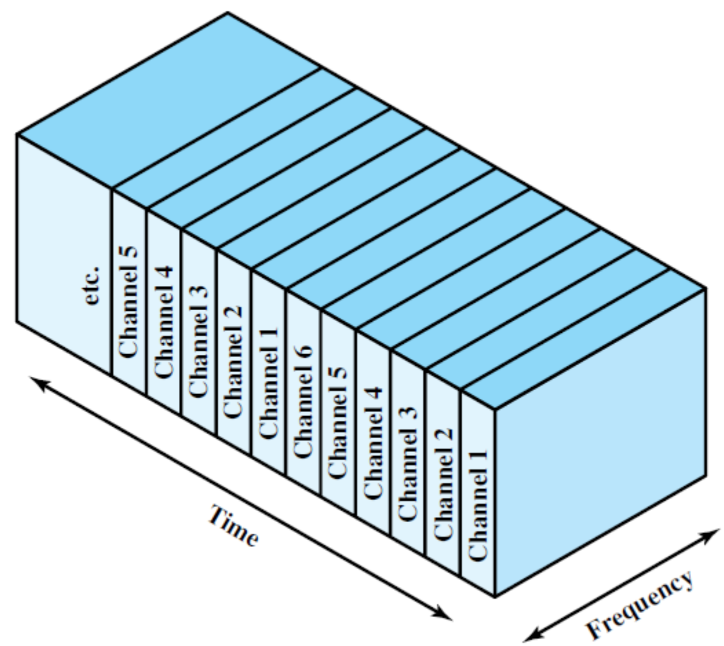


MULTIPLEXING TECHNIQUES

FDM



TDM



OUTLINE

- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Asymmetric Digital Subscriber Line (ADSL)

OUTLINE

Frequency Division Multiplexing (FDM)

Time Division Multiplexing (TDM)

Asymmetric Digital Subscriber Line (ADSL)

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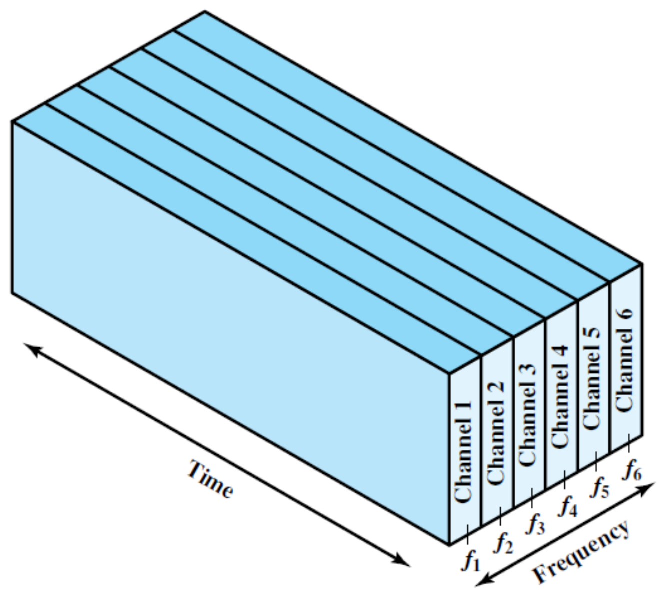
FREQUENCY DIVISION MULTIPLEXING (FDM)

- Possible when the bandwidth of the transmission medium exceeds the required bandwidth of signals
- Number of signals are carried simultaneously on the same medium
- Allocating a different frequency band to each signal
- Can be used with analog signals
- Modulation equipment
  - Moving each signal to the required frequency band
- Multiplexing equipment
  - Combine the modulated signals

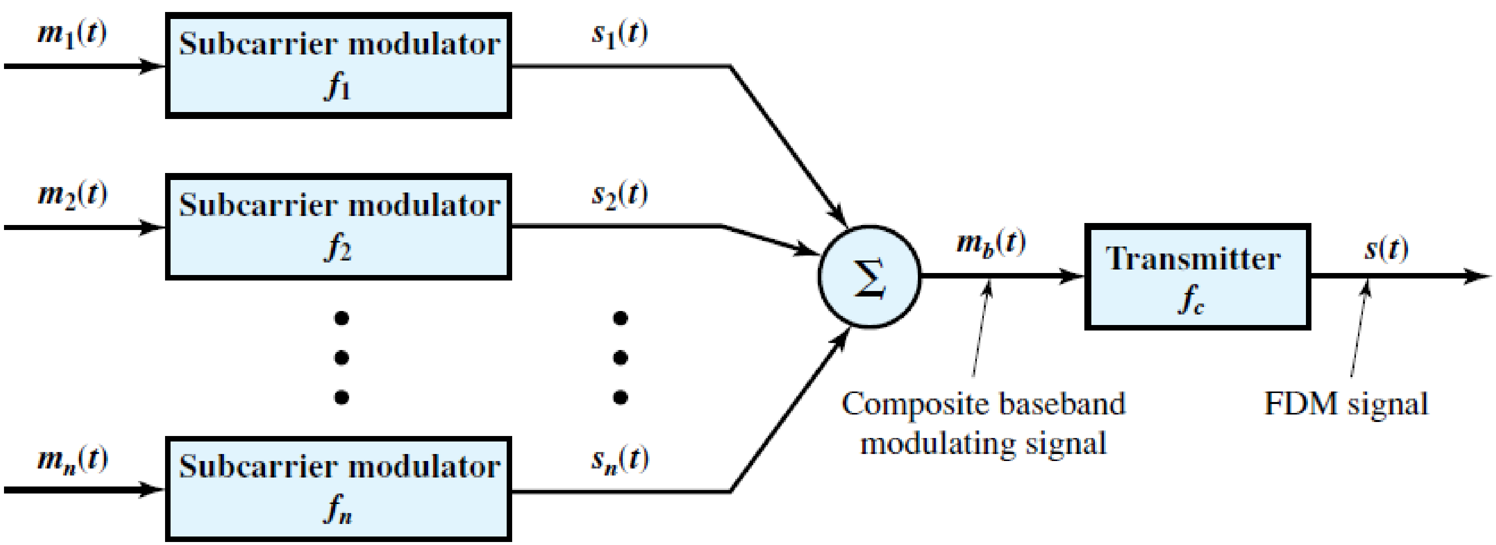
FDM

- Channel: A certain bandwidth centered on a carrier frequency for each signal
- Channels are separated by guard bands

