

CS/ECE 439: Wireless Networking

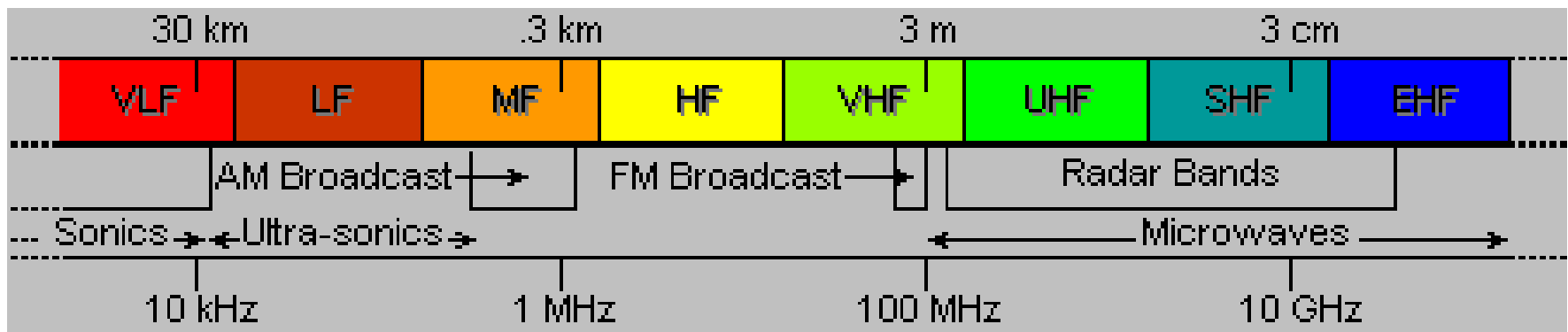
Physical Layer

Limitation (of Wireless) Communication



RF Introduction

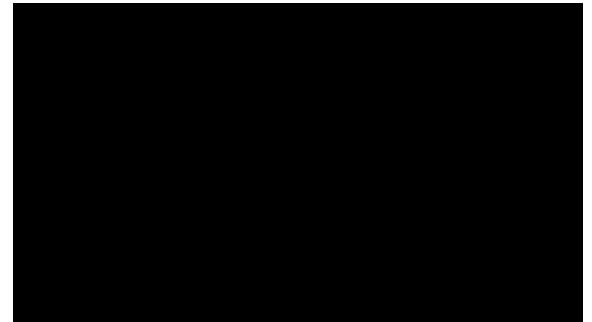
- ▶ RF = Radio Frequency
 - ▶ Electromagnetic signal that propagates through “ether”
 - ▶ Ranges 3 KHz .. 300 GHz
 - ▶ Or 100 km .. 0.1 cm (wavelength)



- ▶ Travels at the speed of light
- ▶ Can take both a time and a frequency view

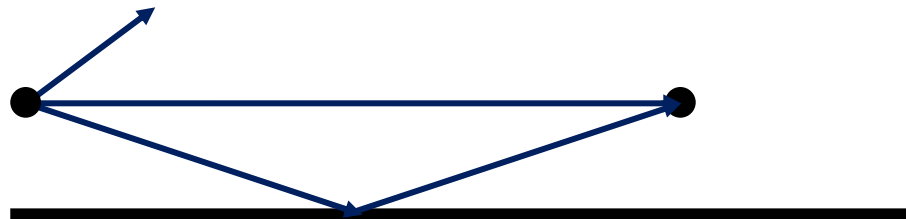
Cartoon View 1 – Energy Wave

- ▶ Think of it as energy that radiates from one antenna and is picked up by another antenna
 - ▶ Helps explain properties such as attenuation
 - ▶ Density of the energy reduces over time and with distance
- ▶ Useful when studying attenuation
 - ▶ Receiving antennas catch less energy with distance
 - ▶ Notion of cellular infrastructure

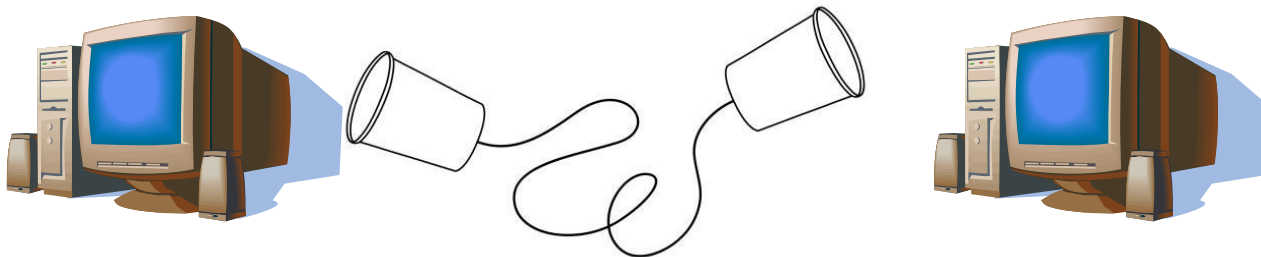
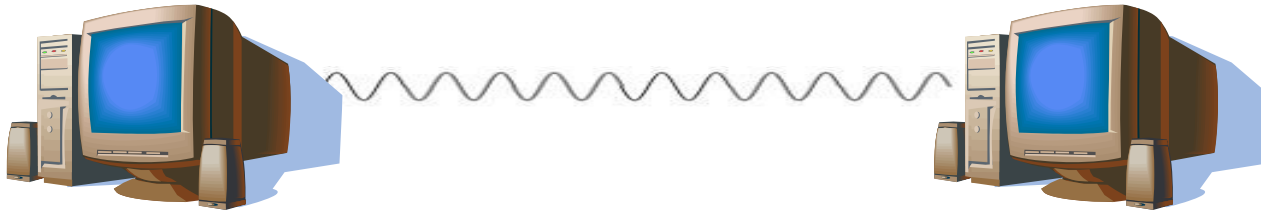


