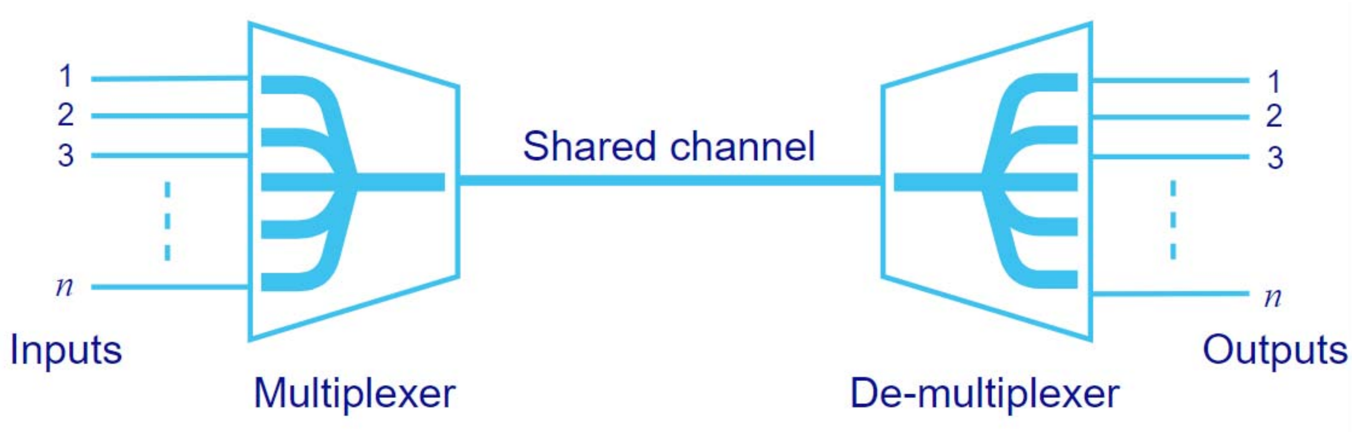
Multiplexing & Multiple-Access Techniques

References:

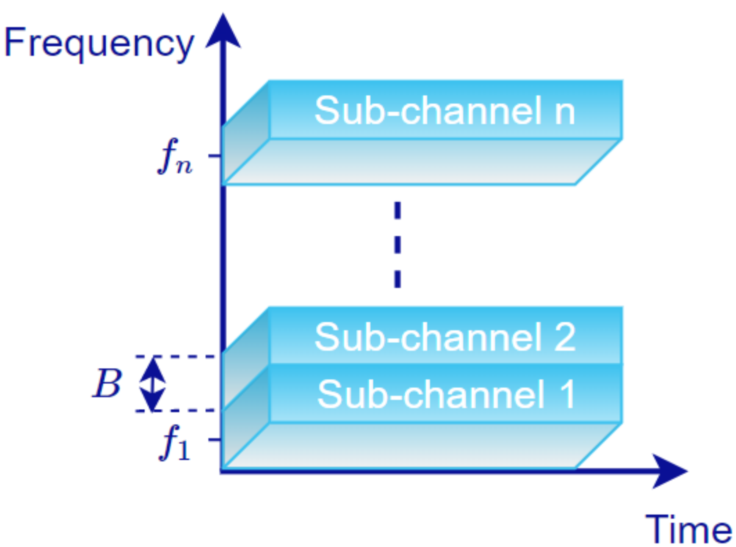
Chapters 8 &17 of William Stallings, *Data and Computer Communications*, 10th Edition, Pearson, 2014

Chapter 6 of James Kurose, Keith Ross, *Computer Networking: A Top-Down Approach*, 7th Edition, Pearson, 2017

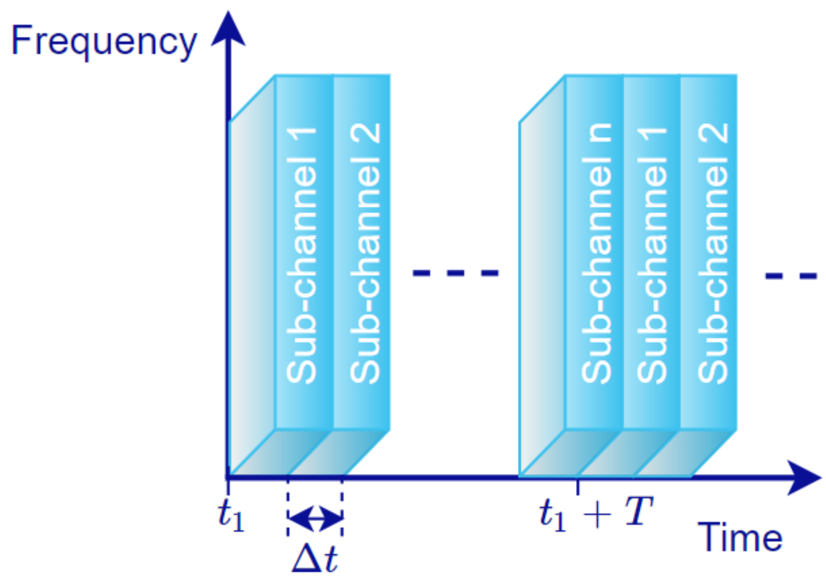
Multiplexing



Frequency Division Multiplexing (FDM)



Time Division Multiplexing (TDM)



Frequency-Division Multiplexing (FDM)

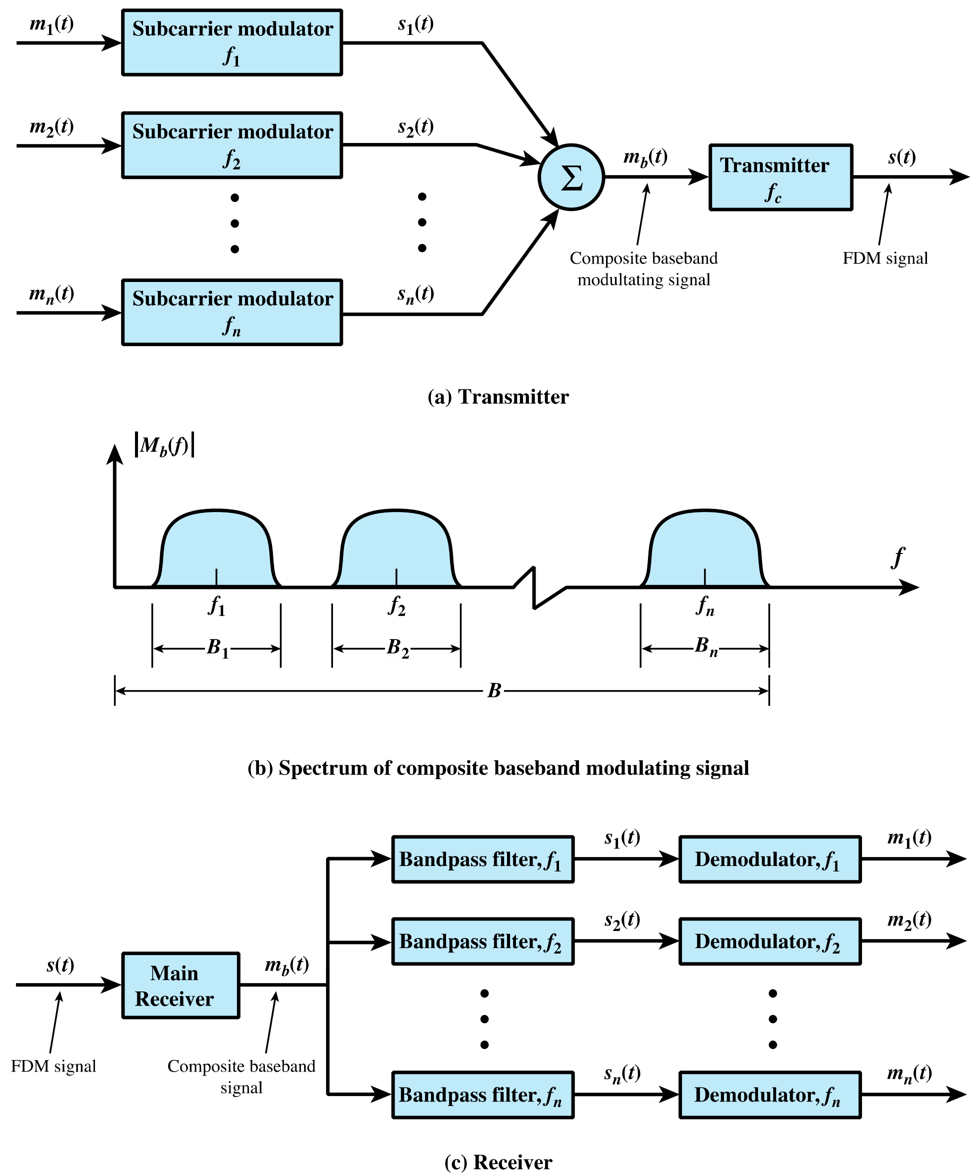


Figure 8.3 FDM System

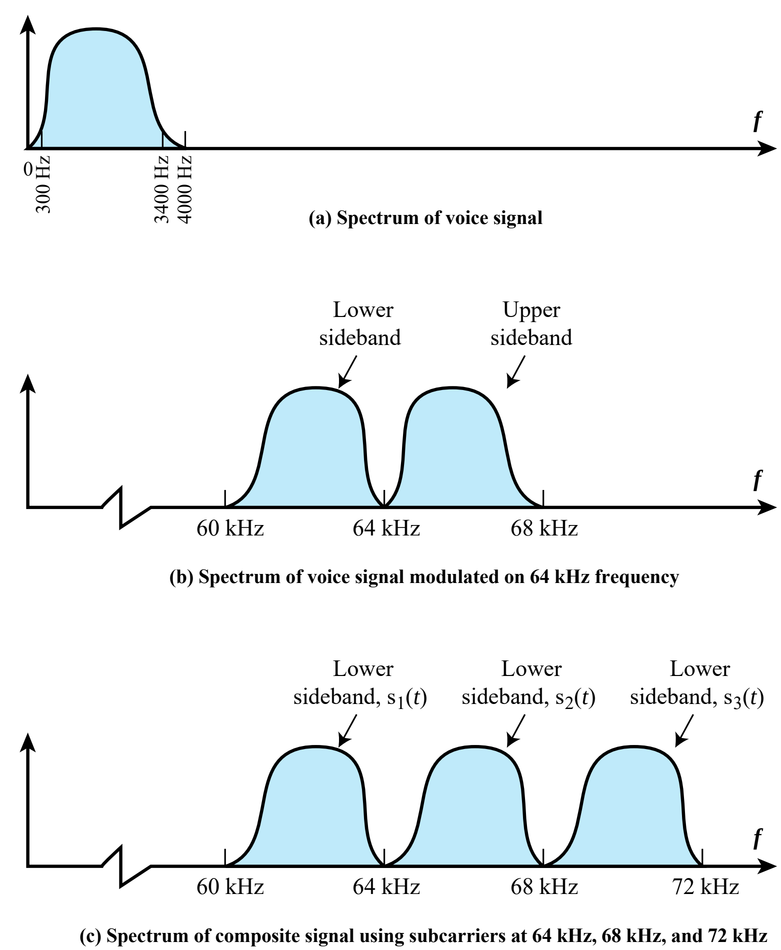


Figure 8.4 FDM of Three Voiceband Signals

Analog Carrier Systems

- Long-distance links use an FDM hierarchy
- AT&T (USA) and ITU-T (International) variants
- Original signal can be modulated many times

Group

- 12 voice channels (4kHz each) = 48kHz
- Range 60kHz to 108kHz

Supergroup

- FDM of 5 group signals supports 60 channels
- Carriers between 420kHz and 612 kHz

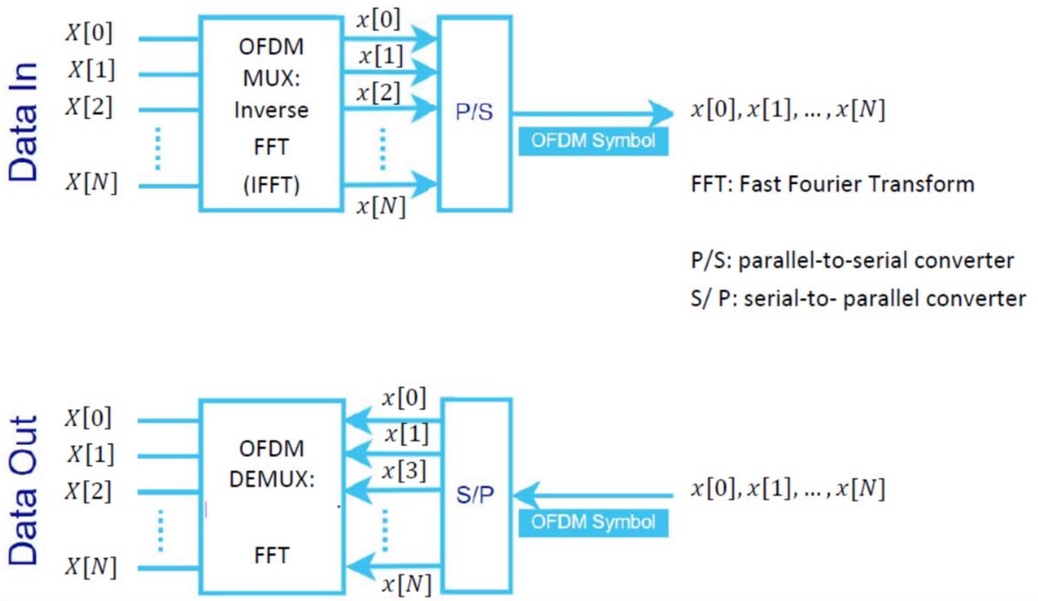
Mastergroup

- FDM of 10 supergroups supports 600 channels

North American and International FDM Carrier Standards (Table 8.1)