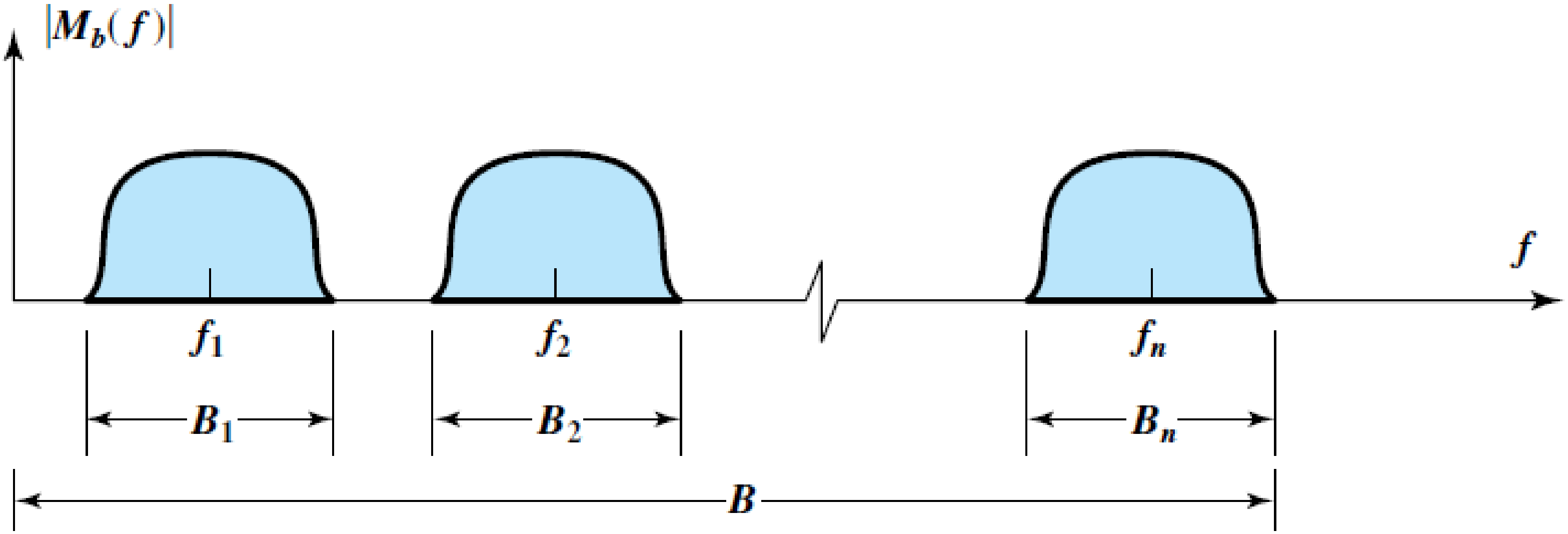


FDM TRANSMITTER

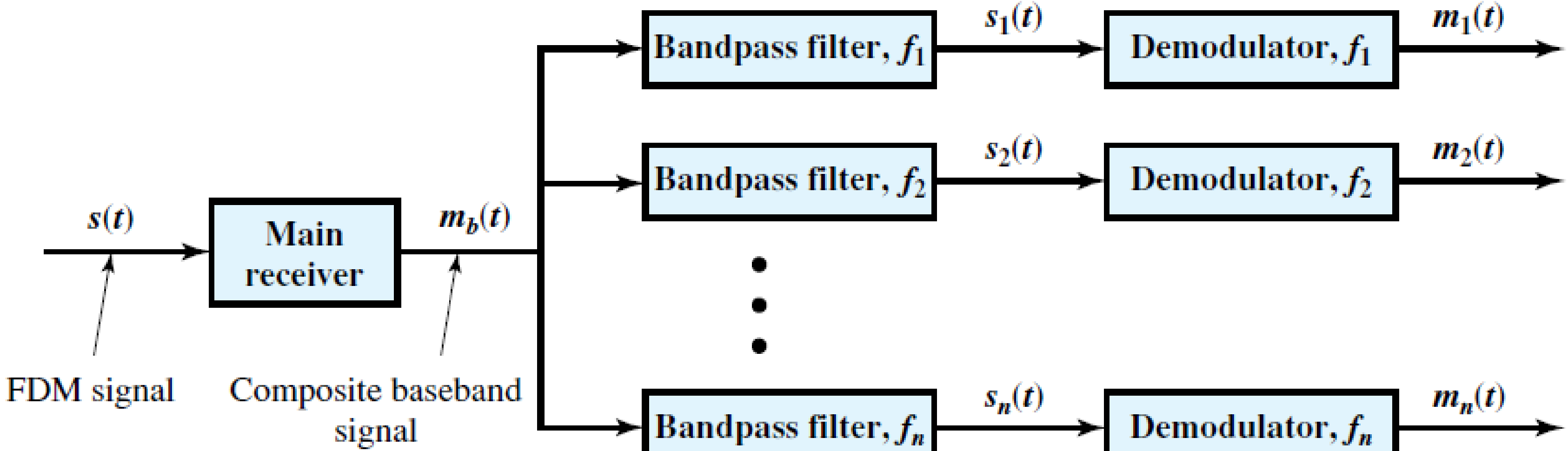
- Each signal is modulated onto a subcarrier
- Resulting analog, modulated signals are then summed to produce a composite baseband signal
- The composite signal may then be shifted as a whole to another carrier frequency by an additional modulation step



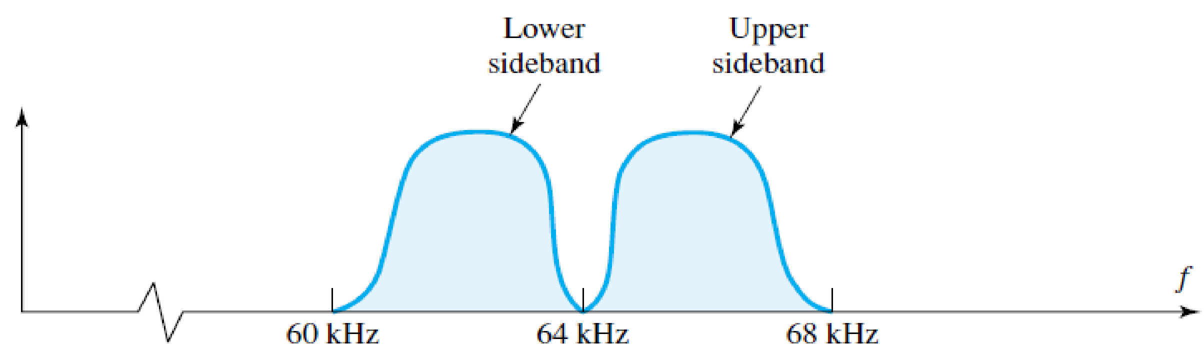
SPECTRUM OF COMPOSITE BASEBAND MODULATING SIGNAL



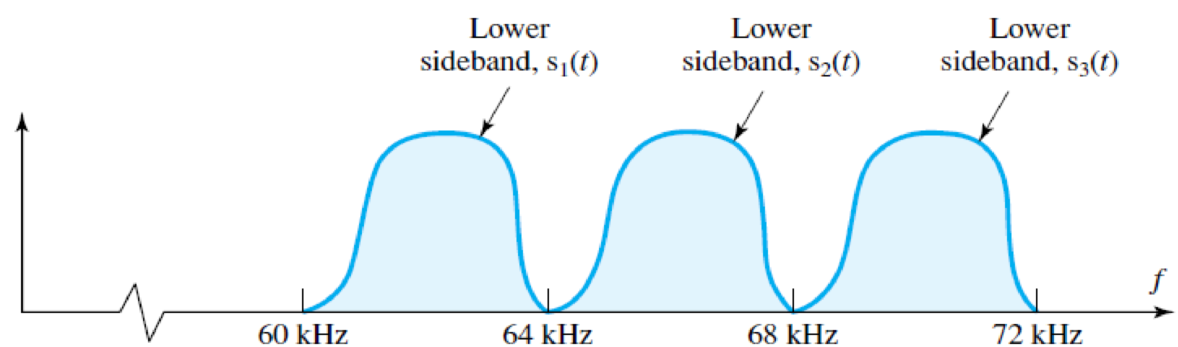
FDM RECEIVER



(a) Spectrum of voice signal



(b) Spectrum of voice signal modulated on 64 kHz frequency



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

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	

WAVELENGTH DIVISION MULTIPLEXING (WDM)

- Multiple beams of light at different frequencies transmitted on the same fiber
- A form of FDM
- Commonly called wavelength division multiplexing (WDM)
- The light streaming through the fiber consists of many colors, wavelengths, each carrying a separate channel of data

ITU WDM CHANNEL SPACING

Frequency (THz)	Wavelength in Vacuum (nm)	50 GHz	100 GHz	200 GHz
196.10	1528.77	X	X	X
196.05	1529.16	X		
196.00	1529.55	X	X	
195.95	1529.94	X		
195.90	1530.33	X	X	X
195.85	1530.72	X		
195.80	1531.12	X	X	
195.75	1531.51	X		
195.70	1531.90	X	X	X
195.65	1532.29	X		
195.60	1532.68	X	X	
. . .	. . .			
192.10	1560.61	X	X	X

OUTLINE

Frequency Division Multiplexing (FDM)

Time Division Multiplexing (TDM)

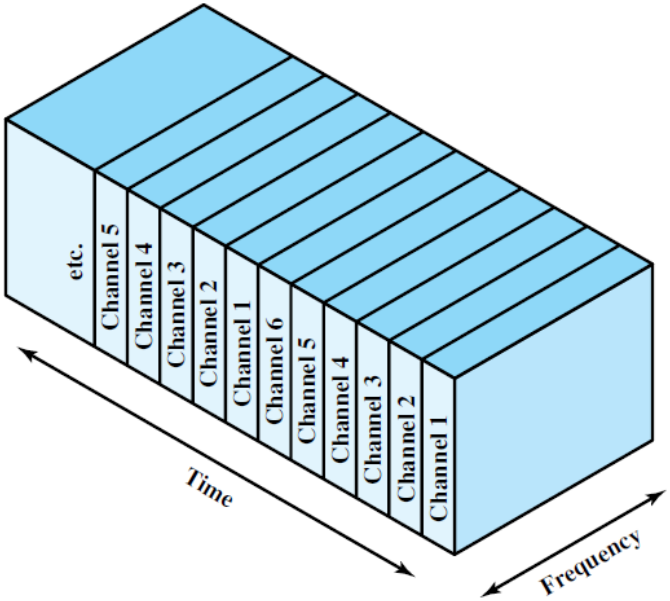
Asymmetric Digital Subscriber Line (ADSL)