Cartoon View 2 – Rays of Energy

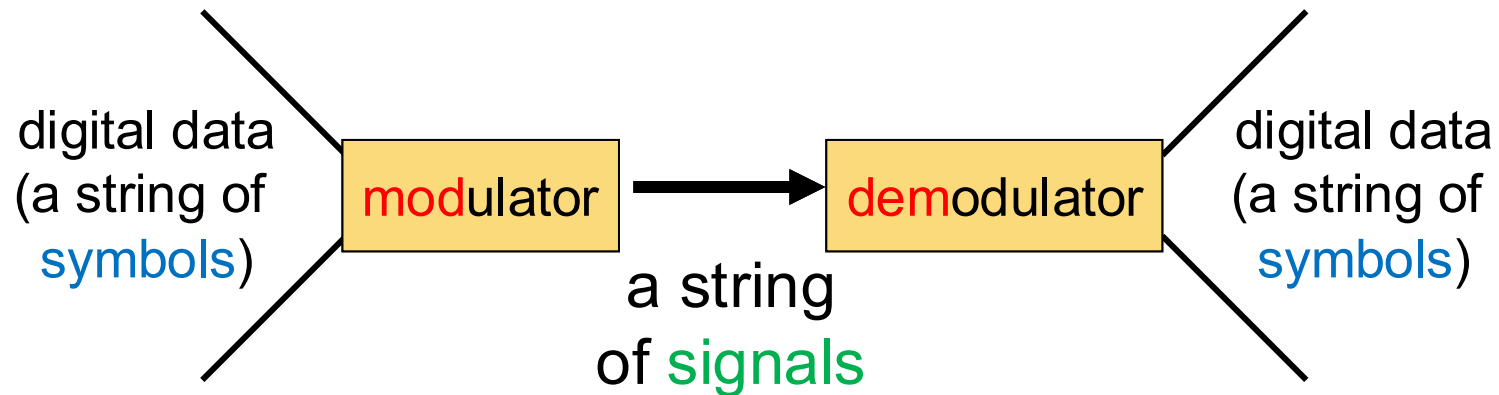
- ▶ Can also view it as a “ray” that propagates between two points
 - ▶ Rays can be reflected etc.
 - ▶ Can provide connectivity without line of sight
- ▶ A channel can also include multiple “rays” that take different paths
 - ▶ Known as multipath



But how can two hosts communicate?