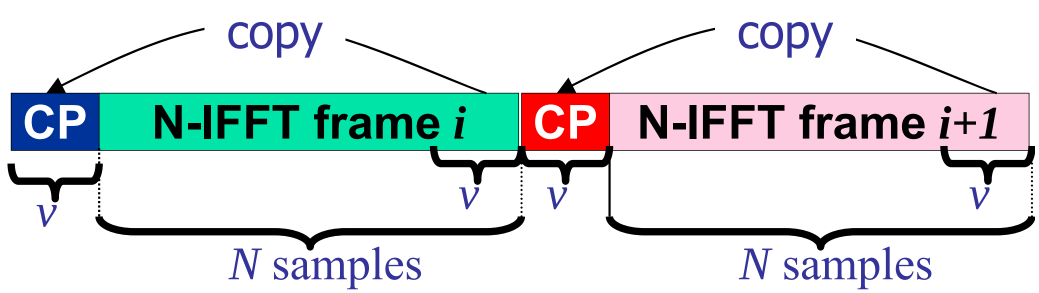
Number of Voice Channels	Bandwidth	Spectrum	AT&T	ITU-T
12	48 kHz	60–108 kHz	Group	Group
60	240 kHz	312–552 kHz	Supergroup	Supergroup
300	1.232 MHz	812–2044 kHz		Mastergroup
600	2.52 MHz	564–3084 kHz	Mastergroup	
900	3.872 MHz	8.516–12.388 MHz		Supermaster group
$N \times 600$			Mastergroup multiplex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

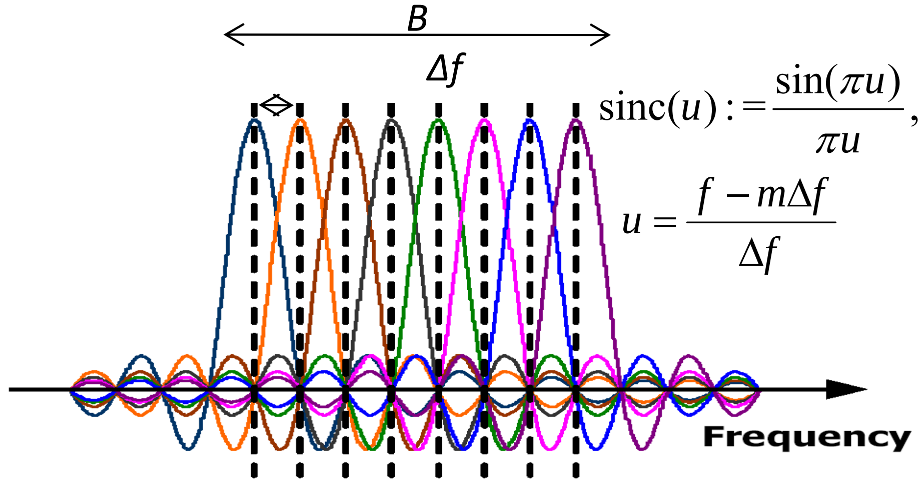
Orthogonal Frequency Division Multiplexing (OFDM)

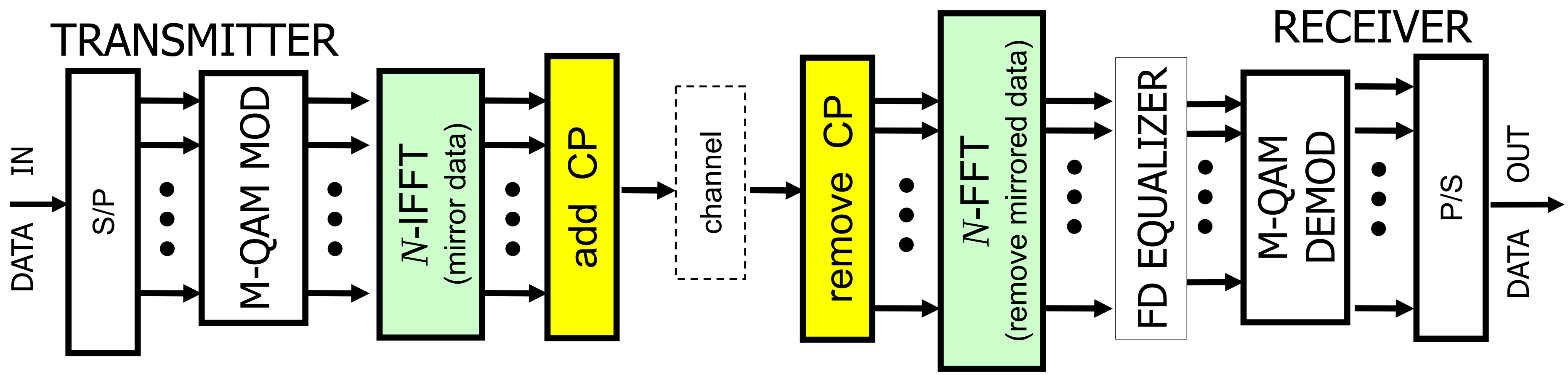


- signal separation in OFDM makes use of orthogonality rather than non-overlapping
- *symbol* rate of $1/T$ symbols/s where T is the symbol duration
- available frequency band is divided into N equally spaced sub-bands (or sub-channels)
- $f_k = f_0 + \frac{k}{T}, \;\; k = 0,1,2,\ldots,N-1,$
- $\varphi_k(t) = e^{j2\pi\frac{k}{T}t}, \Delta t = \frac{T}{N}, \sum_{n=0}^{N-1} \varphi_k[n]\varphi_{k'}^*[n] = \sum_{n=0}^{N-1} e^{-j2\pi\frac{(k-k')}{N}n} = \begin{cases} 0, k \neq k' \\ N, k = k' \end{cases}$
- $X[k]=\frac{1}{N}\sum_{n=0}^{N-1} x[n]e^{-jk\frac{2\pi}{N}} \quad \overset{\text{DFT}}{\longleftrightarrow} \quad x[n]=\sum_{n=0}^{N-1} X[k]e^{j\frac{2\pi}{N}kn}$

Orthogonal Frequency Division Multiplexing (OFDM):

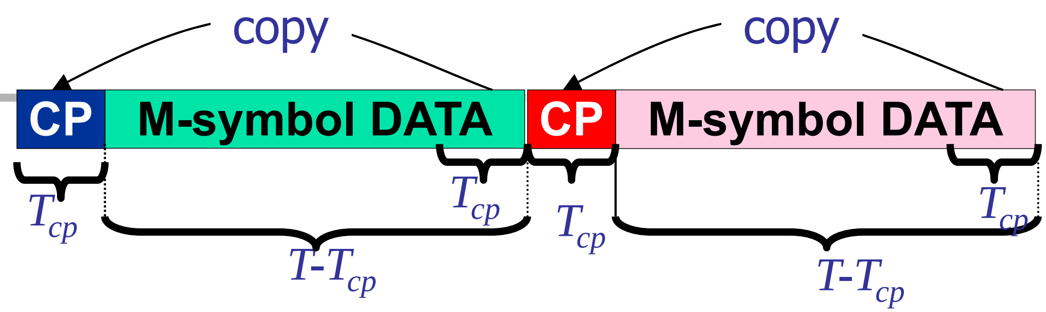






- Break data stream into lower-rate substreams modulated onto N narrowband (Δf) sub-channels with symbol time-interval T_s and required total bandwidth B
- Substreams must be separable in receiver
  $\rightarrow$ subcarrier orthogonality must be preserved
- Non-overlapped sub-channels: $\Delta f \geq (1+\varepsilon)/T_s \rightarrow B \geq N(1+\varepsilon)/T_s$
- OFDM with overlapped sub-channels: $\Delta f = 1/T_s \rightarrow B = N/T_s$
- OFDM implementation based on efficient IFFT (Tx)/ FFT (Rx)

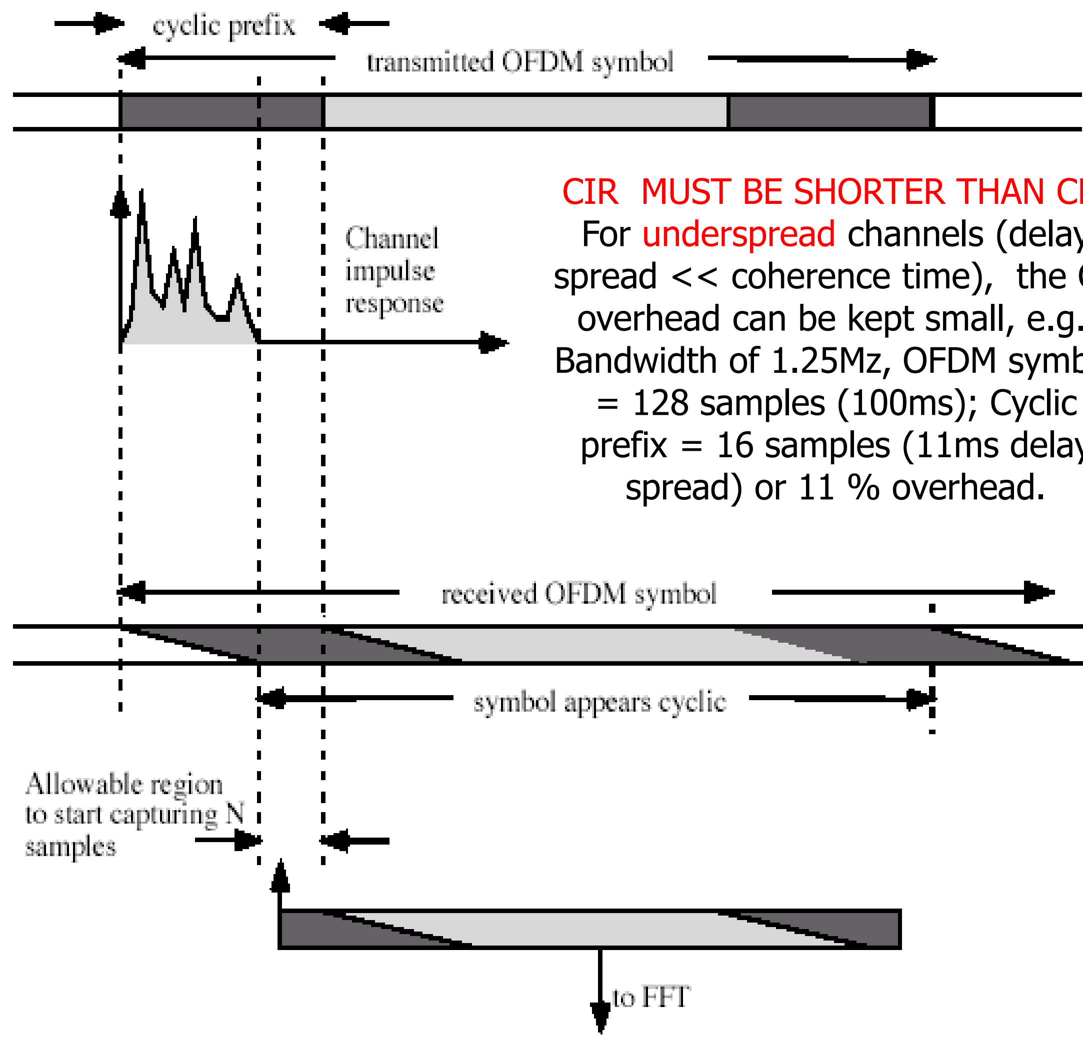
CP to remove ISI & ICI



- Selection of CP length must consider delay spread:

  channel impulse response (CIR) length< CP length
- CP avoids ISI because it acts as a guard space between successive OFDM symbols
- CP avoids ICI by converting the *linear* convolution with the CIR into a *cyclic* (or *circular*) convolution.
- a *cyclic* convolution in the time domain translates into a *scalar* multiplication in the frequency domain:

  → the subcarriers remain orthogonal and there is no ICI.



CIR MUST BE SHORTER THAN CP: For underspread channels (delay spread << coherence time), the CP overhead can be kept small, e.g., Bandwidth of 1.25Mz, OFDM symbol = 128 samples (100ms); Cyclic prefix = 16 samples (11ms delay spread) or 11 % overhead.

Asymmetrical Digital Subscriber Line (ADSL) & Discrete Multitone (DMT)

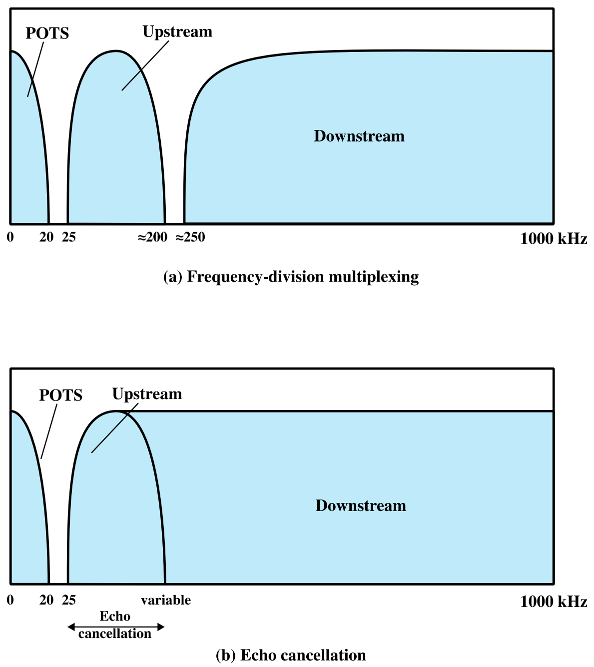


Figure 8.14 ADSL Channel Configuration

- 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
- Multiple carrier signals at different frequencies
- Divide into 4kHz subchannels
- Test and use subchannels with better SNR
- 256 downstream subchannels at 4kHz (60kbps): in practice 1.5-9Mbps