TIME DIVISION MULTIPLEXING

- Multiple digital signals
  - (Or analog signals carrying digital data)
  - Can be carried on a single transmission path
- By interleaving portions of each signal in time
- Interleaving can be at the bit level or in blocks of bytes or larger quantities

TDM

- Multiplexer with six inputs
- Each input: 9.6 kbps.
- Single line with a capacity of at least 57.6 kbps (plus overhead capacity)

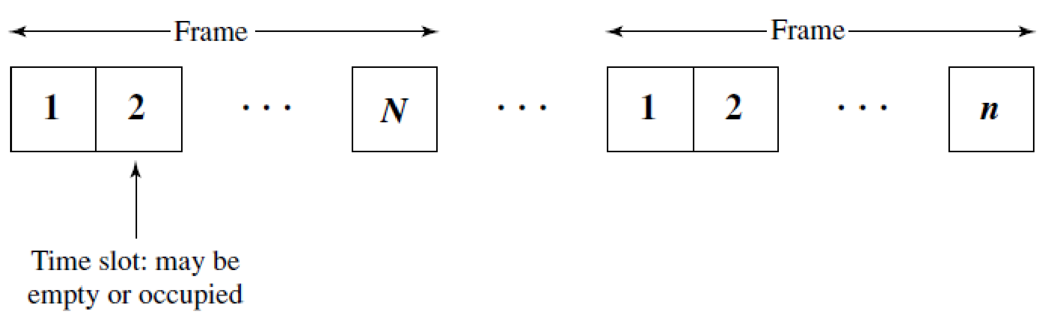


SYNCHRONOUS TIME DIVISION MULTIPLEXING

- Can be used with
  - Digital signals
  - Analog signals carrying digital data
- Data from various sources carried in repetitive frames
- Interleaving bits of data from the various sources

TRANSMITTED DATA FORMAT
TDM FRAMES

- Data are organized into **frames**
- Each frame contains a cycle of time slots
- In each frame, one or more slots dedicated to each source
- **Channel:** Sequence of slots dedicated to one source, from frame to frame
- Slot length = Transmitter buffer length
  - Typically a bit or a byte (character)

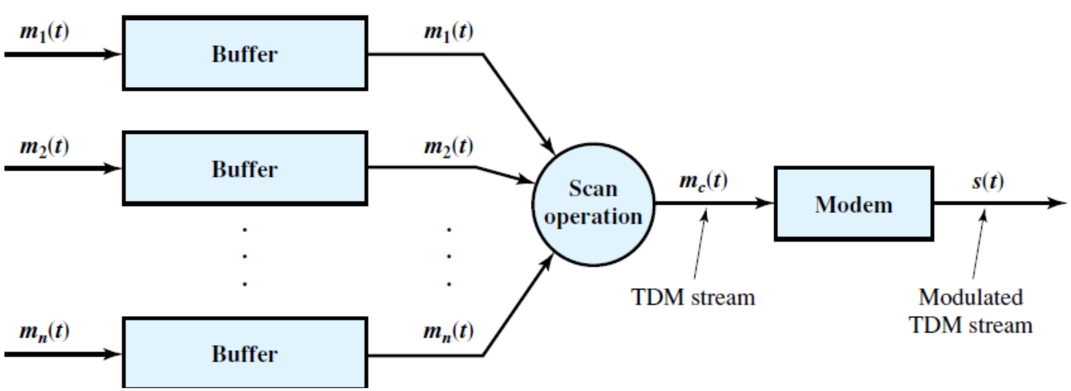


SYNCHRONOUS TDM

- Time slots are preassigned to sources and fixed
- Time slots for each source are transmitted whether or not the source has data to send
- Capacity is wasted to achieve simplicity of implementation
- Can handle sources of different data rates
- Ex:
  - Slowest input device are assigned one slot per cycle
  - Faster devices are assigned multiple slots per cycle

TDM TRANSMITTER

- Incoming data from each source are briefly buffered
  - Each buffer is typically one bit or one character in length
- Buffers are scanned sequentially to form a composite digital stream
- Scan operation is sufficiently rapid
  - Each buffer is emptied before more data can arrive
- Data rate of $m_c(t)$ must at least equal the sum of the data rates of the $m_i(t)$

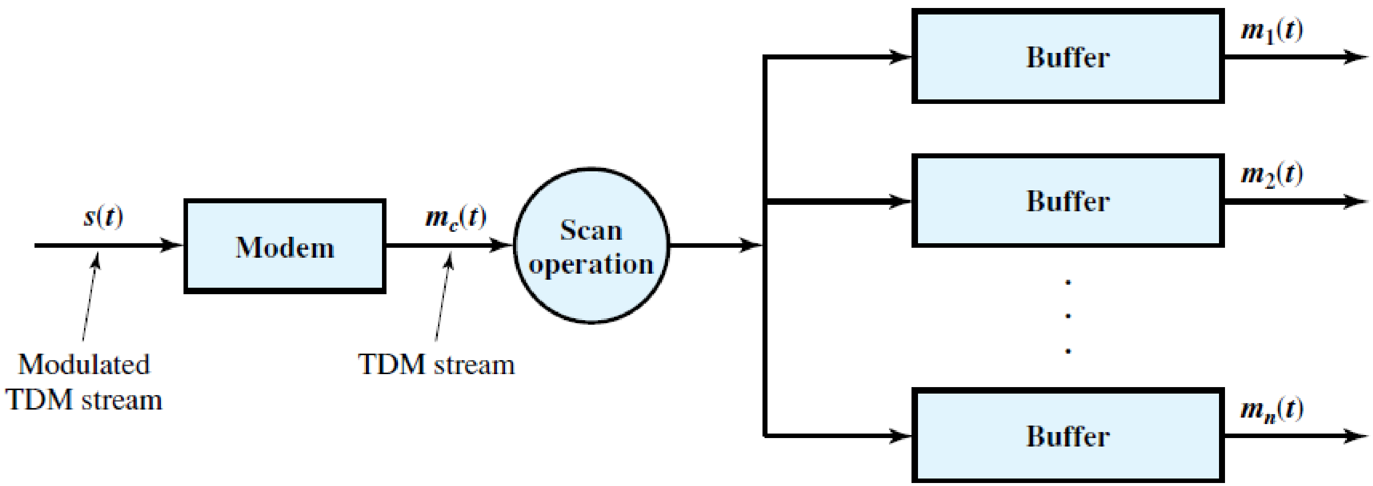


INTERLEAVING

- Byte-interleaving technique
  - Used with asynchronous and synchronous sources
  - Each time slot contains one character of data
  - Start and stop bits of each character are eliminated before transmission and reinserted by the receiver, thus improving efficiency
- Bit-interleaving technique
  - Used with synchronous sources and may also be used with asynchronous sources
  - Each time slot contains just one bit

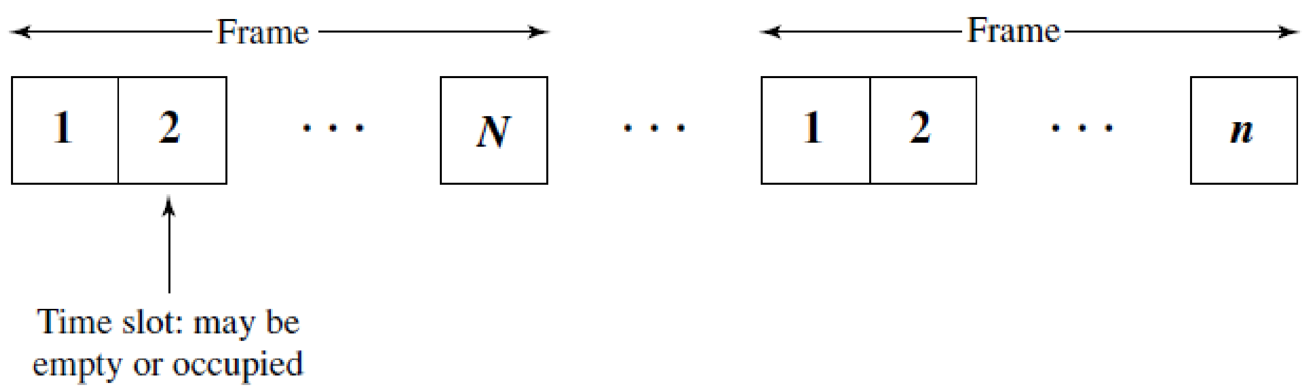
TDM RECEIVER

- Interleaved data are demultiplexed
- Routed to the appropriate destination buffer
- An identical output destination for each input source
  - Receive the output data at the same rate at which it was generated



TDM LINK CONTROL

- Transmitted data stream does not contain headers and trailers
- No need to control mechanisms provided by a data link protocol!