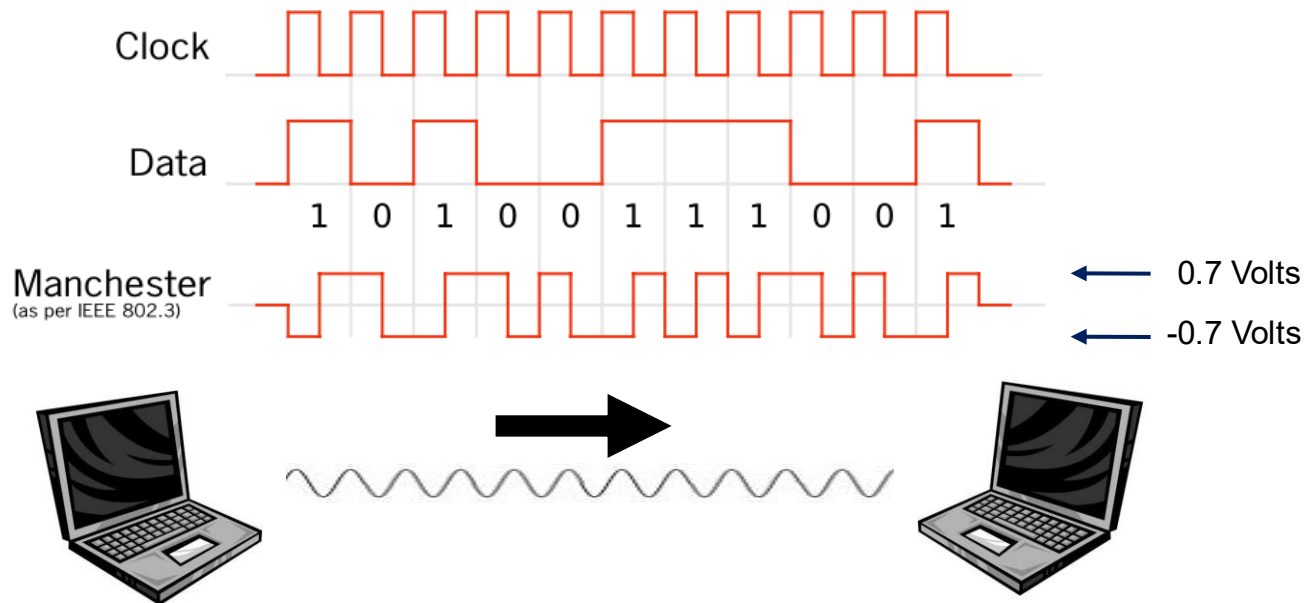


Encoding



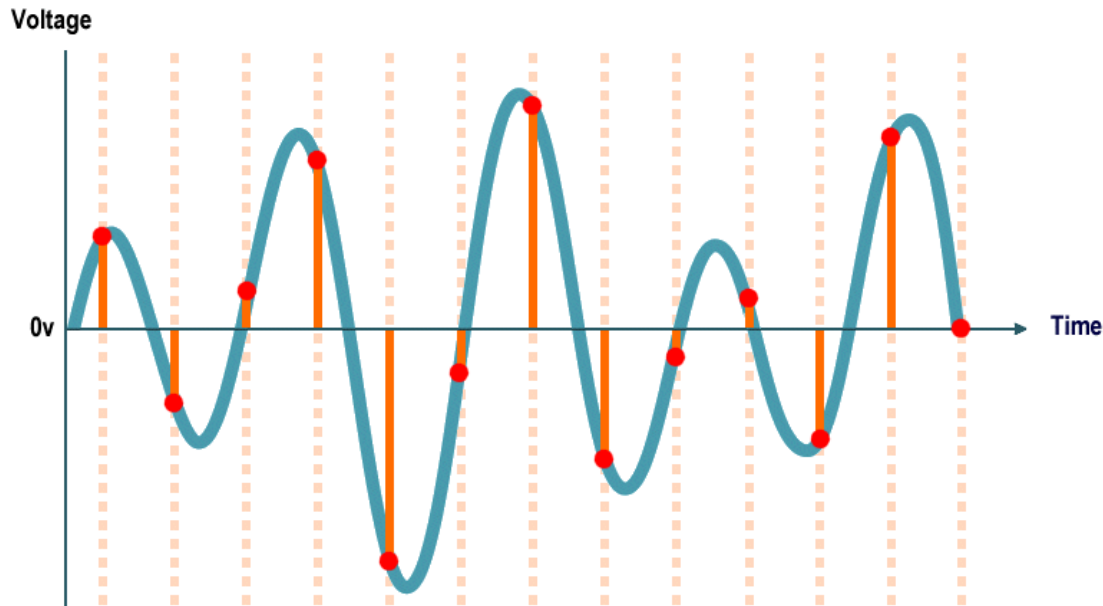
- ▶ Data is encoded in the **signal**
- ▶ Problems with signal transmission
 - ▶ Attenuation: Signal power absorbed by medium
 - ▶ Dispersion: A discrete signal spreads in space
 - ▶ Noise: Random background “signals”

But how can two wireless hosts communicate?



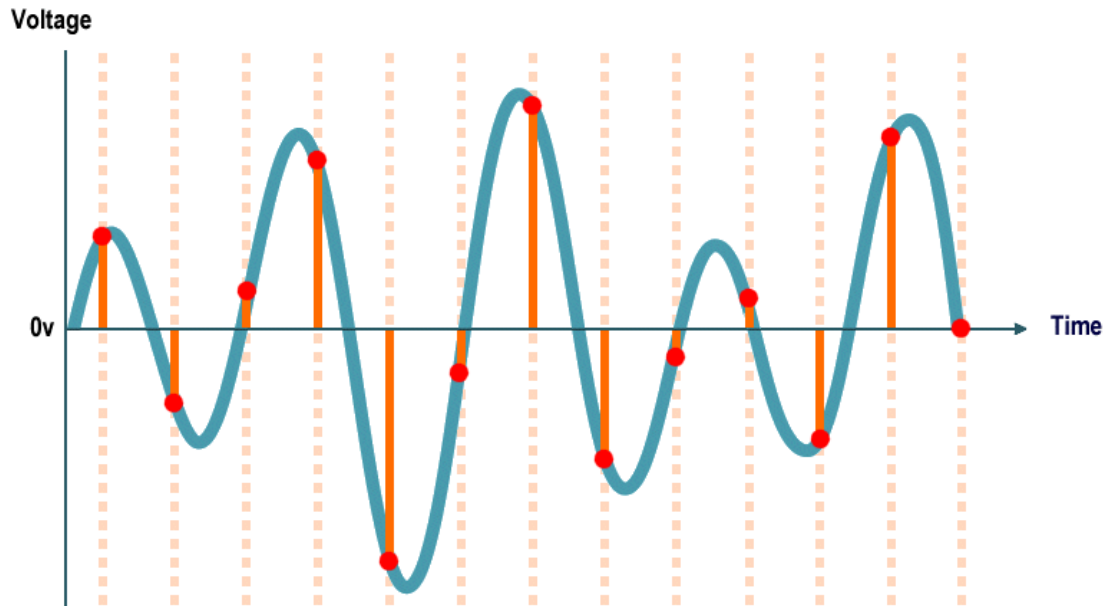
- ▶ Encode information on modulated “Carrier signal”
 - ▶ Phase, frequency, and/or amplitude modulation