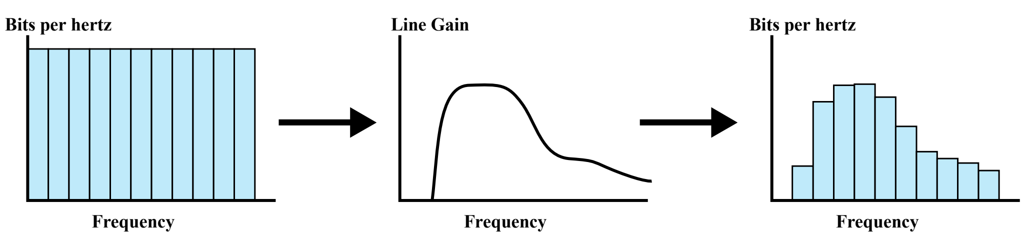


Figure 8.15 DMT Bits per Channel Allocation

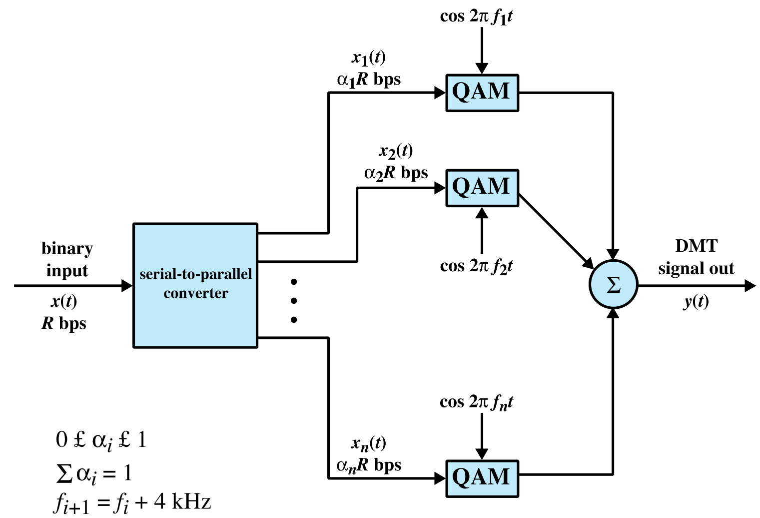
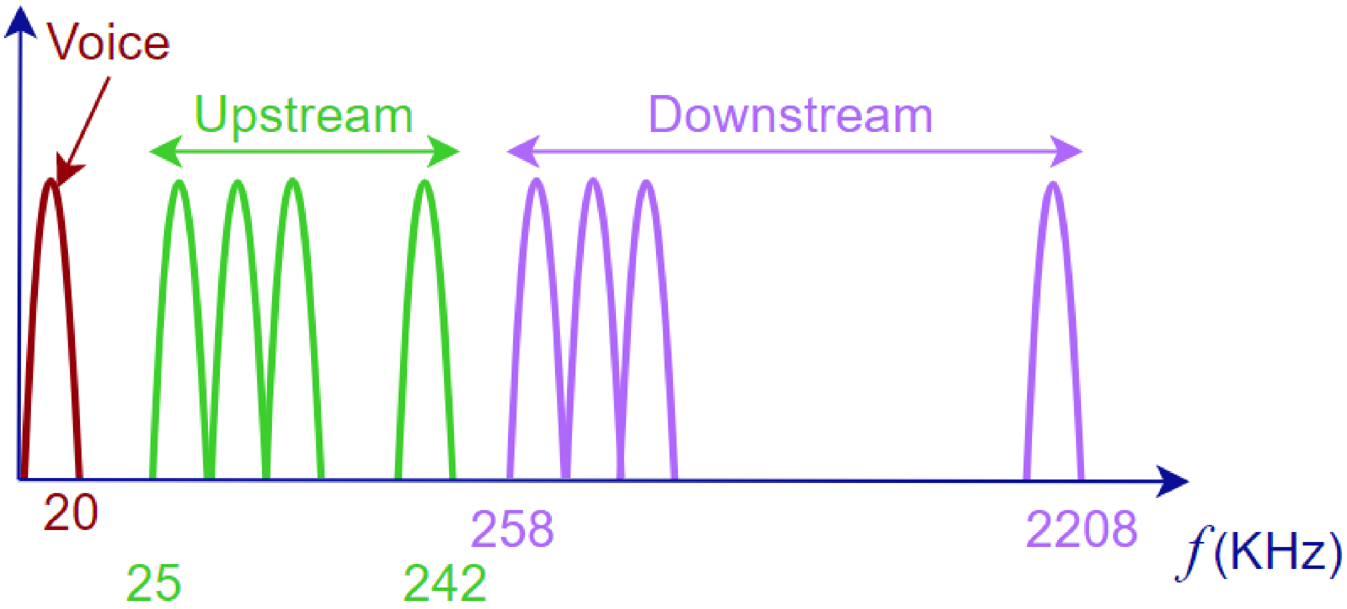
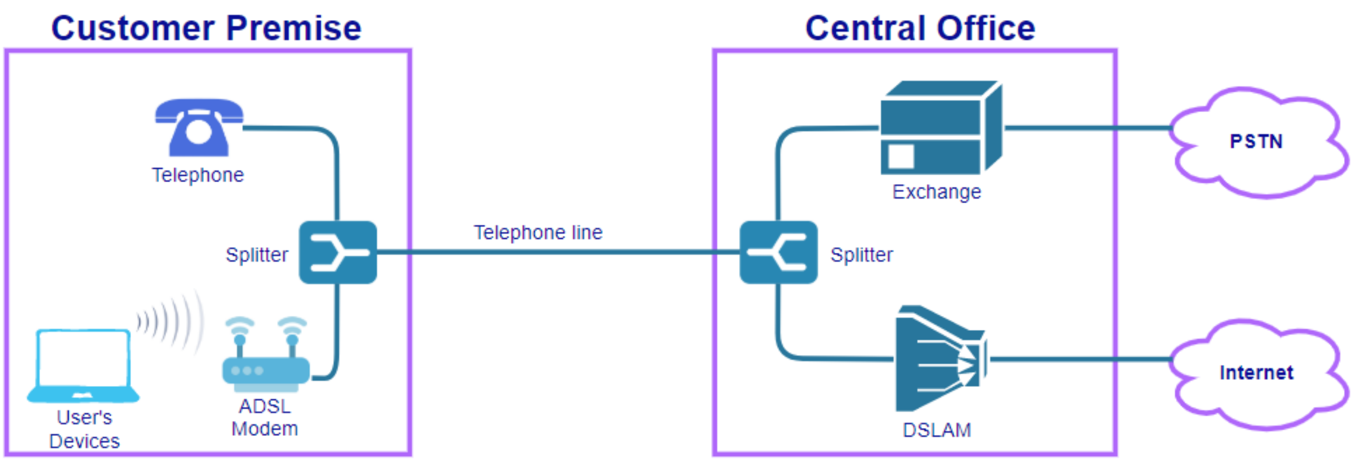


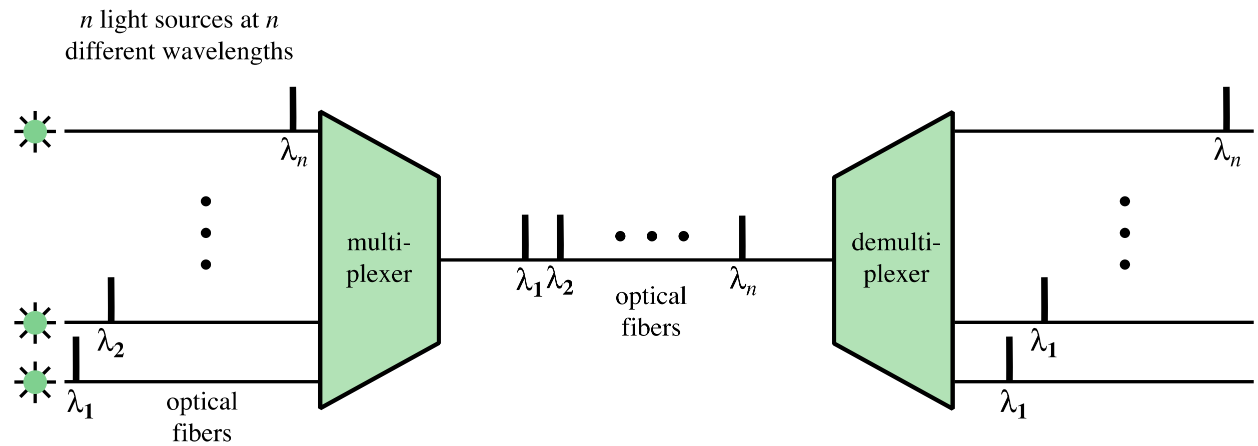
Figure 8.16 DMT Transmitter

ADSL 2+ Annex M frequency band division





Wavelength Division Multiplexing (WDM)



Multiple beams of light at different frequencies

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
- Demultiplexer separates channels at destination

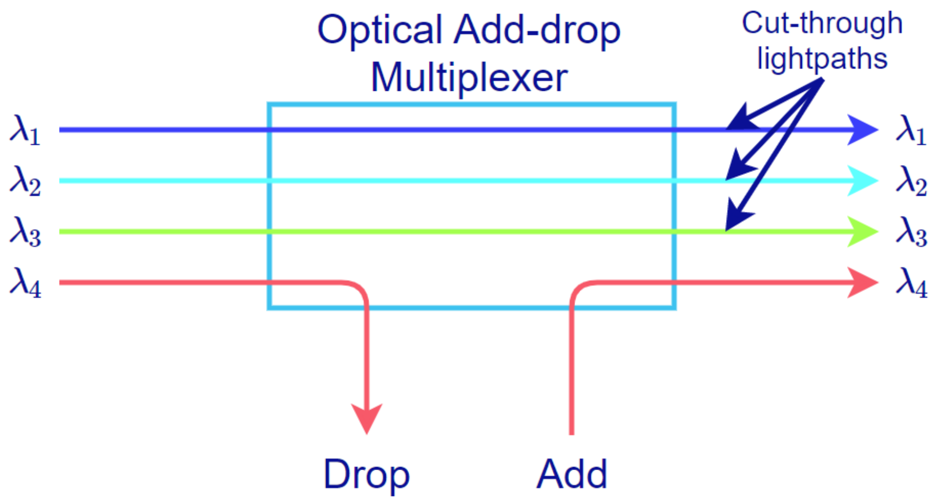
Dense Wavelength Division Multiplexing (DWDM)

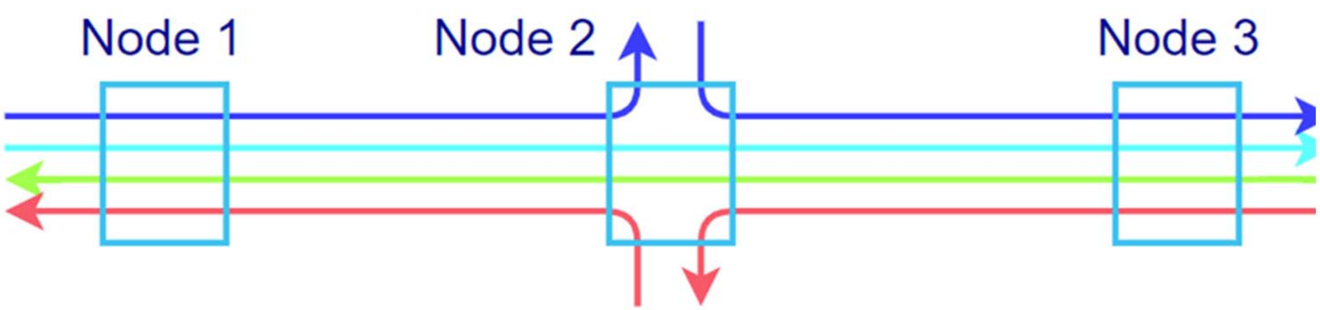
- Use of more channels more closely spaced

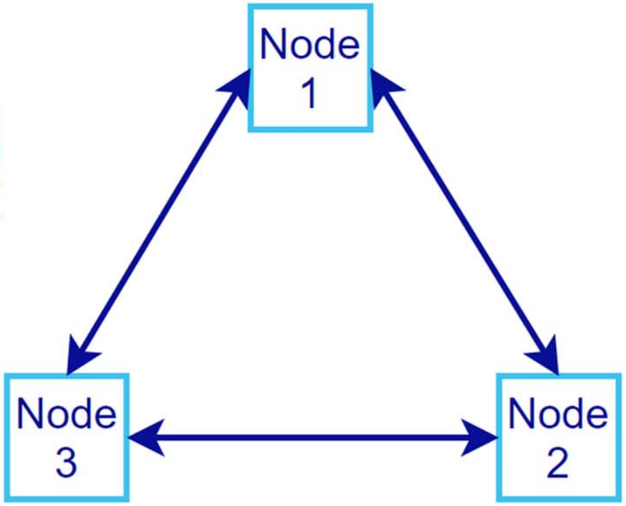
Frequency (THz)	Wavelength in Vacuum (nm)	50 GHz	100 GHz	200 GHz
196.10	1528.77	X	X	X
196.05	1529.16	X		
196.00	1529.55	X	X	
195.95	1529.94	X		
195.90	1530.33	X	X	X
195.85	1530.72	X		
195.80	1531,12	X	X	
195.75	1531.51	X		
195.70	1531.90	X	X	X
195.65	1532.29	X		
195.60	1532.68	X	X	
…	…			
192.10	1560.61	X	X	X

ITU WDM Channel Spacing (G.692)

optical add-drop multiplexer







Time-Division Multiplexing (TDM)

- No headers and trailers

FRAMING:

- No flag or SYNC characters bracketing TDM frames
- Must still provide synchronizing mechanism between source and destination clocks
- 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 can carry on
- Error control
  - Errors detected and handled on individual channel

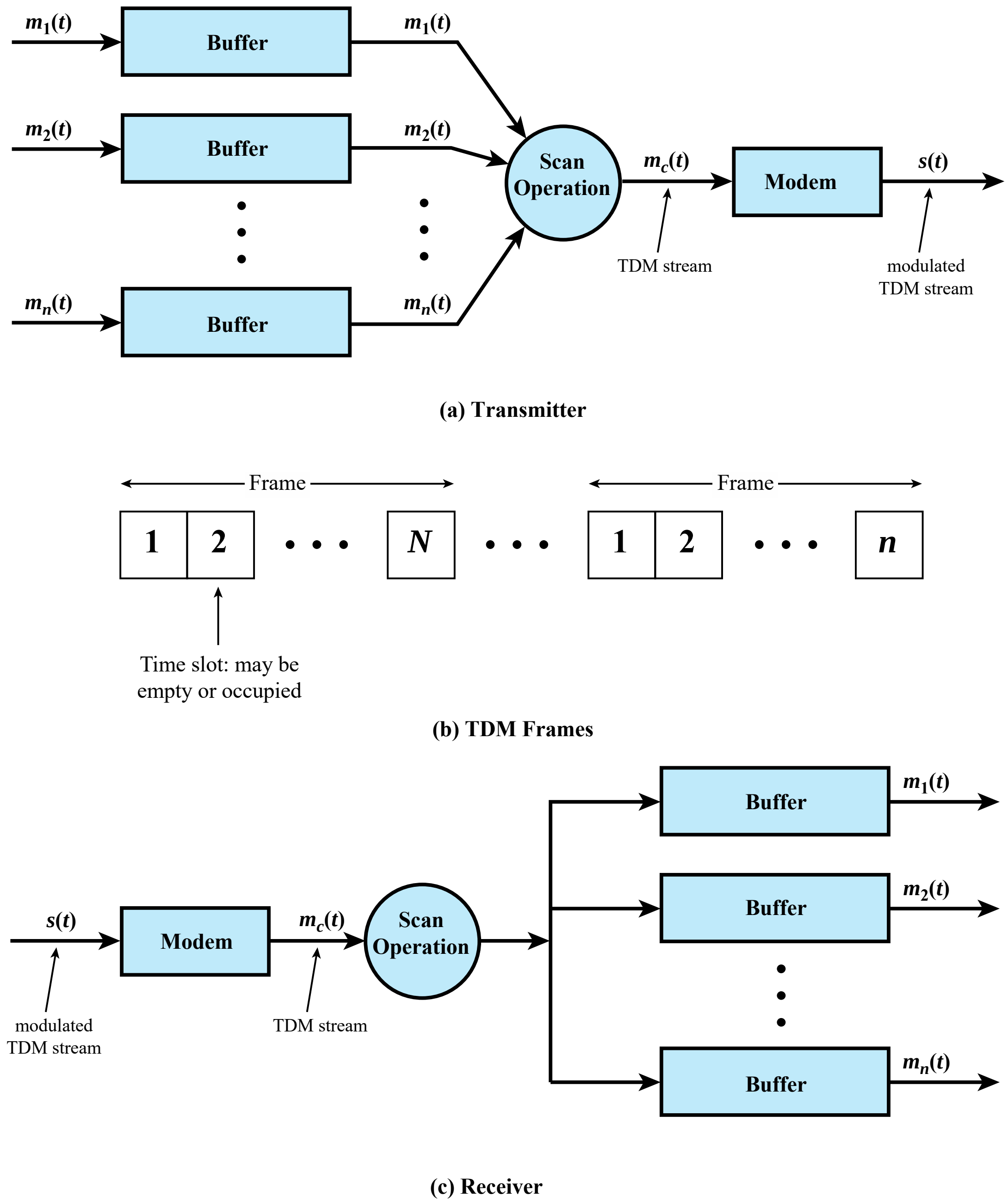


Figure 8.6 Synchronous TDM System

synchronization

Pulse Stuffing is 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

- Problem of synchronizing various data sources
- Variation among clocks could cause loss of synchronization
- Issue of data rates from different sources not related by a simple rational number