NO NEED TO FLOW CONTROL

Fixed data rate on the multiplexed line

- Multiplexer/Demultiplexer operate at that rate

Solution for saturated output device

- Other output lines receive data at predetermined times
- Cease flow of data from the corresponding input
- Corresponding channel will carry empty slots
- Frames as a whole maintain the same transmission rate

NO NEED TO ERROR CONTROL

No request to retransmission of entire TDM frame

- An error occurs on one channel!

Other devices do not want a retransmission

- Do not know a retransmission has been requested!

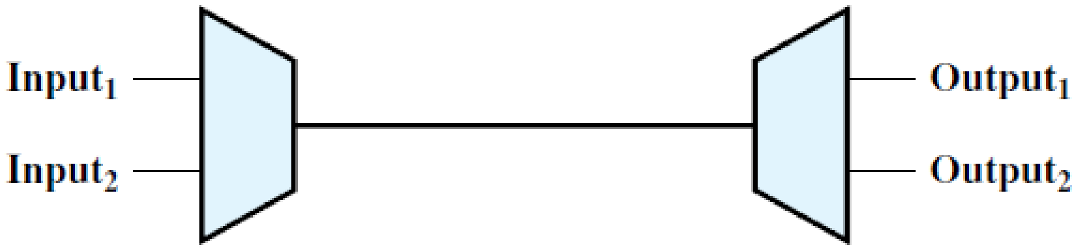
Solution

- Applying error control on a per-channel basis

PER-CHANNEL FLOW CONTROL AND ERROR CONTROL

- Using a data link control protocol
- Shuffling octets of HDLC frames from the sources
- Reassembling the pieces correctly before seen
- Transparency of Multiplexing/demultiplexing

DATA LINK CONTROL ON TDM CHANNELS



(a) Configuration

$Input_1 \cdots\cdots\cdots\cdots$ 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

$Input_2 \cdots$ 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

$\cdots f_2$ 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

TDM FRAMING

A link control protocol not needed to manage the overall TDM link

No flag or SYNC characters to bracket TDM frames

Requiring frame synchronization

Added-digit framing

- The most common mechanism for framing
- One control bit added to each TDM frame
- control channel: Identifiable pattern of bits, from frame to frame

TDM FRAMING EXAMPLE

Alternating bit pattern, 101010. . . .

Unlikely to be sustained on a data channel

Synchronization

- Receiver compares the bits of one frame position to the pattern
- Once framing synchronization is established
- Receiver continues to monitor the framing bit channel

If pattern breaks down, enter a framing search mode

Synchronizing various data sources

A difficult problem in designing

Each source has a separate clock

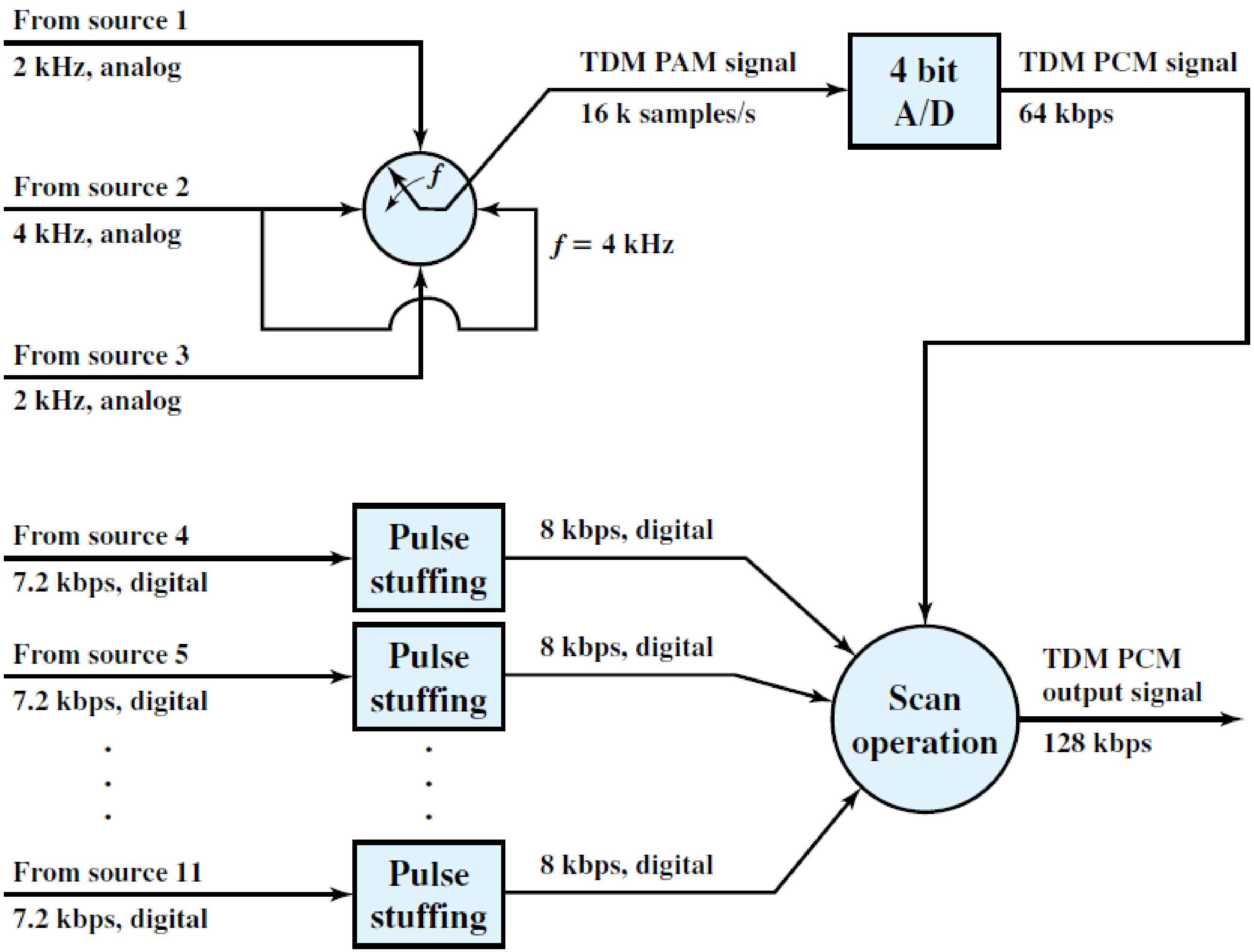
- Variation among clocks cause loss of synchronization

Data rates of the input data streams may not related by a simple rational number

PULSE STUFFING

- Effective solution for synchronizing data sources
- Outgoing data rate of the multiplexer > $\sum$ maximum instantaneous incoming rates
- Extra capacity is used by stuffing extra dummy bits or pulses into each incoming signal
  - Until its rate is raised to that of a locally generated clock signal
- Stuffed pulses are inserted at fixed locations in the multiplexer frame format
  - They can be identified and removed at the demultiplexer

TDM OF ANALOG AND DIGITAL SOURCES



DIGITAL CARRIER SYSTEMS

- Long-distance carrier system to transmit voice signals over high-capacity transmission links
  - Ex: Optical fiber, coaxial cable, microwave
- Hierarchy of TDM structures of various capacities

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

STATISTICAL TIME DIVISION MULTIPLEXING

Devices not all transmitting all of the time

Time slots not preassigned to data sources

User data buffered and transmitted as rapidly as possible using available time slots