Analog vs. Digital Transmission



- ▶ **Analog** and **digital** correspond roughly to **continuous** and **discrete**

Analog vs. Digital Transmission



- ▶ Signals: electric or electromagnetic encoding of data
 - ▶ **Analog**: continuously varying electromagnetic wave
 - ▶ **Digital**: sequence of voltage pulses

Time Domain View:

Periodic versus Aperiodic Signals

► Periodic signal

- Analog or digital signal pattern that repeats over time

$$s(t + T) = s(t)$$

where T is the period of the signal

- Allows us to take a frequency view

► Aperiodic signal

- Analog or digital signal pattern that doesn't repeat over time
- Can “make” an aperiodic signal periodic by taking a slice T and repeating it
- Often what we do implicitly

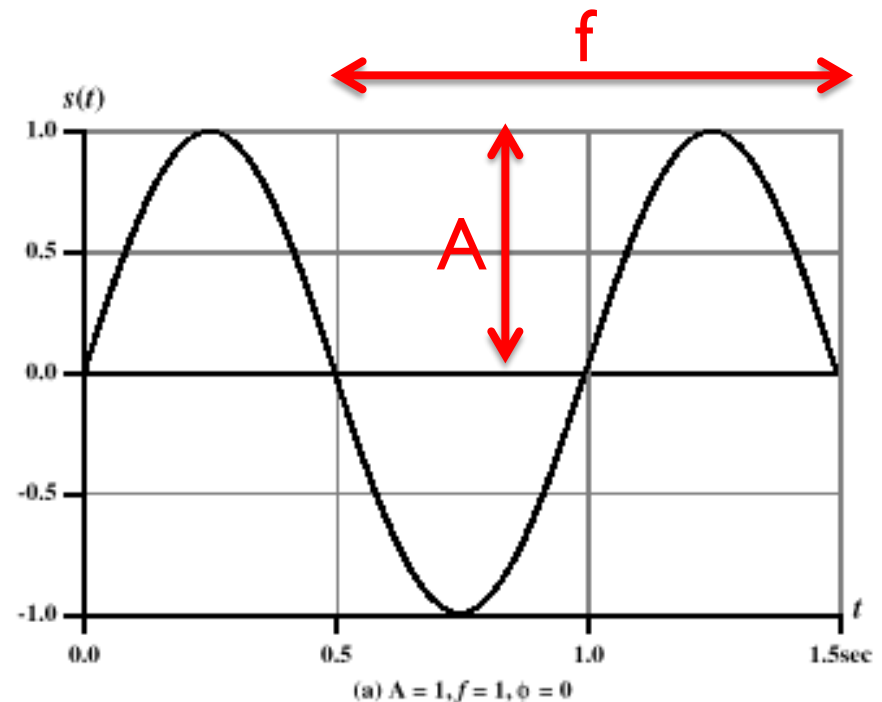


Key Parameters of a (Periodic) Signal

- ▶ **Peak amplitude (A)**
 - ▶ Maximum value or strength of the signal over time
 - ▶ Typically measured in volts
- ▶ **Frequency (f)**
 - ▶ Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
- ▶ **Period (T)**
 - ▶ Amount of time it takes for one repetition of the signal
 - ▶ $T = 1/f$
- ▶ **Phase (ϕ)**
 - ▶ Measure of the relative position in time within a single period of a signal
- ▶ **Wavelength (λ)**
 - ▶ Distance occupied by a single cycle of the signal
 - ▶ Or, the distance between two points of corresponding phase of two consecutive cycles

Sine Wave Parameters

- ▶ General sine wave
 - ▶ $s(t) = A \sin(2\pi ft + \phi)$
- ▶ Effect of parameters
 - ▶ $A = 1, f = 1 \text{ Hz},$
 $\phi = 0$; thus $T = 1 \text{ s}$