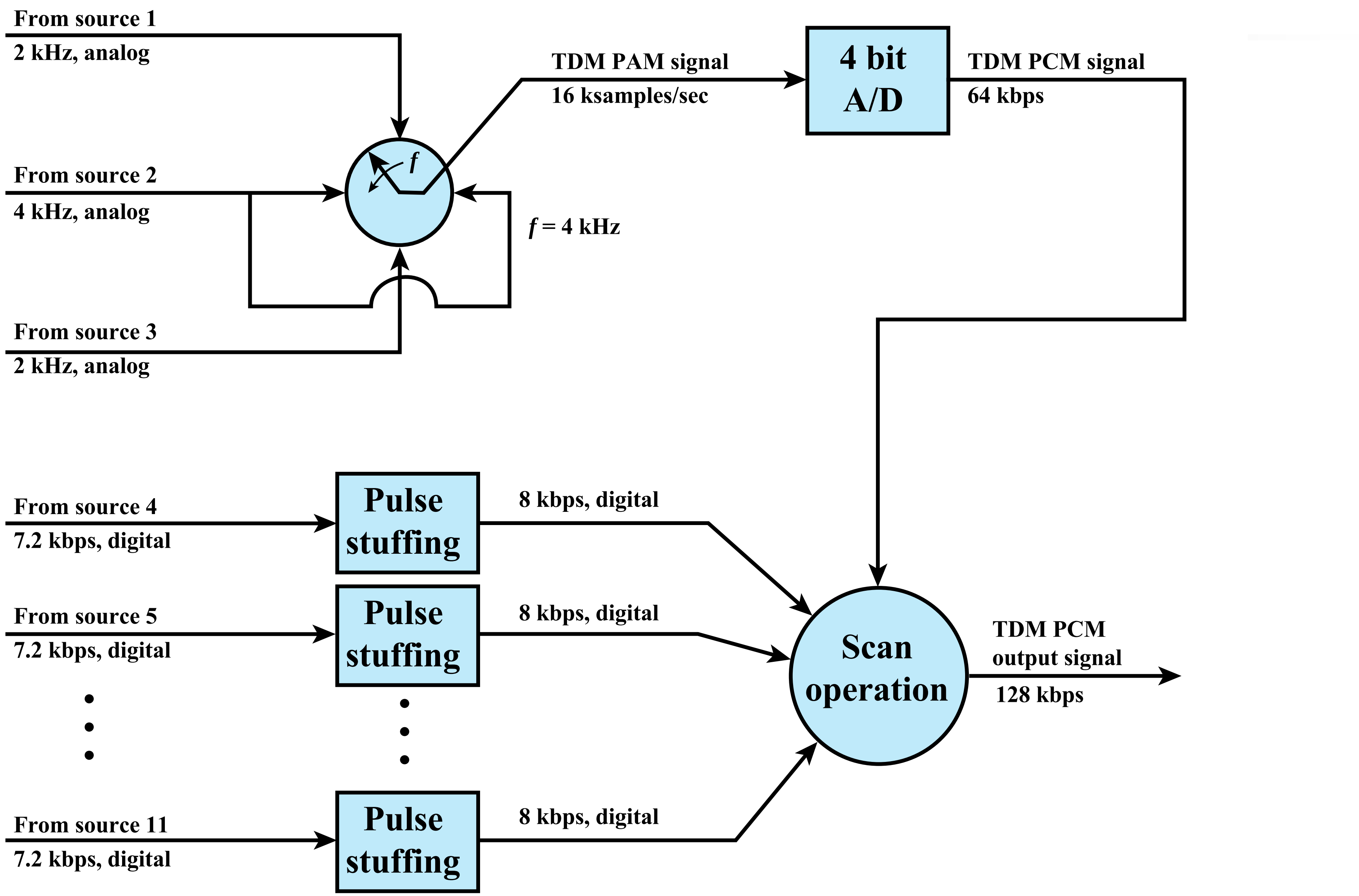
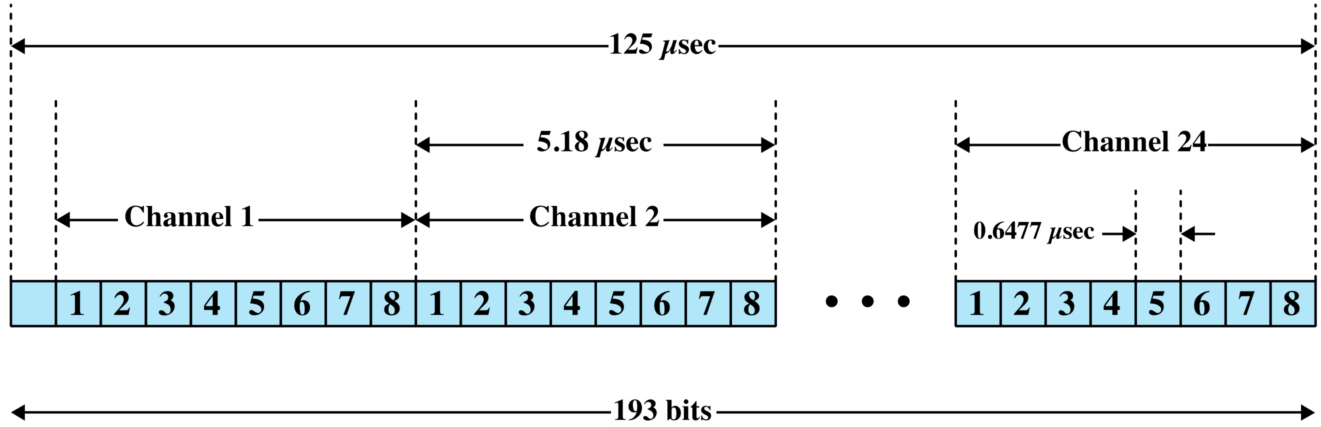


Figure 8.8 TDM of Analog and Digital Sources

North American and International TDM Carrier Standards

North American		
Designation	**Number of Voice Channels**	**Data Rate (Mbps)**
DS-1	24	1.544
DS-1C	48	3.152
DS-2	96	6.312
DS-3	672	44.736
DS-4	4032	274.176

International (ITU-T)		
Level	**Number of Voice Channels**	**Data Rate (Mbps)**
1	30	2.048
2	120	8.448
3	480	34.368
4	1920	139.264
5	7680	565.148



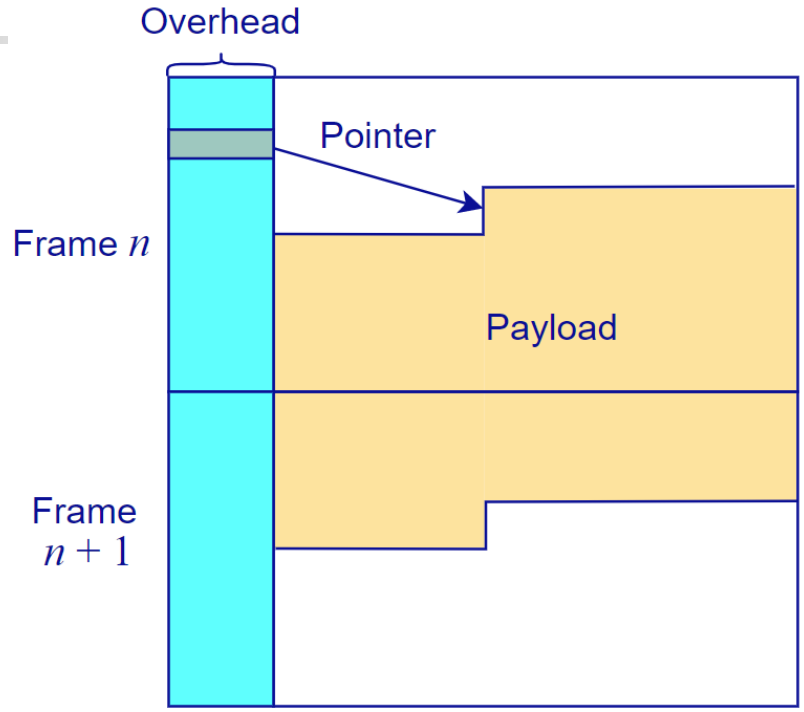
Notes:

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

SONET/SDH

- Synchronous Optical Network (ANSI)
- Synchronous Digital Hierarchy (ITU-T)
- High speed capability of optical fiber
- Defines 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 (e.g., 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-12/OC-12	STM-4	622.08 Mbps	601.344 Mbps
STS-48/OC-48	STM-16	2.48832 Gbps	2.405376 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

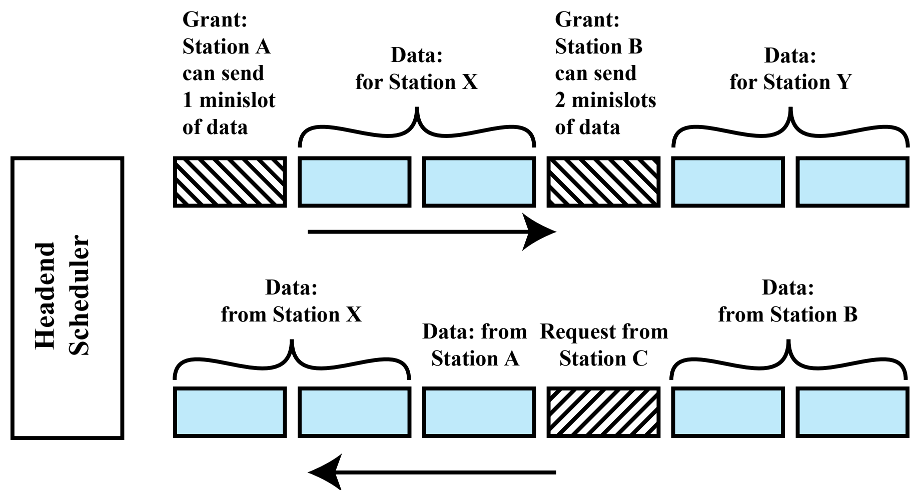
Cable Modems

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



- Dedicate two cable TV channels to data transfer
- Each channel shared by number of subscribers using statistical TDM

- 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

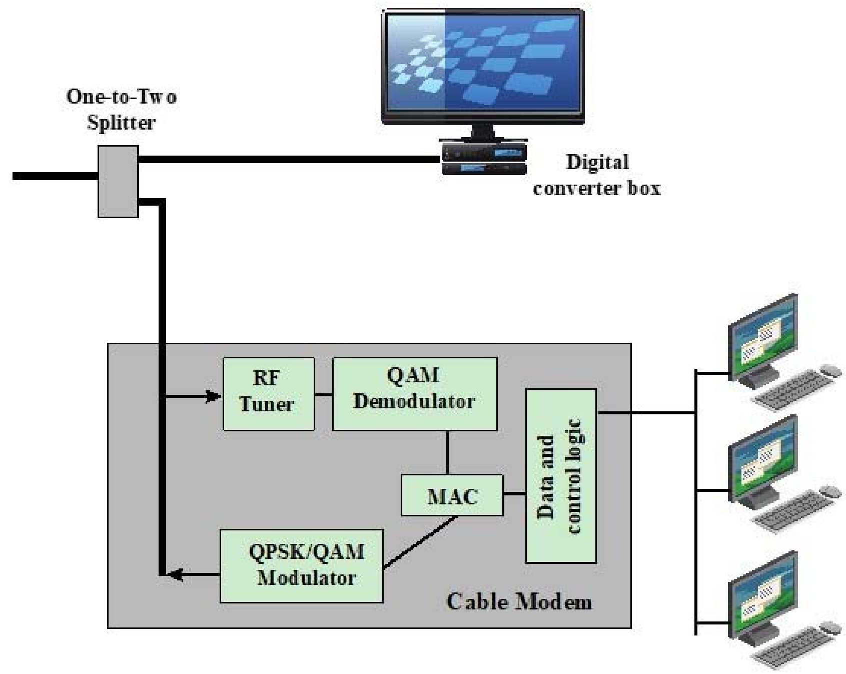
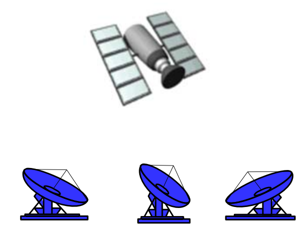


Figure 8.13 Cable Modem Configuration

Multiple access in shared medium

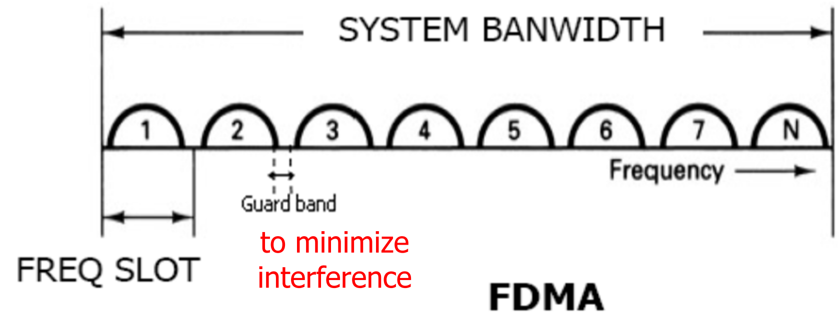
- *Multiple access* (or *channel access*) refers to a scheme to allow multiple communications devices connected to the same medium (or channel) for transmission and resource sharing. A multiple-access (MA) scheme consists of two mechanisms: *channelization* and *access control*.
- *Channelization* refers to the way to share the available communications resources of the common transmission medium. The available communications resources are essentially divided into multiple sub-channels to be accessed by multiple communications devices. In this context, *channelization* has a similar concept as multiplexing and is provided by the physical layer.