More efficient service than synchronous TDM

STATISTICAL TDM

Dynamically allocating time slots on demand

- n I/O lines
- Only k time slots available on the TDM frame $(k < n)$

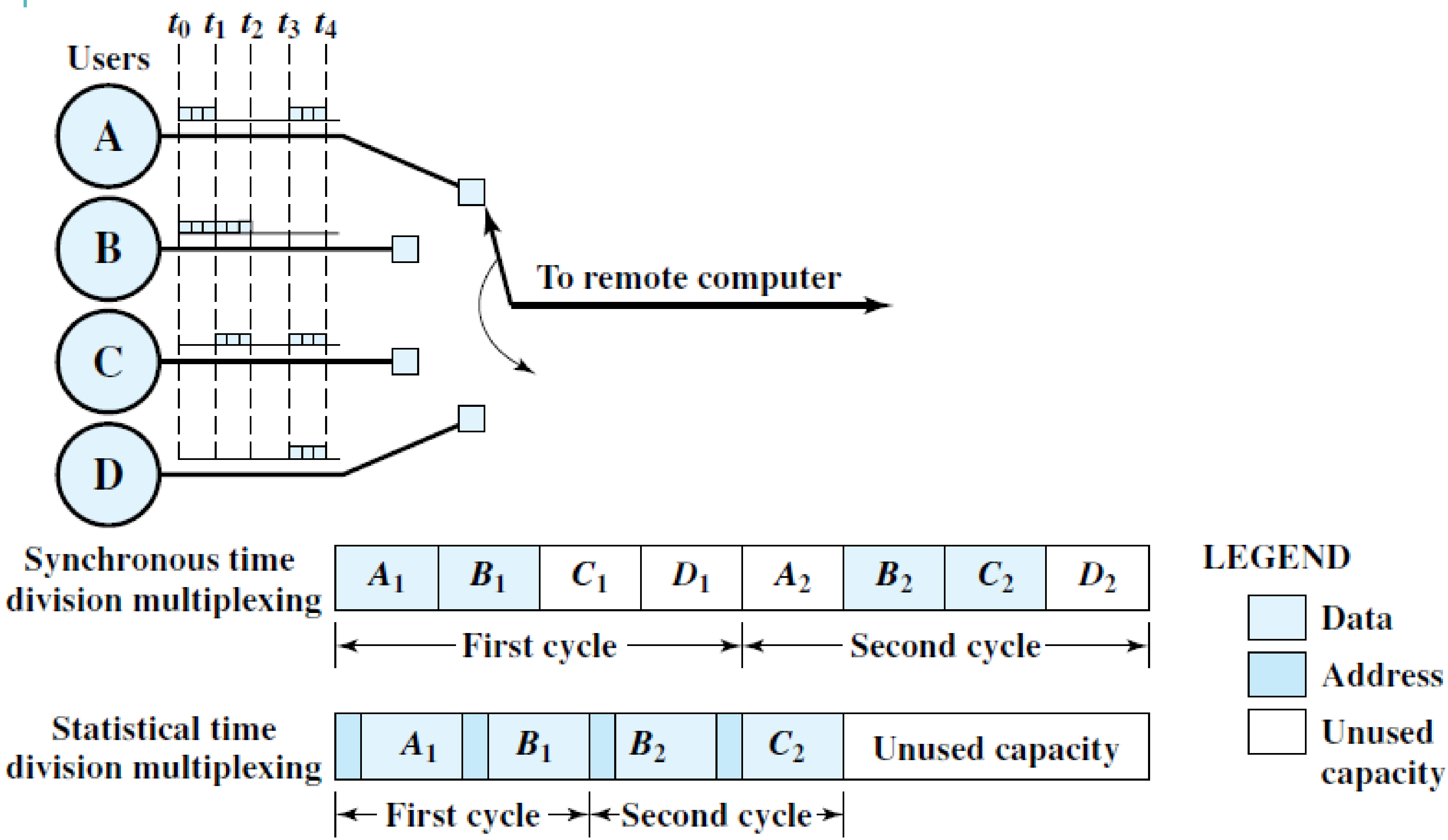
Function of multiplexer

- Scanning the input buffers
- Collecting data until a frame is filled
- Sending the frame

Function of Demultiplexer

- Receiving a frame
- Distributing the slots of data to the appropriate output buffers

SYNCHRONOUS TDM VS. STATISTICAL TDM



STATISTICAL TDM ADVANTAGES

Multiplexed line data rate < Sum of data rates of devices

Can use a lower data rate

- To support as many devices as synchronous multiplexer

Using a link of the same data rate

- Can support more devices than synchronous multiplexer

STATISTICAL TDM DISADVANTAGES

- The positional significance of the slots is lost
- It is not known ahead of time which source's data will be in any particular slot
- Data arrive from and are distributed to I/O lines unpredictably
- Address information is required to assure proper delivery
- More overhead per slot

STATISTICAL TDM FRAMING

The frame structure has an impact on performance

Desirable to minimize overhead bits to improve throughput

Typically using a synchronous protocol such as HDLC

Within the HDLC frame, the data frame must contain control bits for the multiplexing

STATISTICAL TDM FRAME FORMAT 1

- Only one source of data is included per frame
- That source is identified by an address
- The length of the data field is variable
- Can work well under light load
- Inefficient under heavy load

Flag	Address	Control	Statistical TDM subframe	FCS	Flag

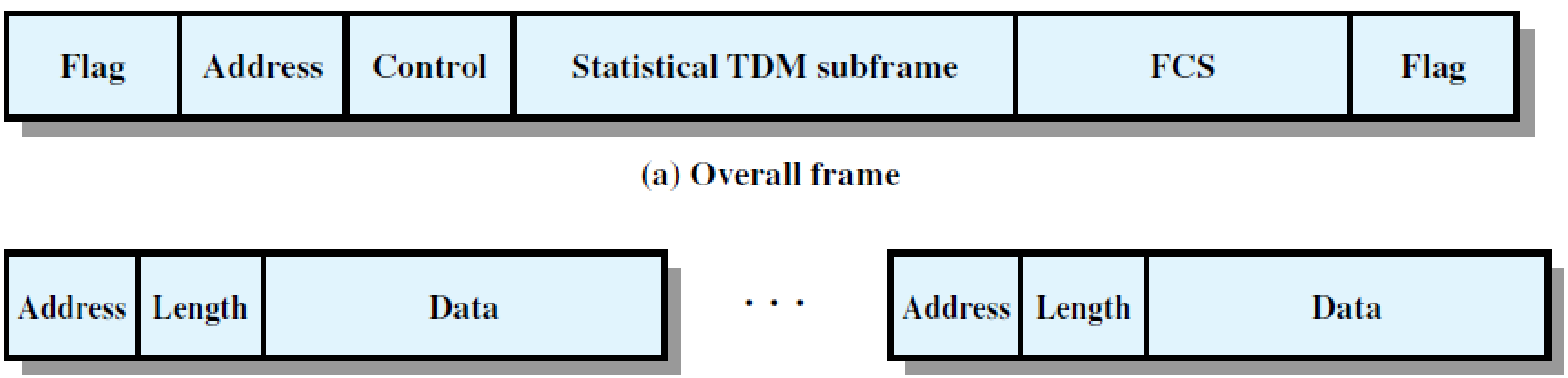
(a) Overall frame

Address	Data

(b) Subframe with one source per frame

STATISTICAL TDM FRAME FORMAT 2

- Allowing multiple data sources to be packaged in a single frame
- Improving Efficiency
- Needed to specify the length of data for each source



(a) Overall frame

(c) Subframe with multiple sources per frame

STATISTICAL TDM PERFORMANCE

- Average amount of input < Capacity of multiplexed line
- Multiplexed line data rate < Sum of data rates of devices
- Problem?
  - In peak periods the input exceeds capacity
- Solution?
  - Include a buffer in multiplexer to hold temporary excess input