- ▶ note: $2\pi \text{ radians} = 360^\circ =$
 1 period

Sine Wave Parameters

► General sine wave

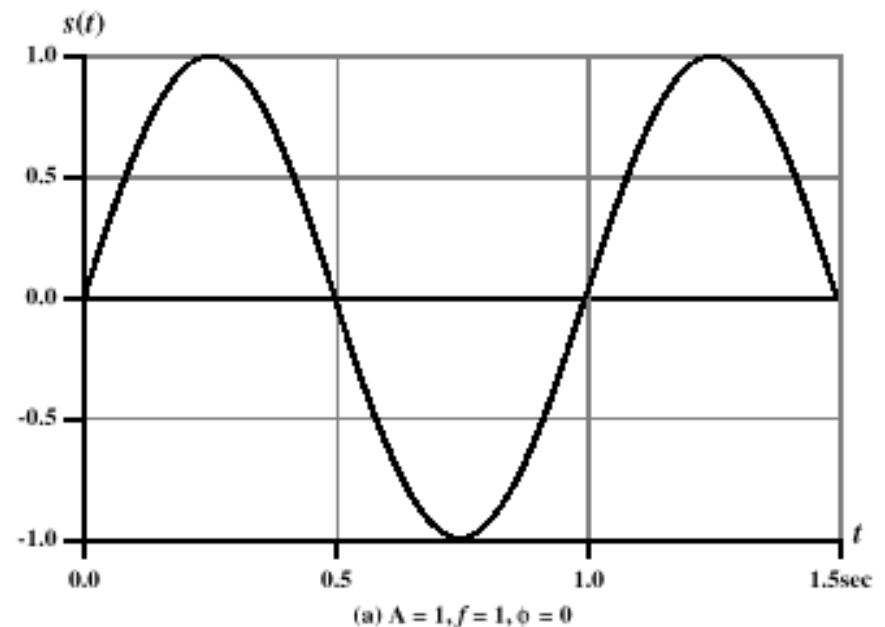
► If x-axis = time

- y-axis = value of a signal at a given point in *space*

► If x-axis = space

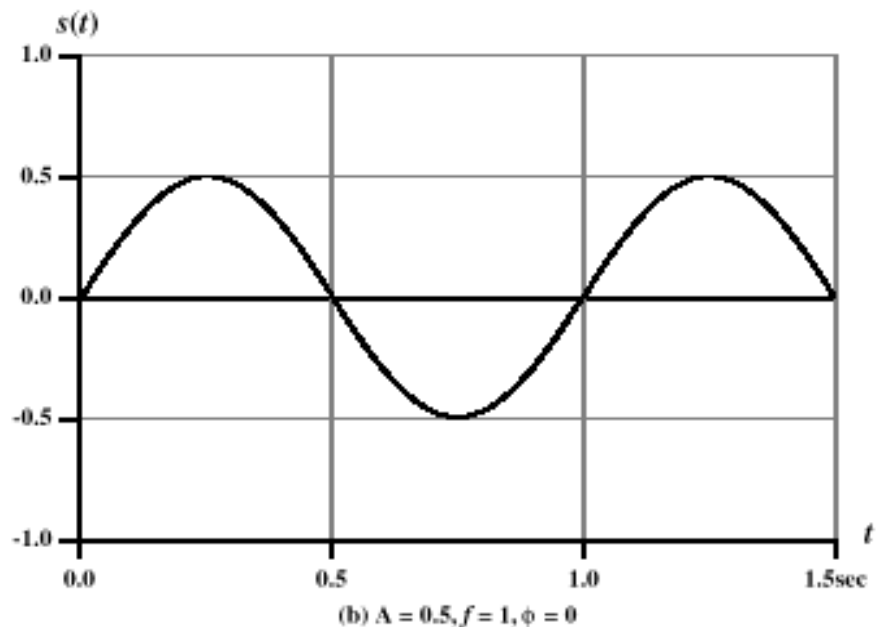
- y-axis = value of a signal at a given point in *time*

► Note. 2π radians = 360° = 1 period



Sine Wave Parameters

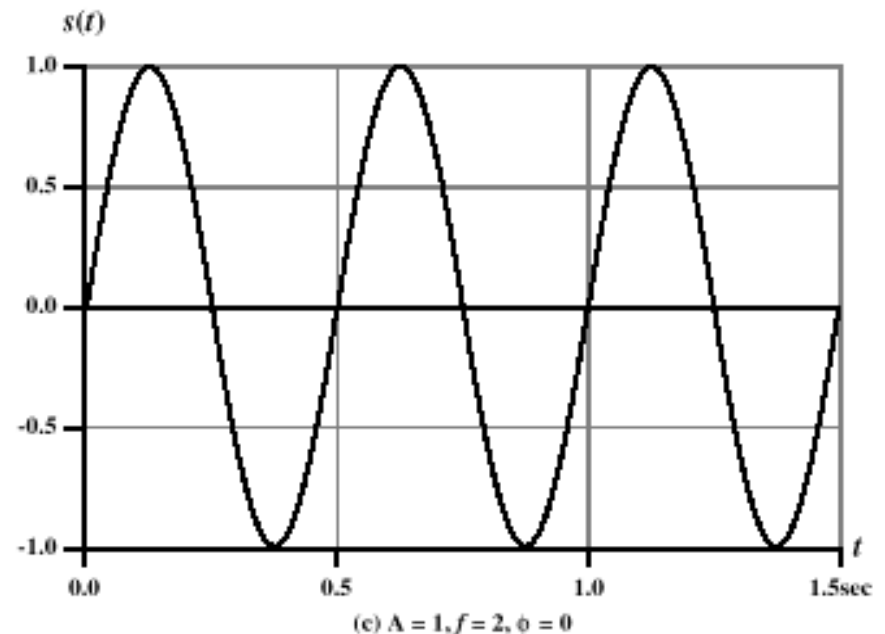
- ▶ General sine wave
 - ▶ $s(t) = A \sin(2\pi ft + \phi)$
- ▶ Effect of parameters
 - ▶ Reduced peak amplitude; $A=0.5$