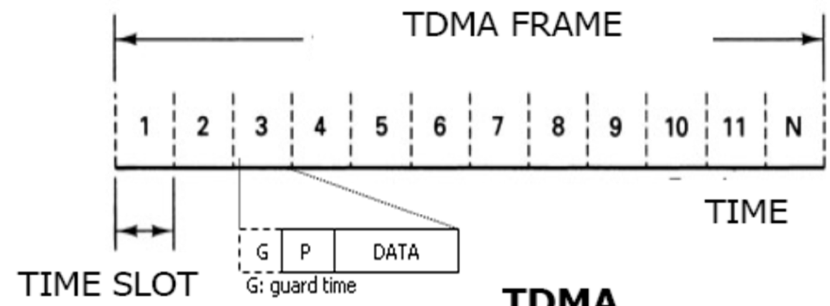
- *Access control* refers to *how* a communications device (or user) can access a sub-channel, including various issues such as addressing, sub-channel assignment and related resolution protocols. In this context, it is also known as medium access control (MAC), which is a sub-layer in the data link layer of the OSI model and a component of the link layer of the TCP/IP model.

Channelization & Multiple Access schemes

Frequency Division Multiple Access (FDMA): Divide the bandwidth of the communication medium into N **non-overlapping frequency slots** and assign a slot to each user upon request.

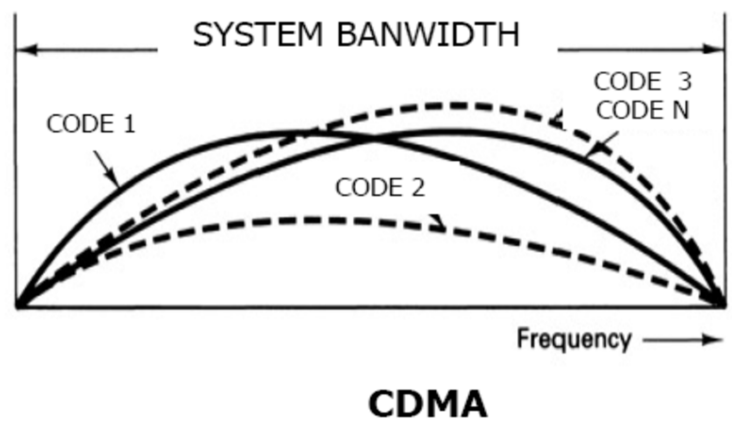


Time Division Multiple Access (TDMA): Use the entire bandwidth of the communication medium and establish a time frame T_f. Divide this time frame into N **non-overlapping time slots**, each of duration T_f/N. Assign a time-slot to each user upon request.

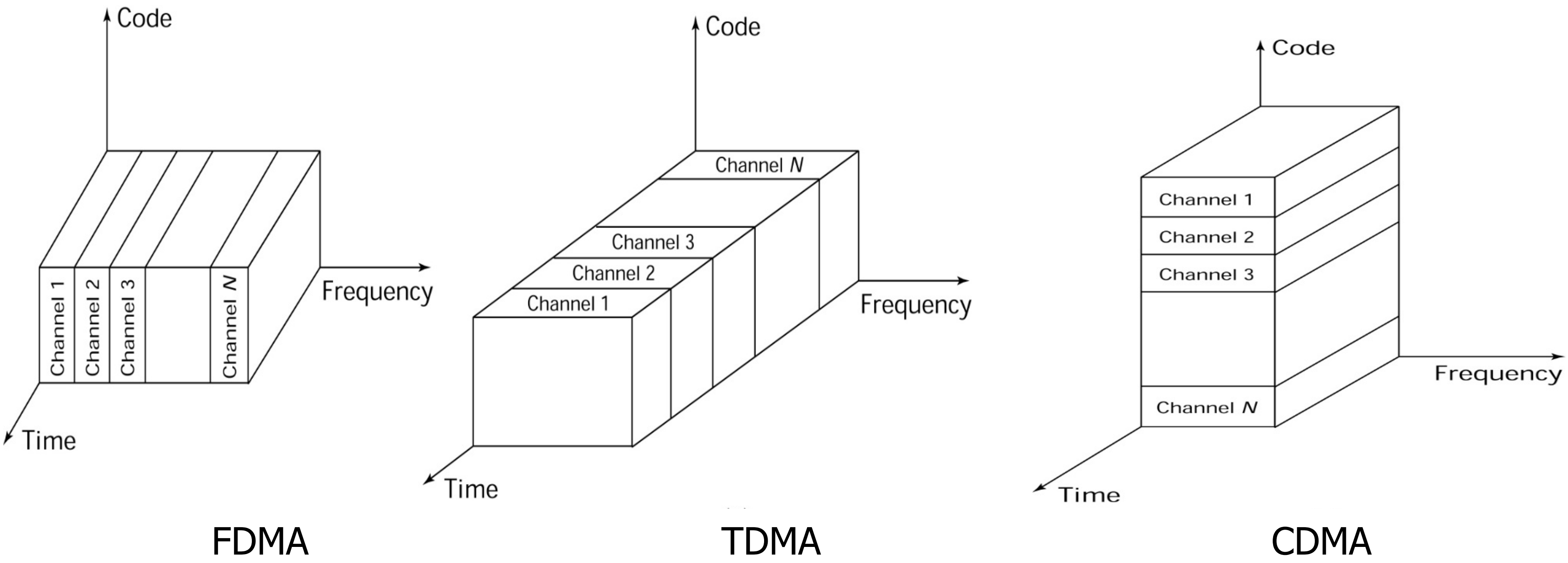


G: guard time to account for lack of perfect synchronization among the subscriber station

Code Division Multiple Access (CDMA): (also called SSMA) Allow users to share the entire bandwidth simultaneously by use of spread-spectrum codes. Signals from various users are separated at the receiver by cross-correlation of the received signal with each of the possible user codes. By designing the code sequences to have relatively small cross-correlations, the crosstalk inherent in the demodulation of the signals received from multiple transmitters is minimized.



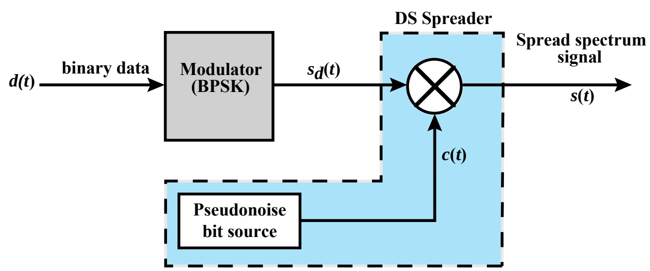
Channelization & Multiple Access schemes



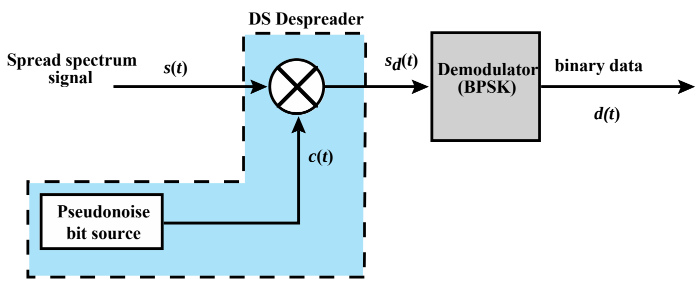
Spread Spectrum SSMA:

- Form of encoding for wireless communications
- Can be used to transmit either analog or digital data, using an analog signal
- Was initially developed for military and intelligence requirements
- Essential idea is to spread the information signal over a wider bandwidth to make jamming and interception more difficult
  - Frequency hopping
  - Direct sequence

Spread Spectrum (SS)



(a) Transmitter



(b) Receiver

Figure 17.10 Direct Sequence Spread Spectrum System

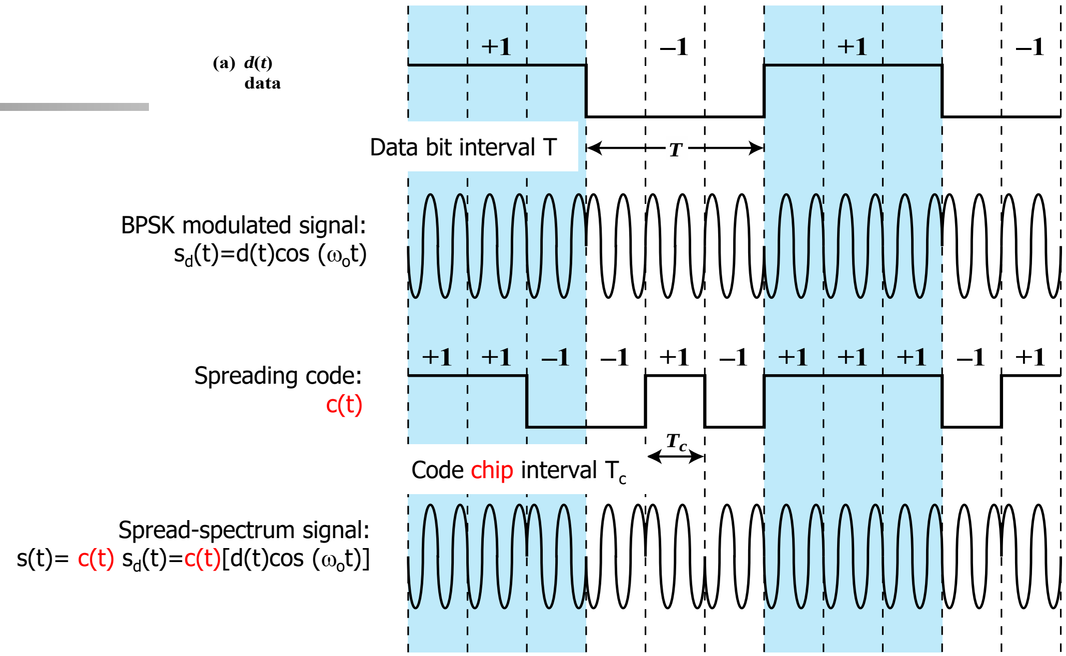
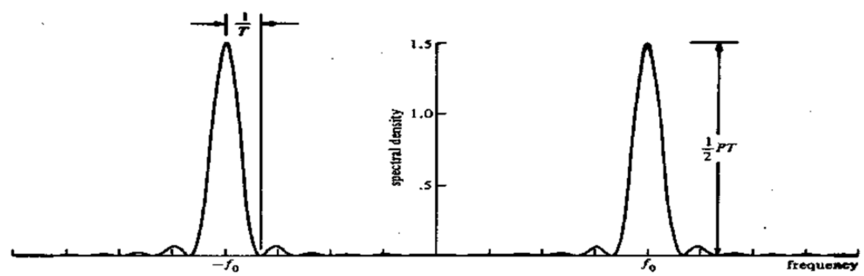
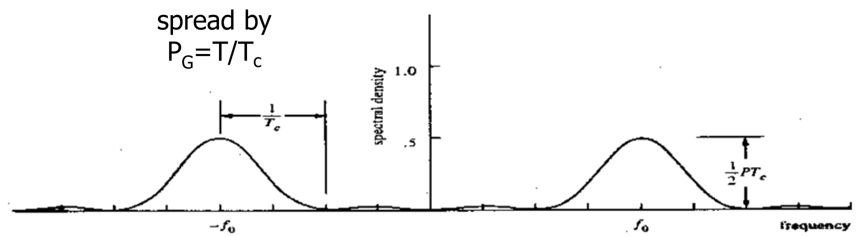


Figure 17.11 Example of Direct-Sequence Spread Spectrum Using BPSK



Spectrum (power spectral density) of BPSK modulated signal $s_d(t)$

Bandwidth is spread by $P_G=T/T_c$



Spectrum (power spectral density) of direct-sequence spread-spectrum signal s(t)