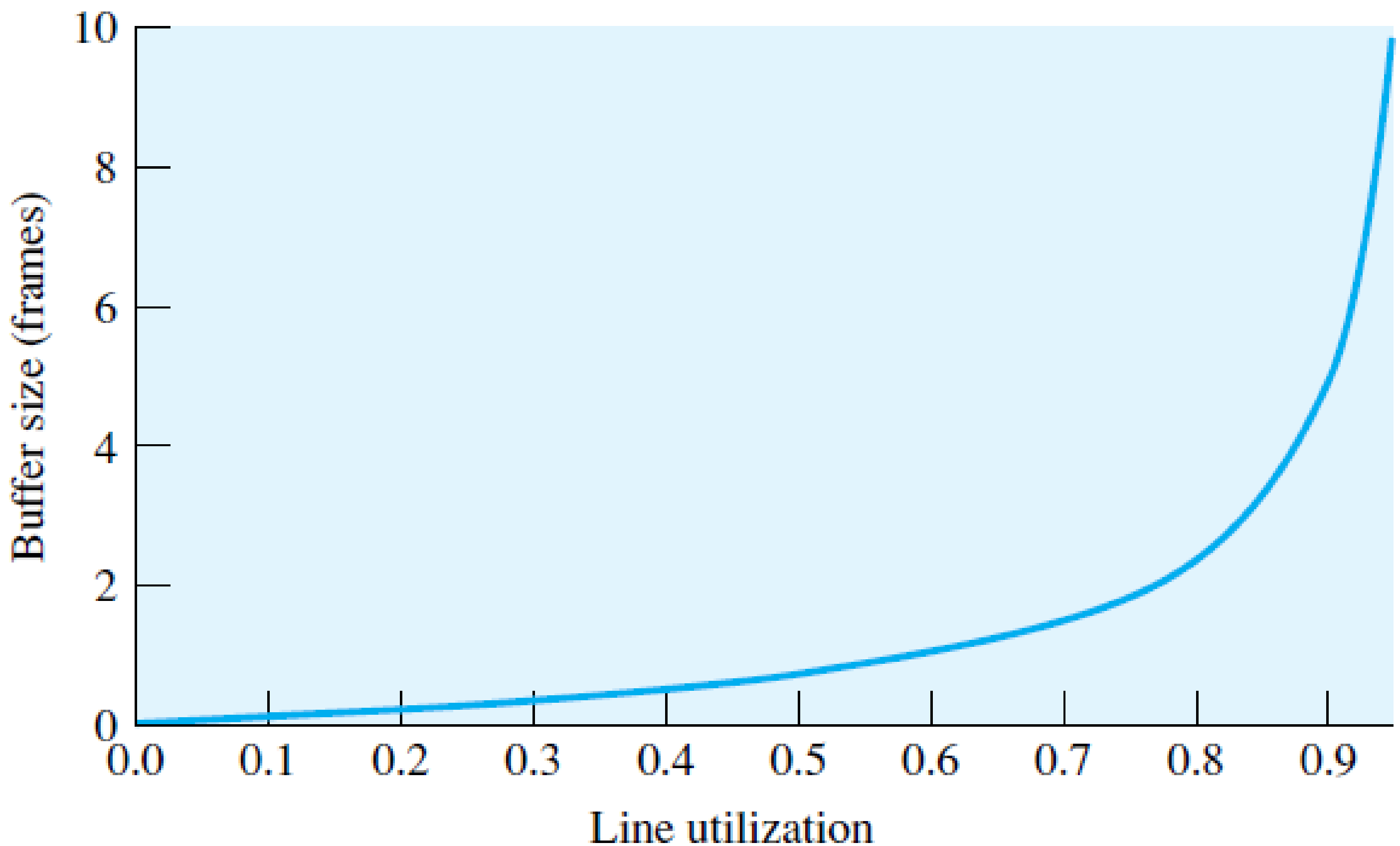
A TRADEOFF!

- A tradeoff between
  - Size of the buffer
  - Data rate of the line
- We would like to use
  - The smallest possible buffer
  - The smallest possible data rate
- But a reduction in one requires an increase in the other
- Memory is cheap
  - Not concerning the cost of the buffer
  - More buffering → Longer delay
- Tradeoff between
  - System response time and
  - Speed of the multiplexed line

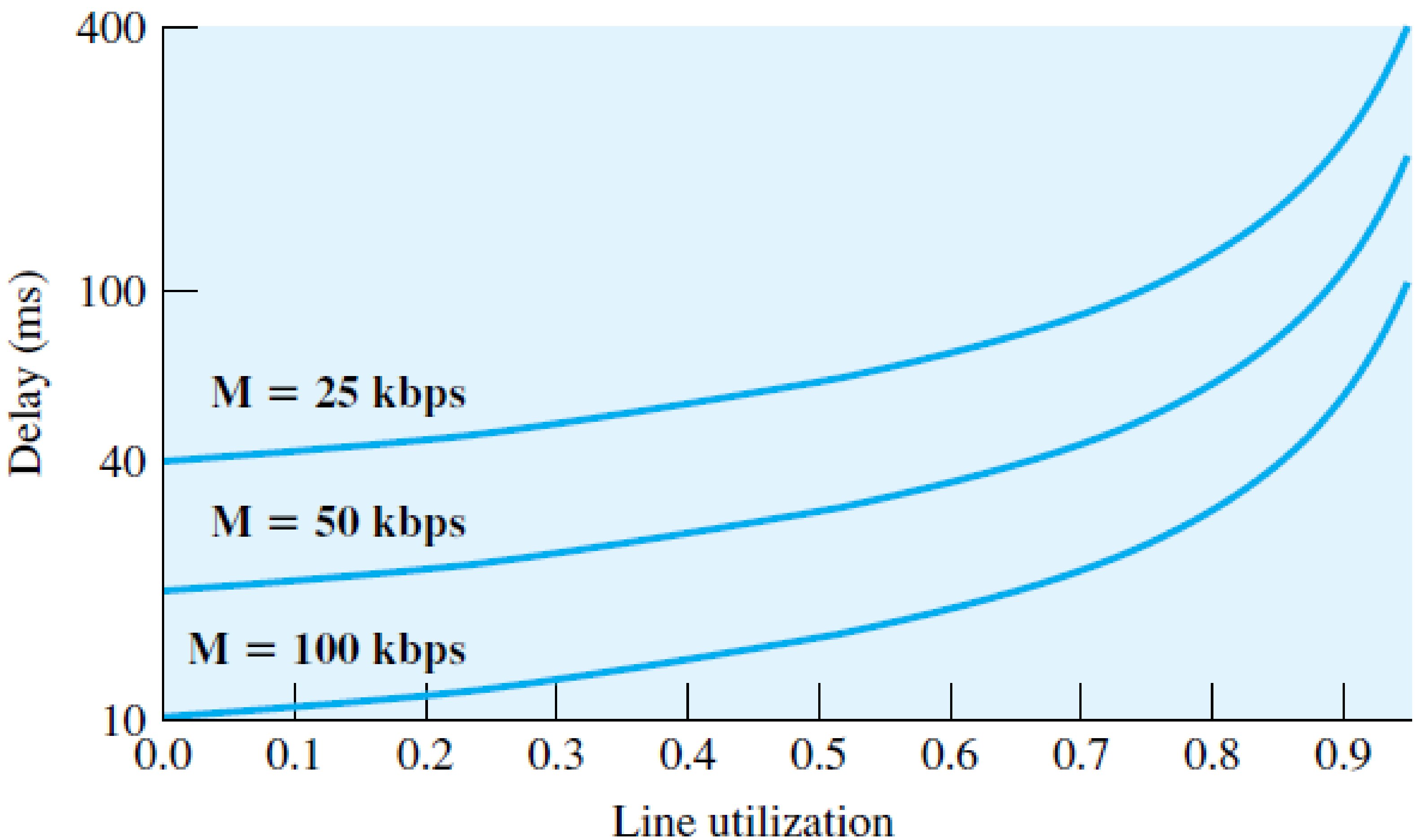
PERFORMANCE EVALUATION

$$
\begin{aligned}
I &= \text{number of input sources} \\
R &= \text{data rate of each source, bps} \\
M &= \text{effective capacity of multiplexed line, bps} \\
\alpha &= \text{mean fraction of time each source is transmitting, } 0 < \alpha < 1 \\
K &= \frac{M}{IR} = \text{ratio of multiplexed line capacity to total maximum input}
\end{aligned}
$$

MEAN BUFFER SIZE VS. UTILIZATION



MEAN DELAY VS. UTILIZATION



OUTLINE

- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- **Asymmetric Digital Subscriber Line (ADSL)**

DIGITAL SUBSCRIBER LINE

Link between subscriber and network

The most challenging part in a network

- Billions of potential endpoints worldwide
- Installing new cable for each new customer?