- ▶ note: $2\pi \text{ radians} = 360^\circ = 1 \text{ period}$

Sine Wave Parameters

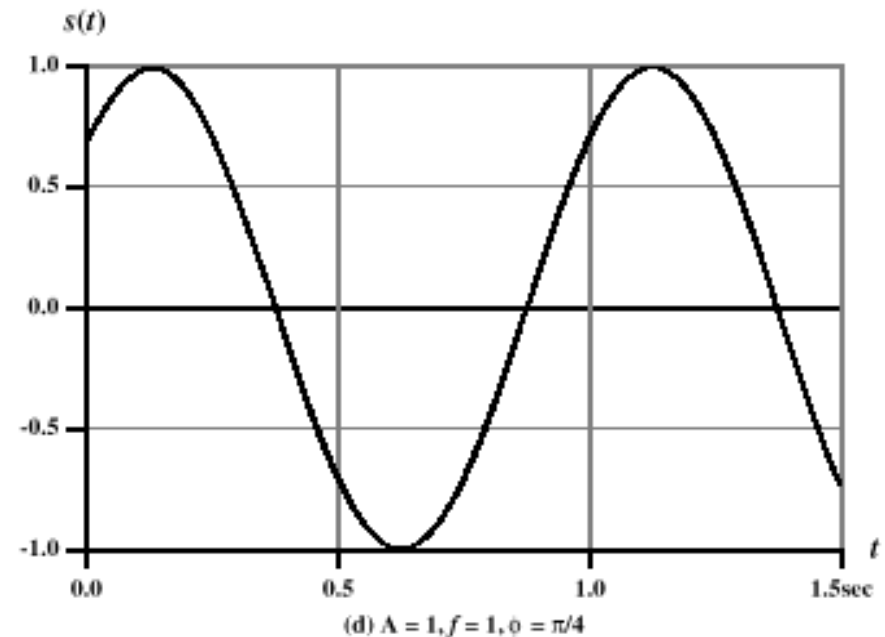
- ▶ General sine wave
 - ▶ $s(t) = A \sin(2\pi ft + \phi)$
- ▶ Effect of parameters
 - ▶ Increased frequency;
 $f = 2$, thus $T = 1/2$



- ▶ note: $2\pi \text{ radians} = 360^\circ = 1 \text{ period}$

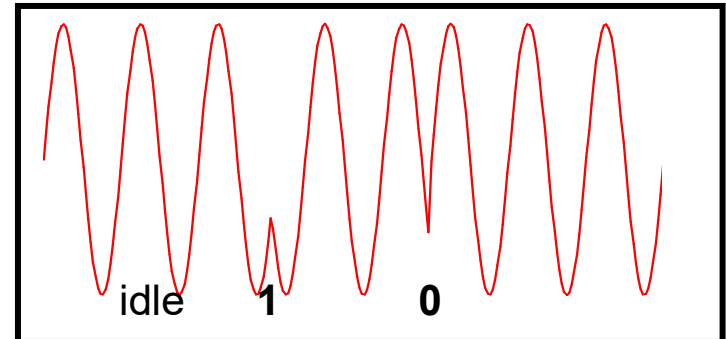
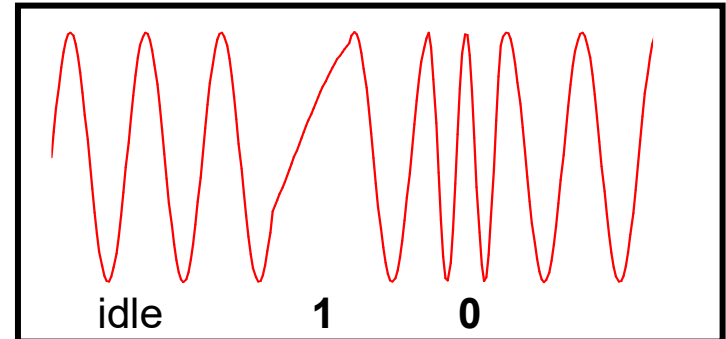
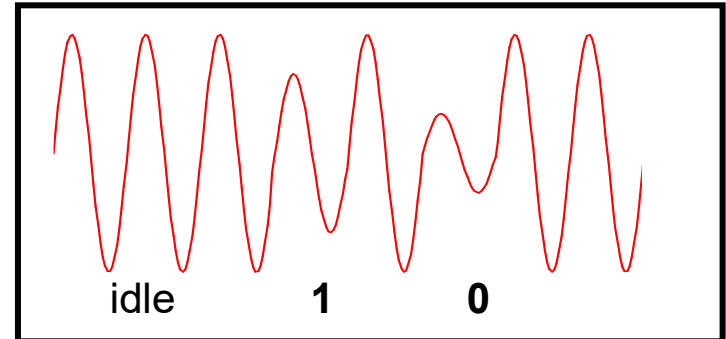
Sine Wave Parameters

- ▶ General sine wave
 - ▶ $s(t) = A \sin(2\pi ft + \phi)$
- ▶ Effect of parameters
 - ▶ Phase shift
 $\phi = \pi/4$ radians
(45 degrees)
- ▶ note: 2π radians = $360^\circ = 1$ period



Signal Modulation

- ▶ **Amplitude modulation (AM)**
 - ▶ Change the strength of the signal
 - ▶ High values -> stronger signal
- ▶ **Frequency modulation (FM)**
 - ▶ Change the frequency of the signal
- ▶ **Phase modulation (PM)**
 - ▶ Change the phase of the signal