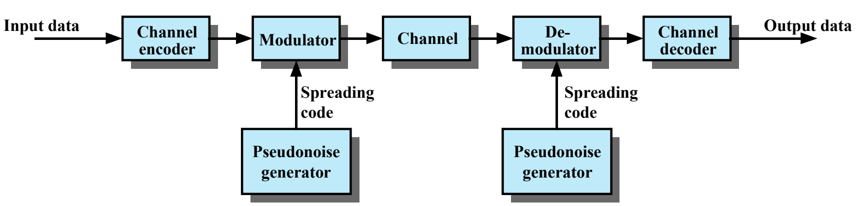
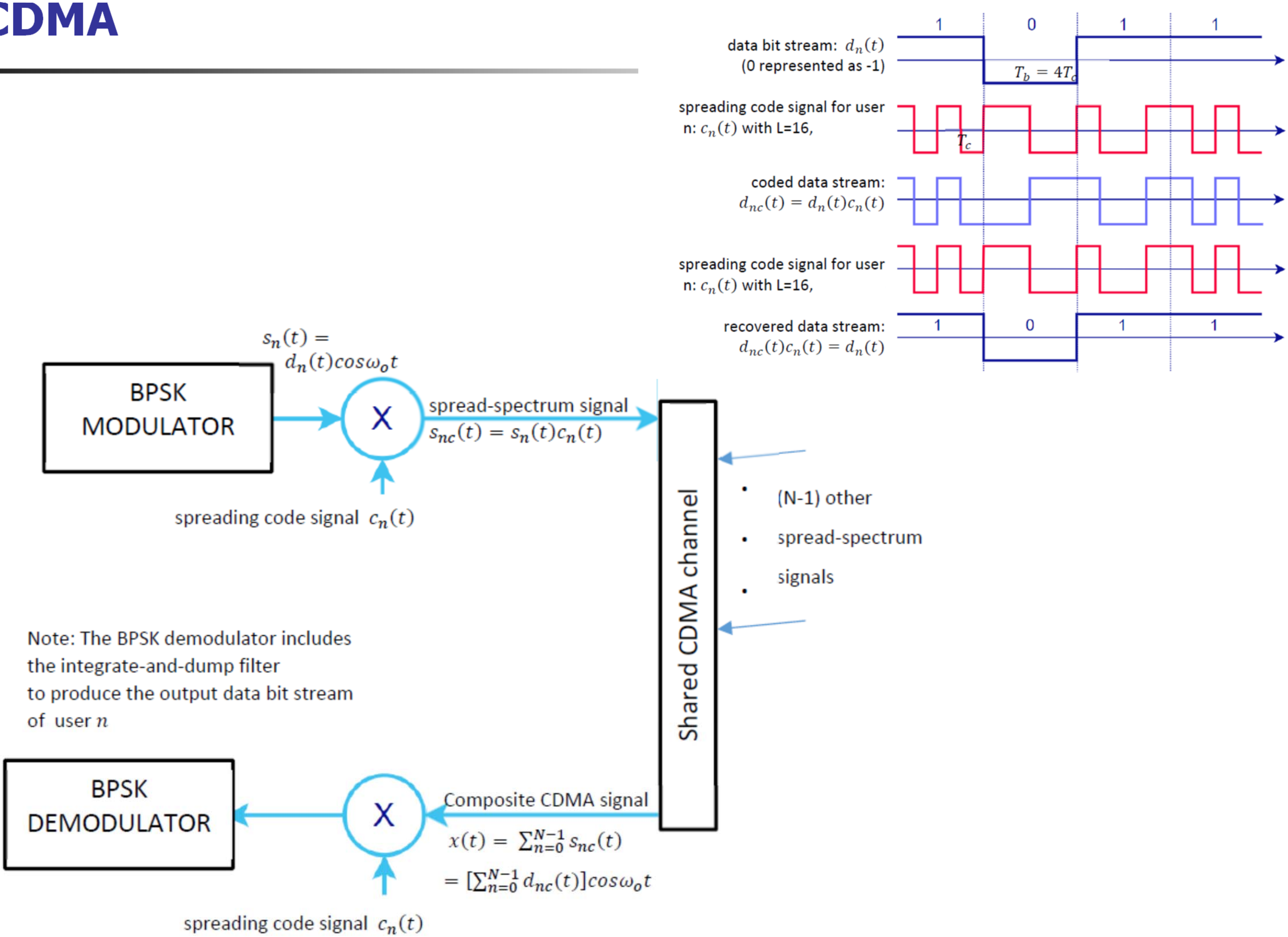


Figure 17.8 General Model of Spread Spectrum Digital Communication System

CDMA



data bit stream: $d_n(t)$
(0 represented as -1)
1
0
1
1
$T_b = 4T_c$
spreading code signal for user n: $c_n(t)$ with L=16,
T_c
coded data stream:
$d_{nc}(t) = d_n(t)c_n(t)$
spreading code signal for user n: $c_n(t)$ with L=16,
recovered data stream:
$d_{nc}(t)c_n(t) = d_n(t)$
1
0
1
1
$s_n(t) = d_n(t)cos\omega_o t$
BPSK MODULATOR
X
spread-spectrum signal
$s_{nc}(t) = s_n(t)c_n(t)$
spreading code signal $c_n(t)$
Shared CDMA channel
(N-1) other
spread-spectrum
signals
Note: The BPSK demodulator includes
the integrate-and-dump filter
to produce the output data bit stream
of user n
BPSK DEMODULATOR
X
Composite CDMA signal
$x(t) = \sum_{n=0}^{N-1} s_{nc}(t)$
$= [\sum_{n=0}^{N-1} d_{nc}(t)]cos\omega_o t$
spreading code signal $c_n(t)$

Recovering data from CDMA signal

- the spreading code $\boldsymbol{c}_n = [c_{n,L-1}, c_{n,L-2}, \dots, c_{n,1}, c_{n,0}]$, $c_{n,i} \in \{+1, -1\}$ is an element of a set of N *orthogonal* codes, i.e., for any $n, n' = 0,1,2, \dots, N-1$,

$$\sum_{i=0}^{L-1} c_{n,i} c_{n',i} = \begin{cases} 0, n \neq n' \\ N, n = n' \end{cases} = N\delta(n - n') \,.$$

- $T_b = LT_c$, and a *synchronous* system such that
- the composite signal in the shared channel is the sum of N coded signals and can be represented as

$$x(t) = \sum_{n=0}^{N-1} s_{nc}(t) = \left[\sum_{n=0}^{N-1} d_{nc}(t)\right] cos\omega_o t \text{ where}$$

- the composite data stream is

$$d_x(t) = \sum_{n=0}^{N-1} d_{nc}(t) = \sum_{k=-\infty}^{+\infty} \sum_{n=0}^{N-1} b_{n,k} \sum_{l=0}^{L-1} c_{n,l} r'(t - kT_b - lT_c).$$

- in the k^{th} bit interval, the composite data stream $d_x(t)$ contains

$$d_{x,k}(t) = \sum_{n=0}^{N-1} b_{n,k} \sum_{l=0}^{L-1} c_{n,l} r'(t - kT_b - lT_c).$$

- At receiver of user n', perform correlation with user-n' code $c_{n'}(t)$:

$$\int_{(k-1)T_b}^{kT_b} d_{x,k}(t) c_{n'}(t) dt = T_b \sum_{n=0}^{N-1} b_{n,k} \left[\sum_{l=0}^{L-1} c_{n',l} c_{n,l}\right] = T_b b_{n',k} \,.$$

- In other words, the k^{th} data bit of user n' can be faithfully recovered from the composite data stream $d_x(t)$.

Random access protocols

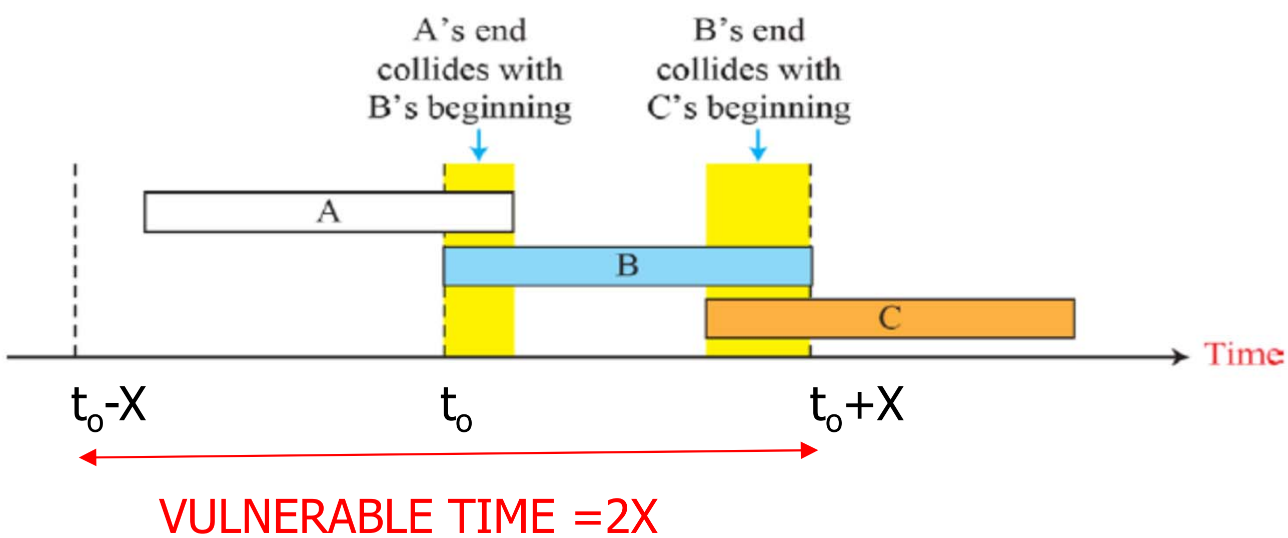
- when node has packet to send
  - transmit at full channel data rate R.
  - no *a priori* coordination among nodes
- two or more transmitting nodes can create "collision",
- random access MAC protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)
- examples of random access MAC protocols:
  - ALOHA
  - slotted ALOHA
  - CSMA, CSMA/CD, CSMA/CA

Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization
- when frame first arrives, just transmit immediately at t_o
- No collision if no other transmission in $[t_o\text{-}X\ ,\ t_o\text{+}X]$
- Random retransmission if collision

Throughput

- **Poisson process**: frame arrivals are *equally likely* at any instant in time at an average rate of λ [arrivals/sec]: $Pr\{k \text{ arrivals in } t \text{ seconds}\} = (\lambda t)^k\, e^{-\lambda t}/k!$
- **load** G : average number of overall transmission *attempts* per X sec, $G = \lambda X$
- P_s : probability of successful transmission (no *other* transmission in t=2X seconds**)** is: $P_s = Pr\{k=0 \text{ arrivals in } 2X\} = e^{-2G}$
- **throughput** S: average number of *successfully transmitted* frames per X sec, $S=GP_s$
- $S_{ALOHA}=Ge^{-2G}$
- **Max** $S_{ALOHA}=1/2e=0.184$ at $G=1/2$

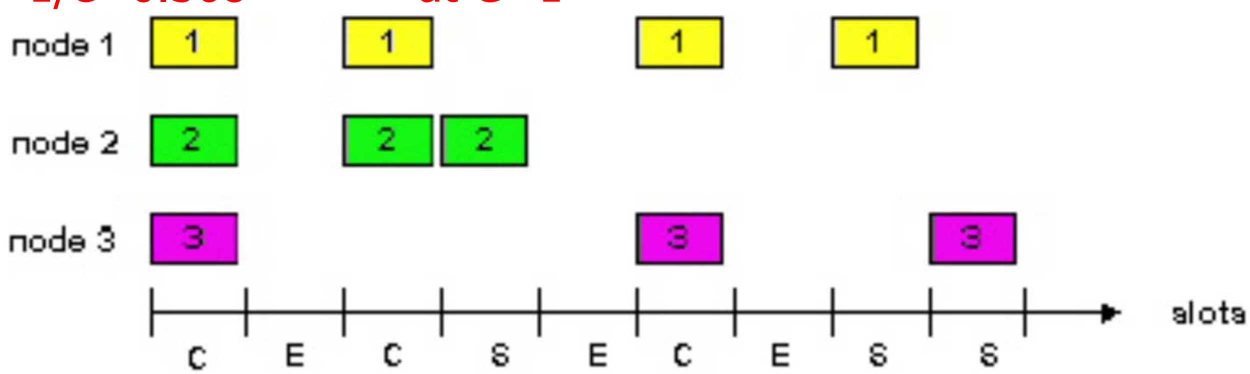


Slotted ALOHA (S-ALOHA)

- Improving the throughput of ALOHA by reducing vulnerable time by introducing time slot
- Assume that all frames has the same size X
- time divided into equal-size (X) slots (each to transmit 1 frame)
- nodes are s*ynchronized* so that each node knows when the slots begin and start to transmit only at the beginning of a slot
- if 2 or more nodes transmit in slot, all nodes detect collision
- when node has a fresh frame to send, it waits until next frame slot and transmits
- if there is a collision, node retransmits the frame after a random number of backoff time-slots

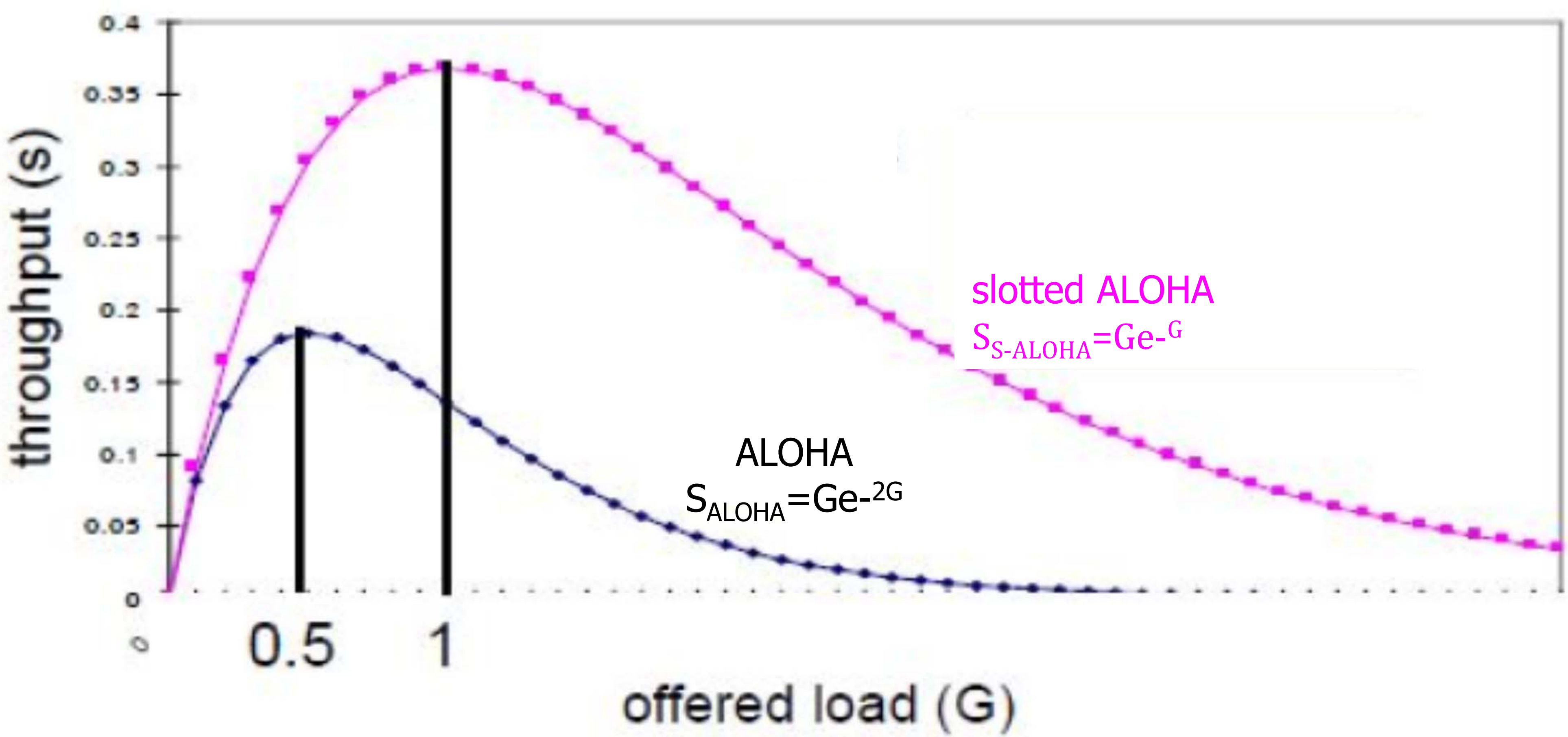
Throughput

- **Poisson process**: frame arrivals are *equally likely* at any instant in time at an average rate of λ [arrivals/sec]: Pr{k arrivals in t seconds}= $(\lambda t)^k e^{-\lambda t}/k!$
- **load** G : average number of overall transmission *attempts* per X sec, G= λX
- P_s : probability of successful transmission (no *other* transmission in t=X seconds**)** is: $P_s = e^{-G}$
- **throughput** S: average number of *successfully transmitted* frames per X sec, $S=GP_s$
- $S_{S\text{-}ALOHA}=Ge^{-G}$, **Max** $S_{S\text{-}LOHA}=1/e=0.368$ at G=1