Exploiting the installed base of twisted-pair wire

- Linking customers to telephone networks
- Installed to carry voice signals in a bandwidth of 4 kHz
- Capable of transmitting signals over 1 MHz or more

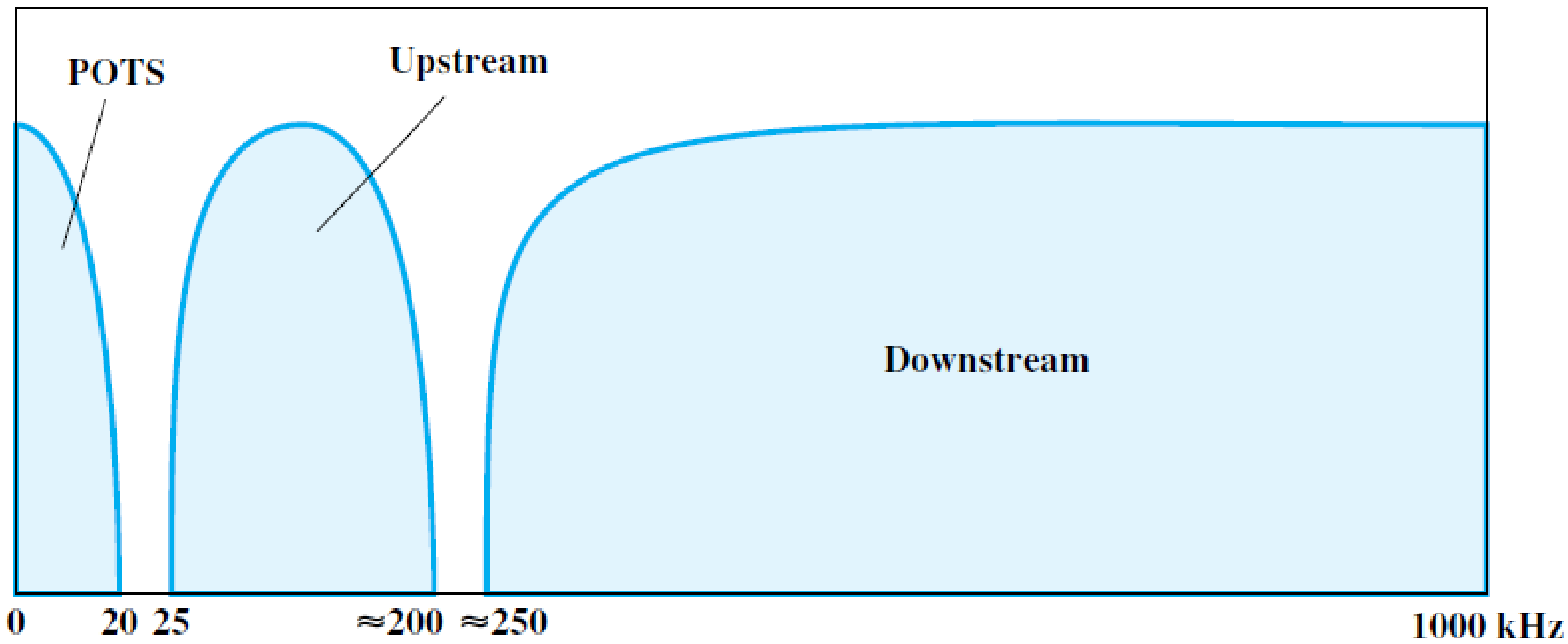
ADSL (ASYMMETRIC DIGITAL SUBSCRIBER LINE)

- Providing high-speed digital data transmission
- Over ordinary telephone wire
- Providing a range of up to 5.5 km
- Asymmetric
  - Providing more capacity downstream than upstream
    - Downstream: from the carrier's central office to the customer's site
    - Upstream: from customer to carrier

ADSL DESIGN

- Using FDM in a novel way to exploit the 1-MHz capacity of twisted pair
- Reserve lowest 25 kHz for voice
  - Known as POTS (plain old telephone service)
  - The voice is carried only in the 0 to 4 kHz band
  - The additional bandwidth to prevent crosstalk
- Use echo cancellation or FDM to allocate two bands
  - A smaller upstream band and a larger downstream band
- Use FDM within the upstream and downstream bands
  - A single bit stream is split into multiple parallel bit streams
  - Each portion is carried in a separate frequency band

ADSL SPECTRUM USING FDM



ECHO CANCELLATION

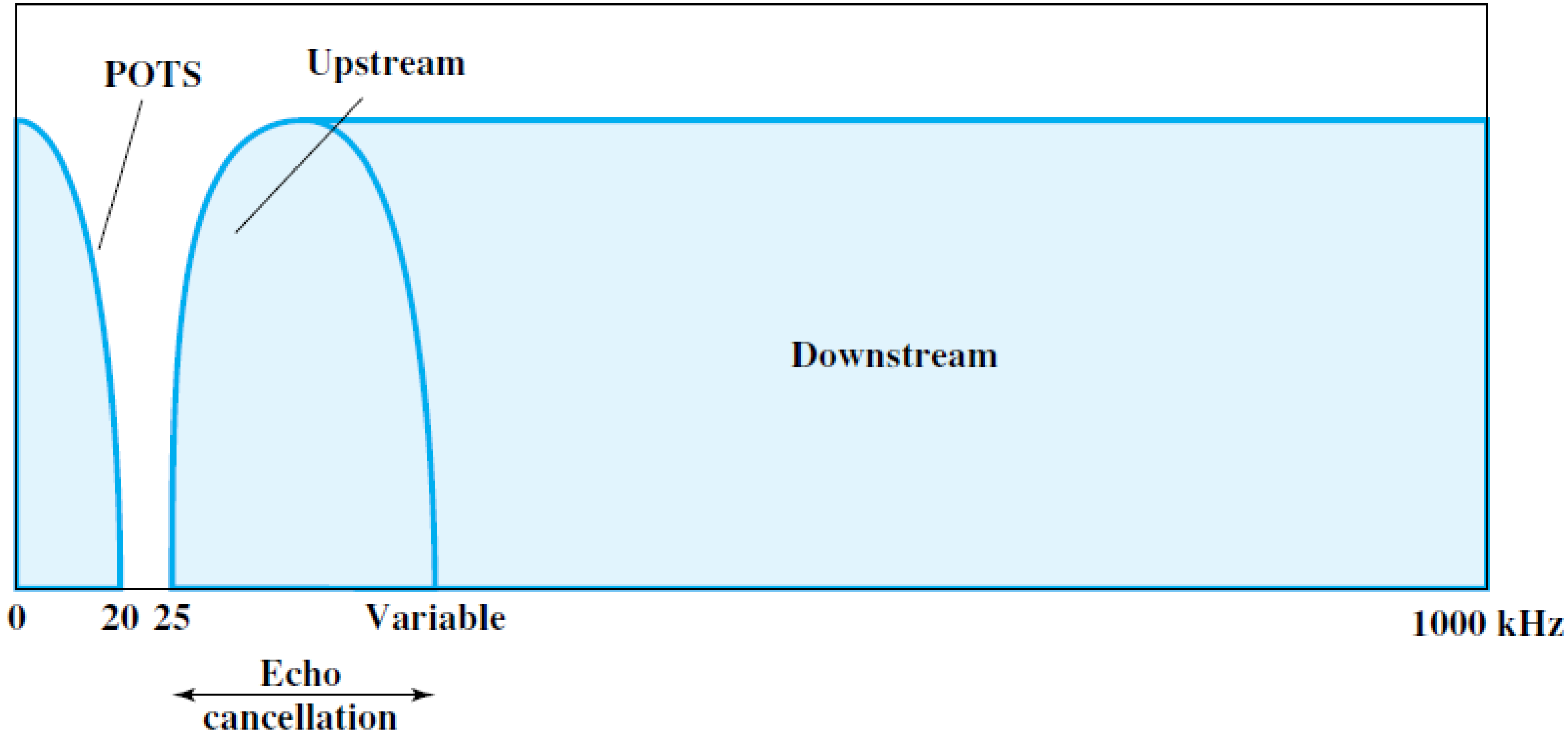
- A signal processing technique
  - Allowing transmission of digital signals in both directions on a single transmission line simultaneously
- A transmitter
  - Subtract the echo of its own transmission from the incoming signal
  - To recover the signal sent by the other side