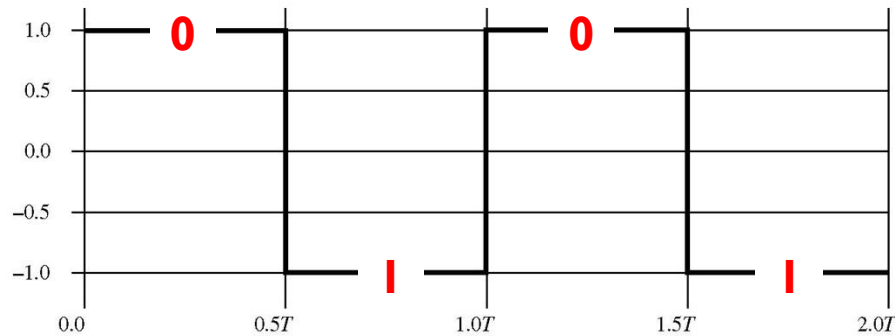


Relationship between Data Rate and Bandwidth

- ▶ **Bandwidth translates to bits**
 - ▶ The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal (data bandwidth)
 - ▶ Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data
- ▶ **Extreme example**
 - ▶ A signal that only changes once a second will not be able to carry a lot of bits or convey a very interesting TV channel

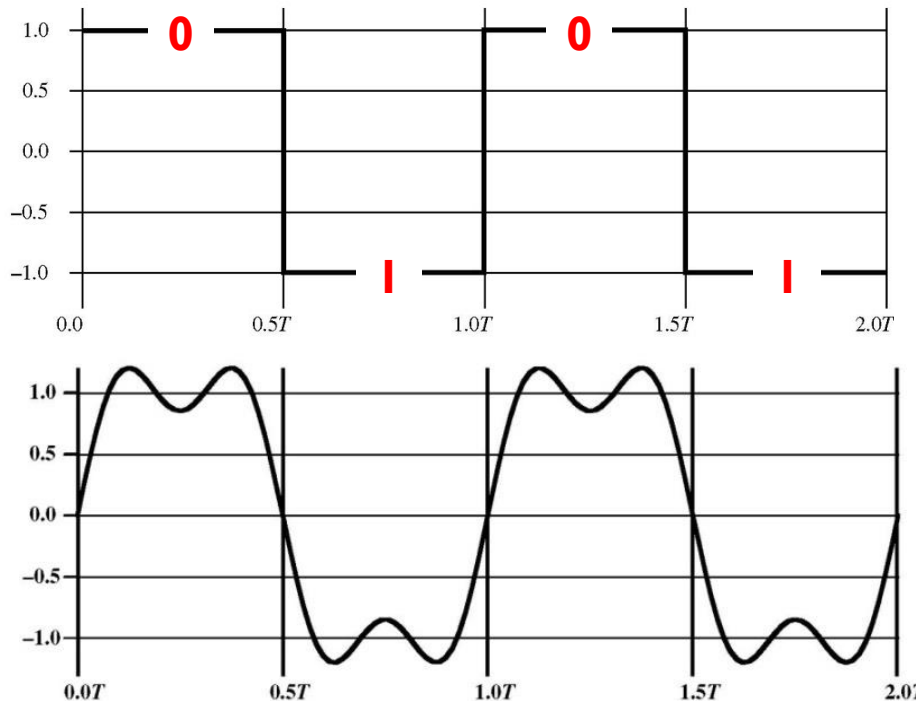


Signals to bits



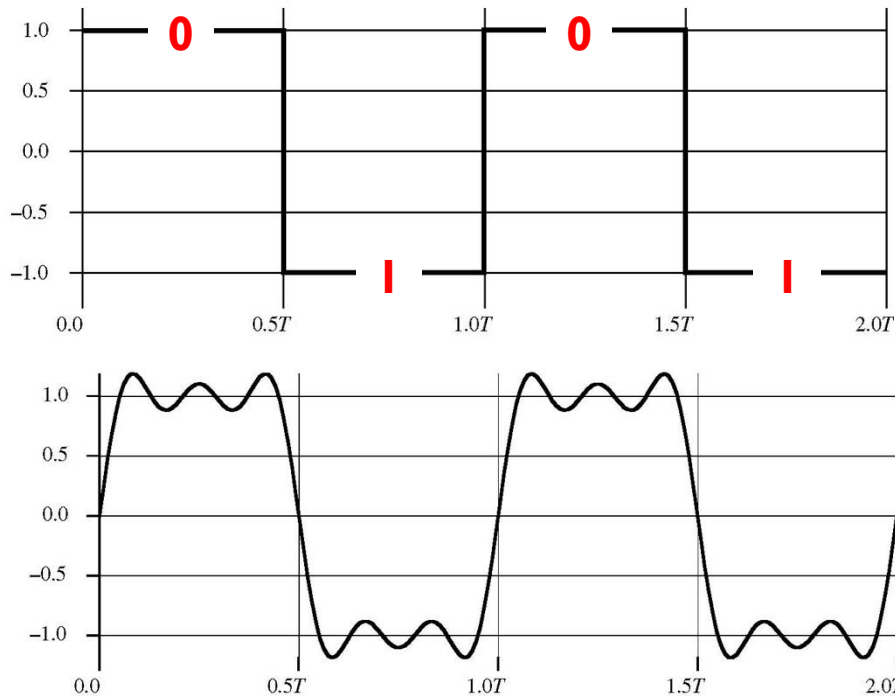
- ▶ Each pulse lasts $1/2f$
- ▶ Data rate = $2f$ bps