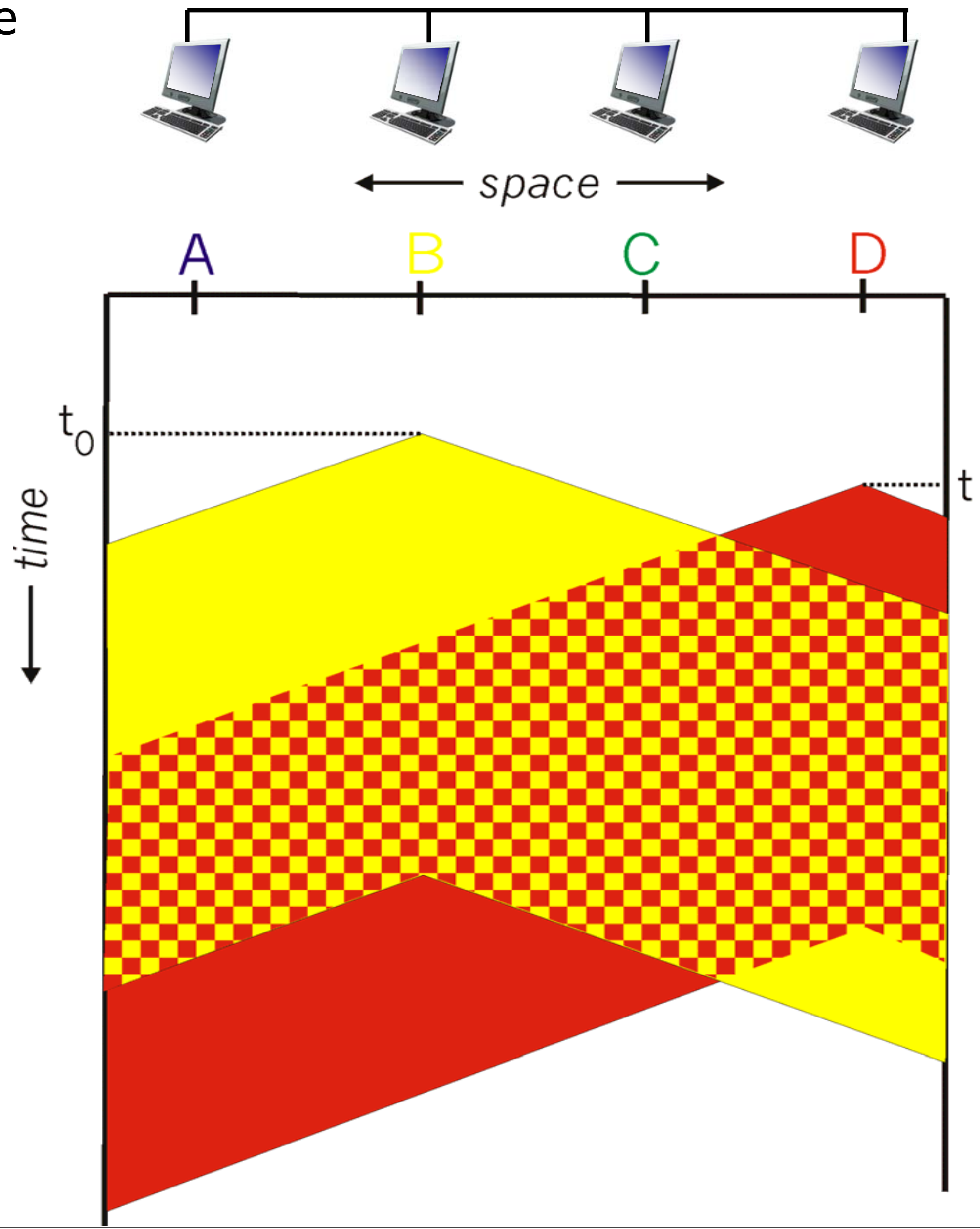
ALOHA & S-ALOHA

- slotted ALOHA reduces vulnerability to collision, but also adds a waiting period for transmission
- if contention is low, it will prevent very few collisions, & delay many of the (few) packets that are sent

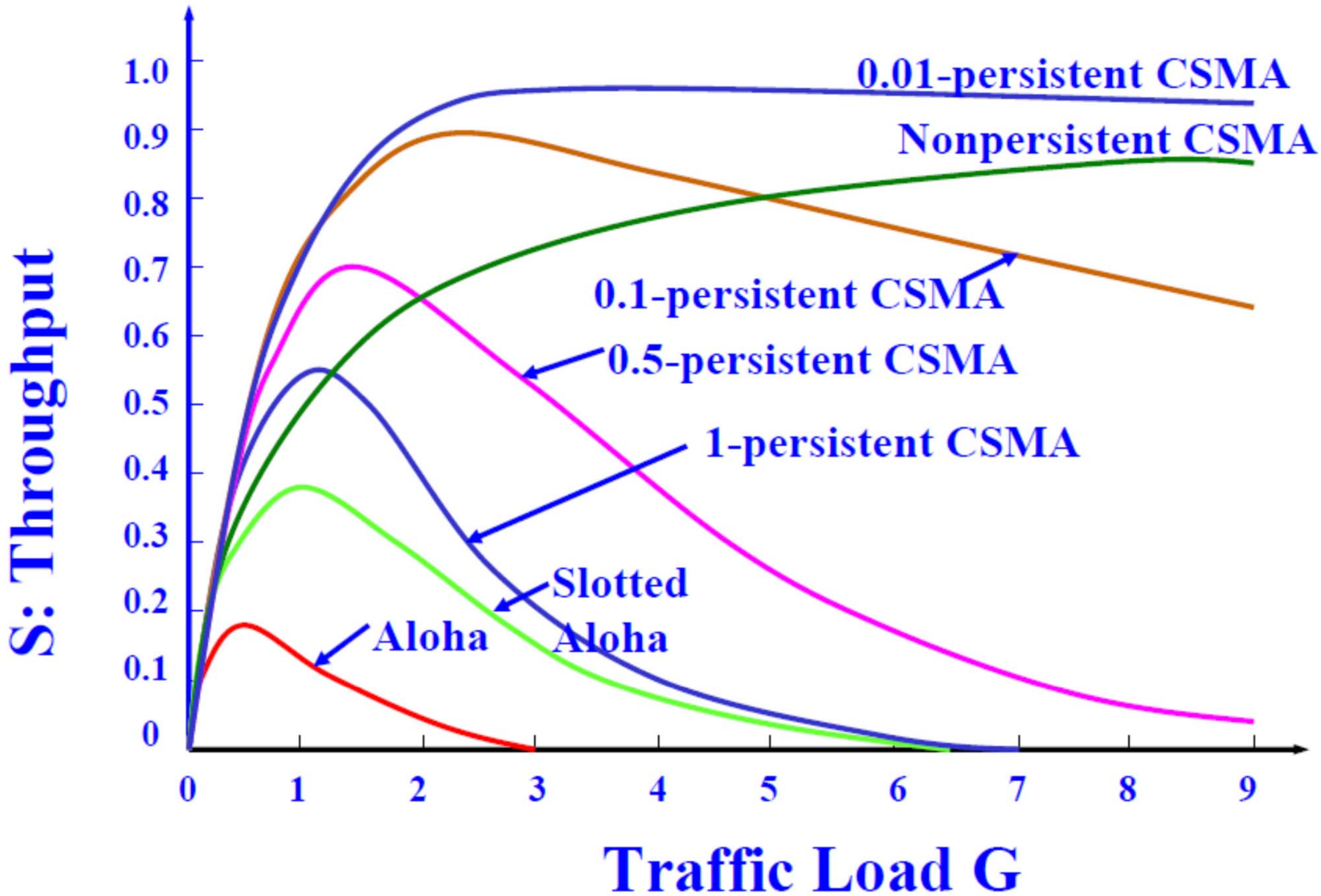


Carrier Sense Multiple Access (CSMA)

- listen before transmit:
  - if channel sensed idle: transmit entire frame
  - if channel sensed busy, defer transmission
- collisions *can* still occur due to propagation delay, e.g., two nodes may not hear each other's transmission
- collision: entire packet transmission time wasted: distance & propagation delay play role in in determining collision probability
- CSMA:
  - unslotted, slotted
  - Non-persistent, 1-, p-Persistent
- p-persistent CSMA Protocol:
- Step 1: If the medium is idle, transmit with probability p, and delay for worst-case propagation delay for one packet with probability (1-p)
- Step 2: If the medium is busy, continue to listen until medium becomes idle, then go to Step 1
- Step 3: If transmission is delayed by one time slot, continue with Step 1

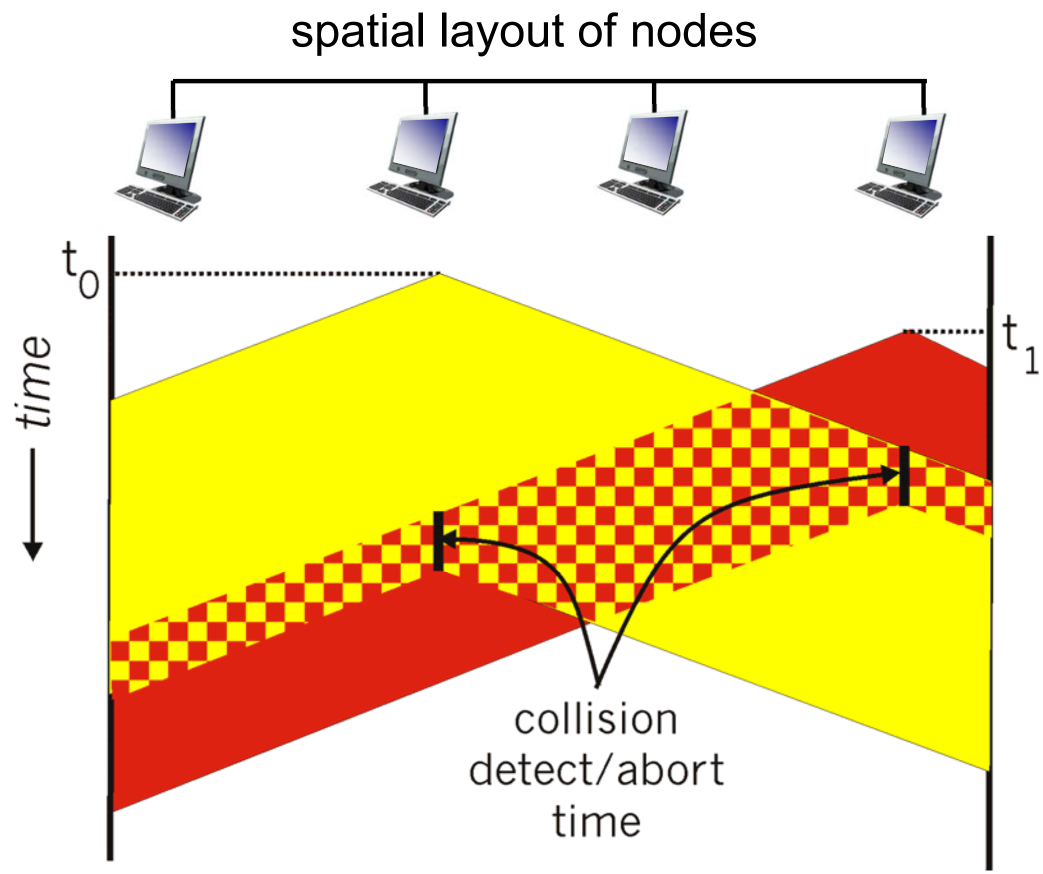


CSMA: thoughput



CSMA/CD (collision detection)

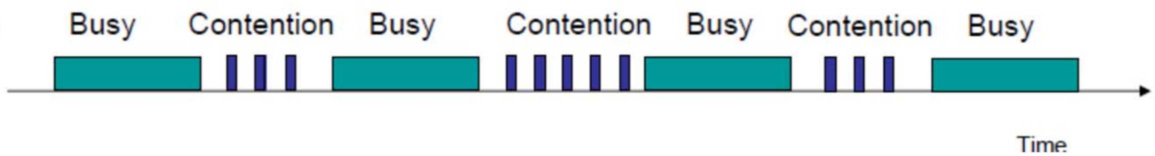
- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage
- collision detection:
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: received signal strength overwhelmed by local transmission strength