ADSL USING ECHO CANCELLATION

- The entire frequency band for the upstream channel overlaps the lower portion of the downstream channel

- ✓ The higher the frequency, the greater the attenuation
  - More of the downstream bandwidth is in the “good” part of the spectrum
- ✓ More flexible for changing upstream capacity
  - The upstream channel can be extended upward without running into the downstream
  - Instead, the area of overlap is extended
- ✗ Need for echo cancellation logic on both ends of the line

ADSL SPECTRUM USING ECHO CANCELLATION

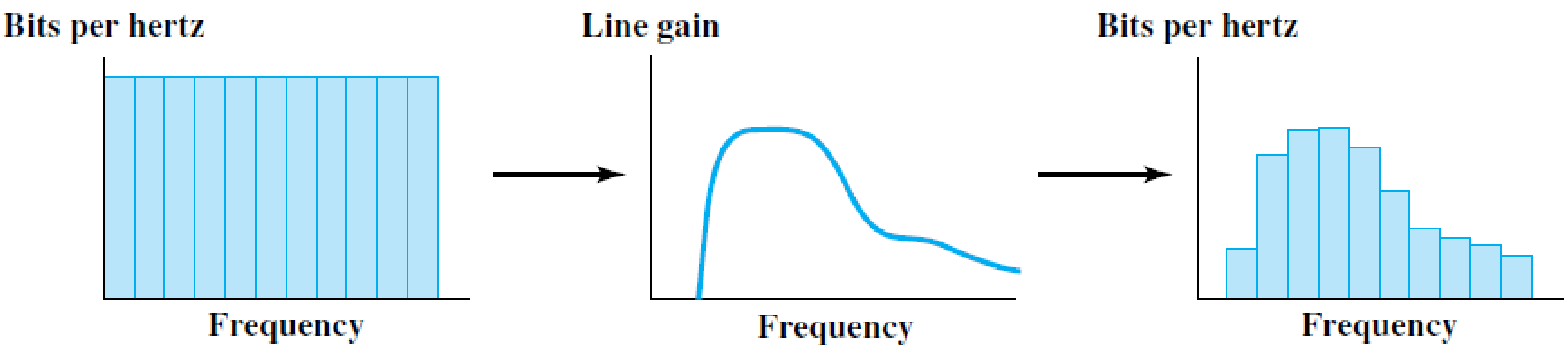


DISCRETE MULTITONE (DMT)

- Uses multiple carrier signals at different frequencies
- Sending some of the bits on each channel
- Available transmission band divided into 4-kHz subchannels
- Modem sends test signals on each subchannel to determine the SNR
- More bits to channels with better signal transmission qualities
- Less bits to channels with poorer signal transmission qualities

DMT BITS PER CHANNEL ALLOCATION

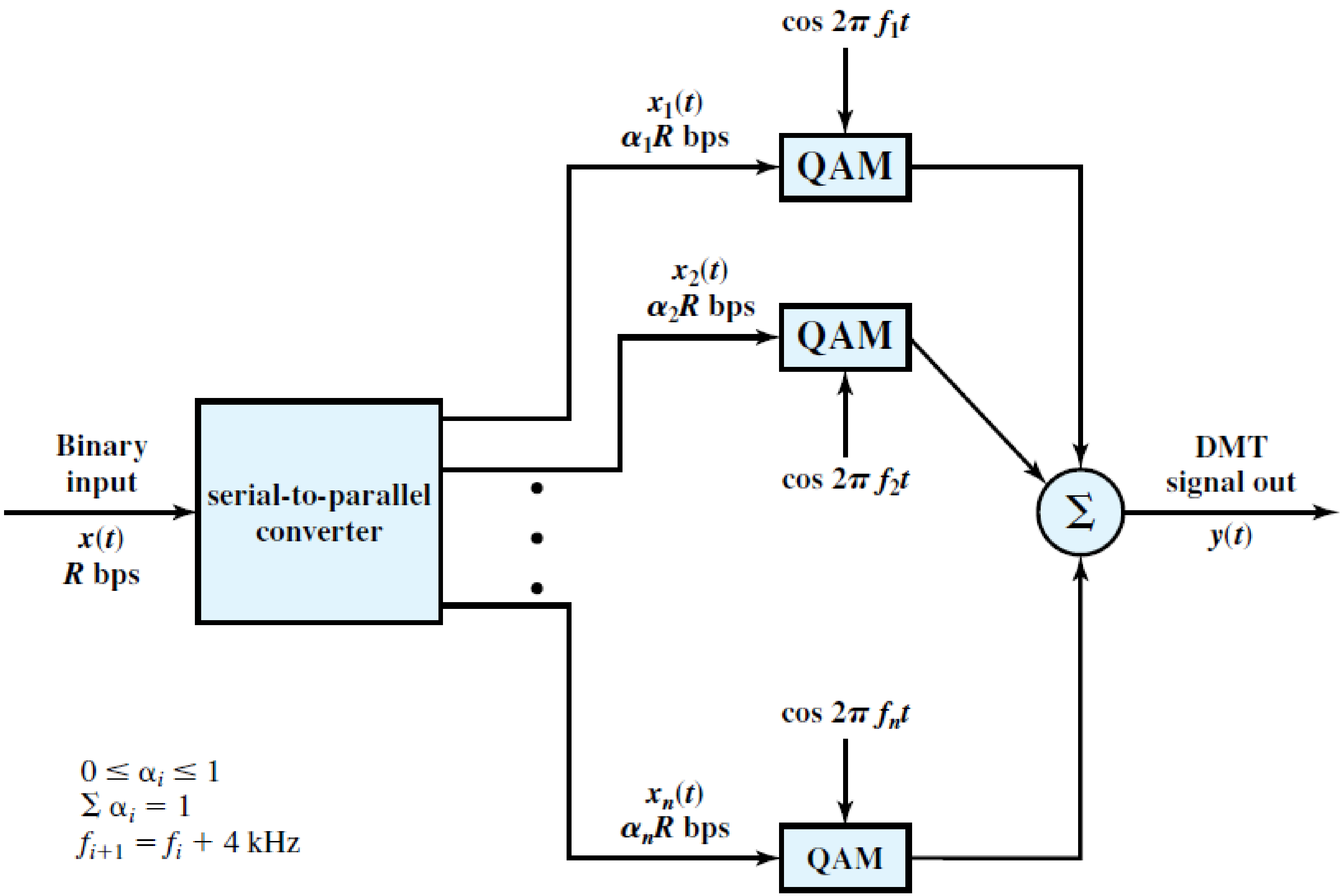
- A typical situation
  - At higher frequencies
    - Increasing attenuation
    - Decreasing signal-to-noise ratio
- The higher-frequency subchannels carry less of the load



DMT TRANSMISSION

- After initialization, the bit stream to be transmitted divided into a number of substreams
- One substream for each subchannel carrying data
- Each substream is then converted to an analog signal using quadrature amplitude modulation (QAM)
- QAM's can assign different numbers of bits per transmitted signal
- Each QAM signal occupies a distinct frequency band
- These signals can be combined by simple addition to produce the composite signal for transmission

DMT TRANSMITTER BLOCK DIAGRAM



ADSL/DMT DESIGNS

- Present ADSL/DMT designs employ 256 downstream subchannels
- In theory
  - Each 4-kHz subchannel carrying 60 kbps
  - Possible to transmit at a rate of 15.36 Mbps
- In practice
  - Transmission impairments prevent this data rate
  - Current implementations:1.5 to 9 Mbps
  - Depending on line distance and quality

xDSL

- Asymmetric Digital Subscriber Line (ADSL)
- High Data Rate Digital Subscriber Line (HDSL)
- Single Line Digital Subscriber Line (SDSL)
- Very High Data Rate Digital Subscriber Line (VDSL)

DIGITAL TRANSMISSION OF THE SUBSCRIBER LINE

	ADSL	HDSL	SDSL	VDSL
Data rate	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	$\geq$ 10 MHz
Bits/cycle	Varies	4	4	Varies

UTP = unshielded twisted pair