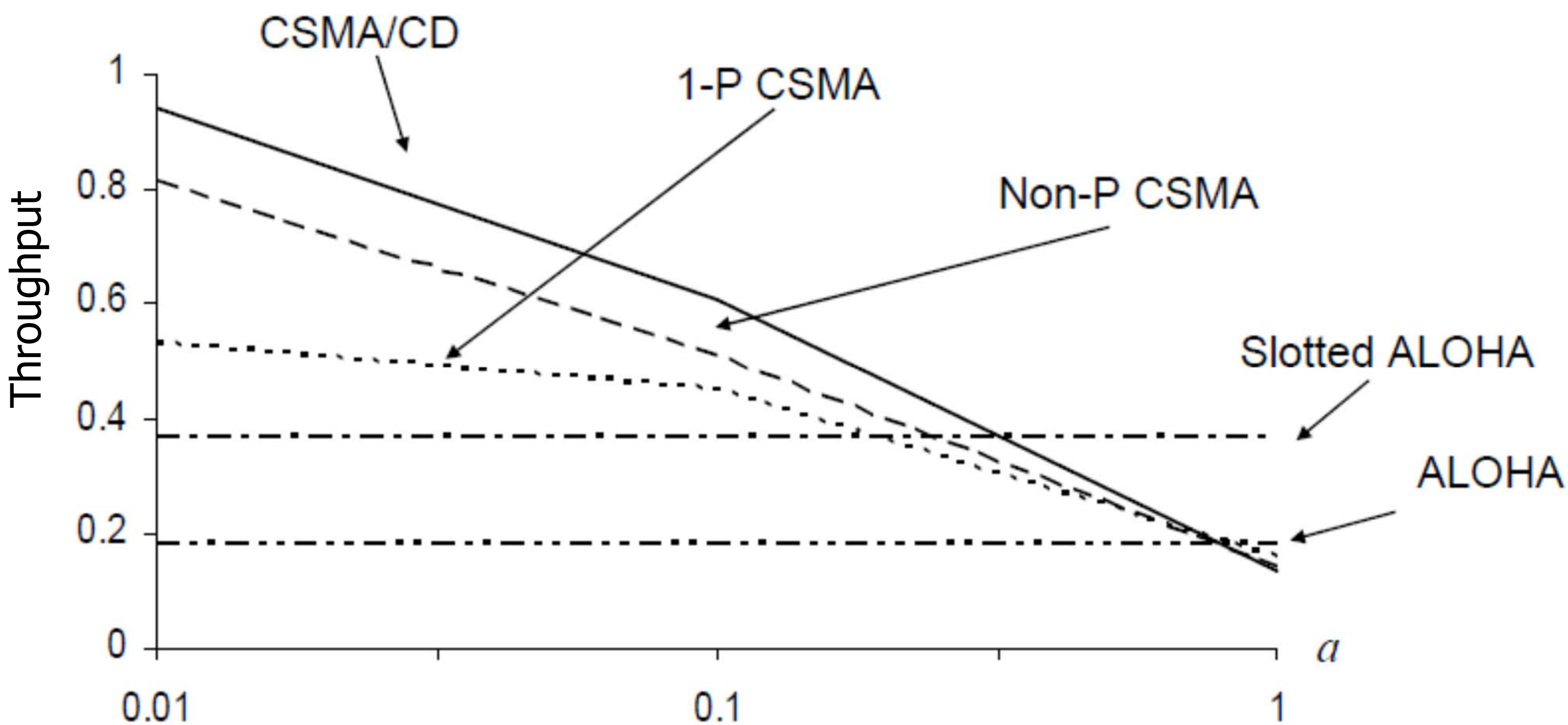
Ethernet CSMA/CD algorithm

1. NIC receives datagram from network layer, creates frame
2. If NIC senses channel idle, starts frame transmission. If NIC senses channel busy, waits until channel idle, then transmits.
3. If NIC transmits entire frame without detecting another transmission, NIC is done with frame !
4. If NIC detects another transmission while transmitting, aborts and sends jam signal
5. After aborting, NIC enters *binary (exponential) backoff:*
   - after *m*th collision, NIC chooses *K* at random from $\{0,1,2, \ldots, 2^m-1\}$. NIC waits $K \cdot 512$ bit times, returns to Step 2
   - longer backoff interval with more collisions

CSMA/CD Throughput



- At maximum throughput, systems alternates between contention periods and frame transmission times:
  - $S_{CSMA/CD,max} = [1+(1+2e)a]^{-1}$, a=propagation time/Tx time, 1+2e=6.44
- CSMA-CD has best throughput for small a
- ALOHA, slotted ALOHA are not sensitive to a, and offer better throughput for larger a



"Taking turns" MAC protocols

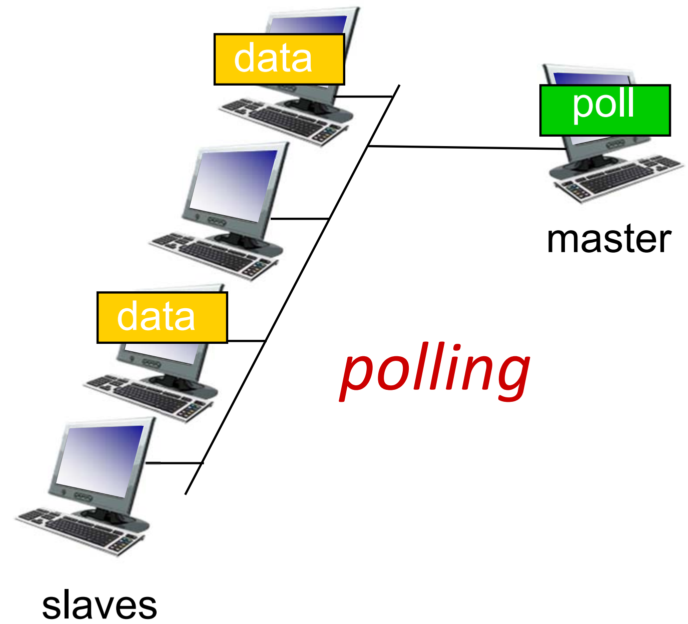
- channel partitioning MAC protocols:
  - share channel *efficiently* and *fairly* at high load
  - inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!
- random access MAC protocols:
  - efficient at low load: single node can fully utilize channel
  - high load: collision overhead
- "taking turns" protocols: look for best of both worlds!

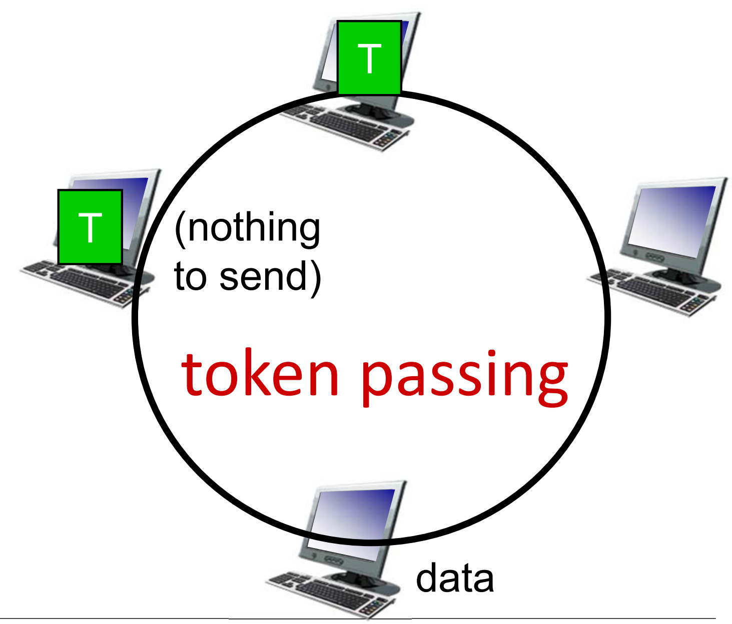
polling:

- master node "invites" slave nodes to transmit in turn
- typically used with "dumb" slave devices
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)

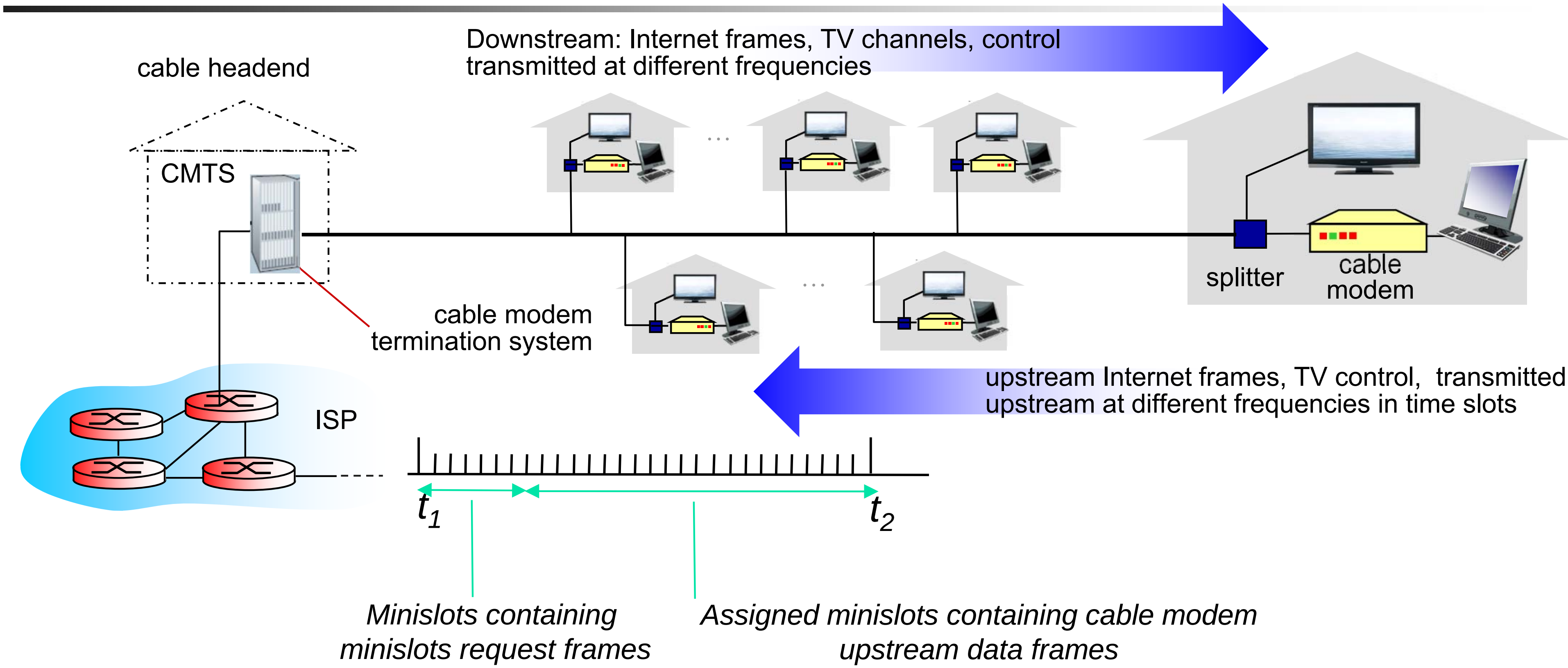
token passing:

- control *token* passed from one node to next sequentially.
- token message
- concerns:
  - token overhead
  - latency
  - single point of failure (token)





Cable access network

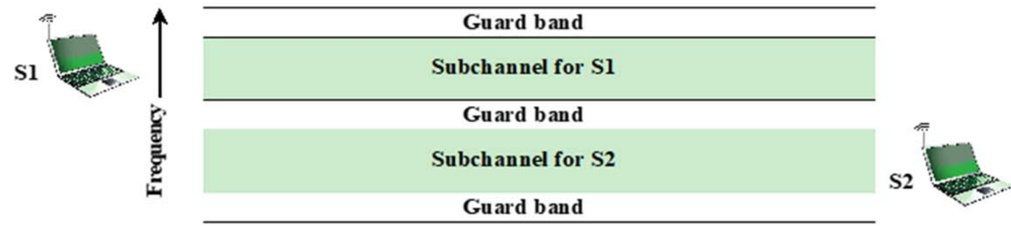


- multiple 40Mbps downstream (broadcast) channels: single CMTS (cable modem termination system) transmits into channels
- multiple access 30 Mbps upstream channels: all users contend for certain upstream channel time slots (others assigned)

DOCSIS: data over cable service interface spec

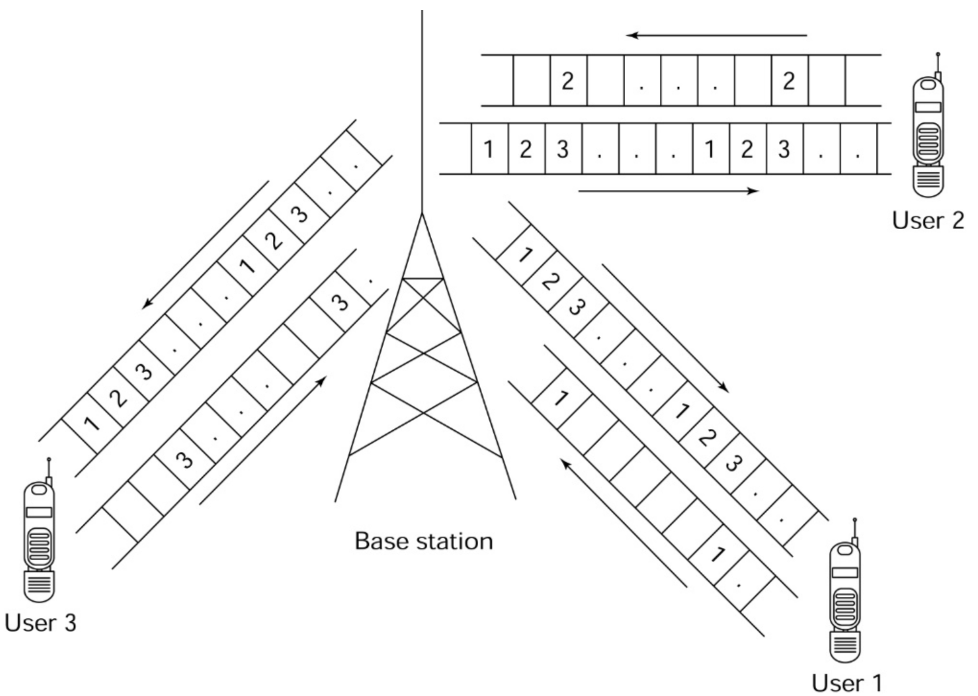
- FDM over upstream, downstream frequency channels
- TDM upstream: some slots assigned, some have contention
  - downstream MAP frame: assigns upstream slots
  - request for upstream slots (and data) transmitted random access (binary backoff) in selected slots

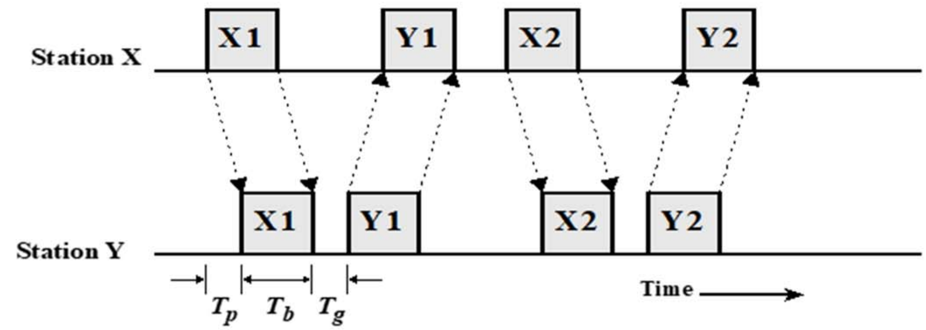
Duplexing



(a) Frequency-division duplex (TDD)

Example of TDM (downlink)/TDMA (uplink)





T_p = Propagation delay

T_b = Burst transmission time

T_g = Guard time

(b) Time-division duplex (TDD)

Figure 8.18 Duplex Access Techniques