Signals to bits



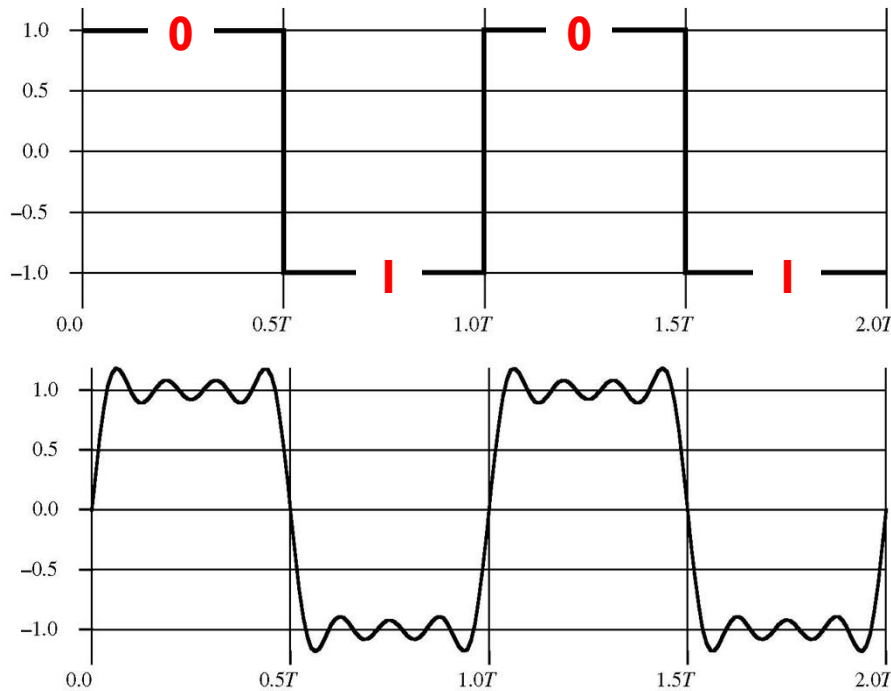
- ▶ Each pulse lasts $1/2f$
 - ▶ Data rate = $2f$ bps
- ▶ Add two sine waves
 $(4/\pi)[\sin 2\pi ft] + (1/3)\sin(2\pi 3ft)]$

Signals to bits



- ▶ Each pulse lasts $1/2f$
 - ▶ Data rate = $2f$ bps
- ▶ Add a sine wave with frequency $5f$

Signals to bits

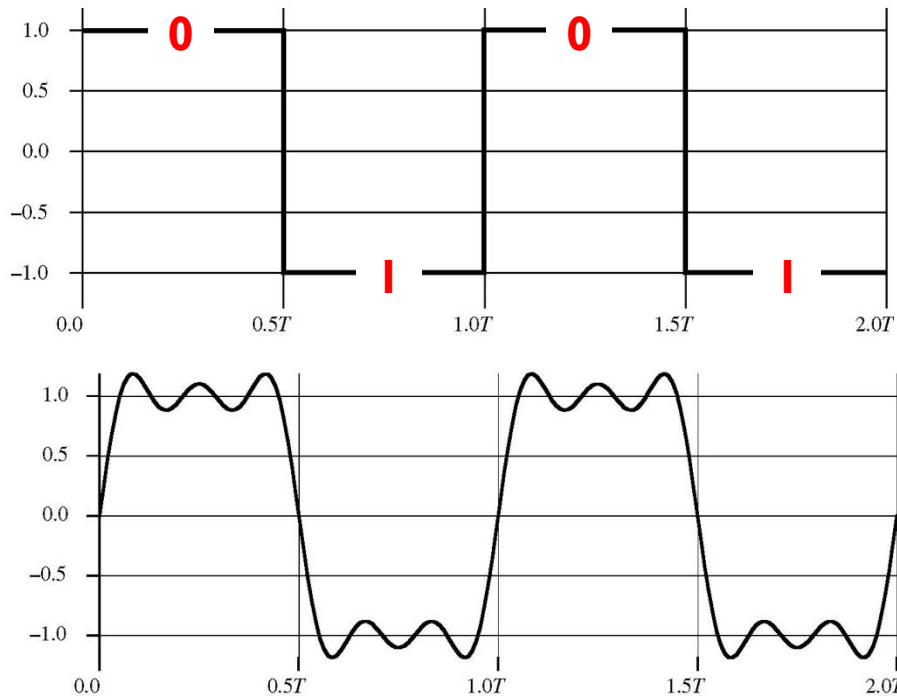


- ▶ Each pulse lasts $1/2f$
 - ▶ Data rate = $2f$ bps
- ▶ Add a sine wave with frequency $7f$
 - ▶ And so on ...

Infinite frequencies = infinite bandwidth!

not quite ...

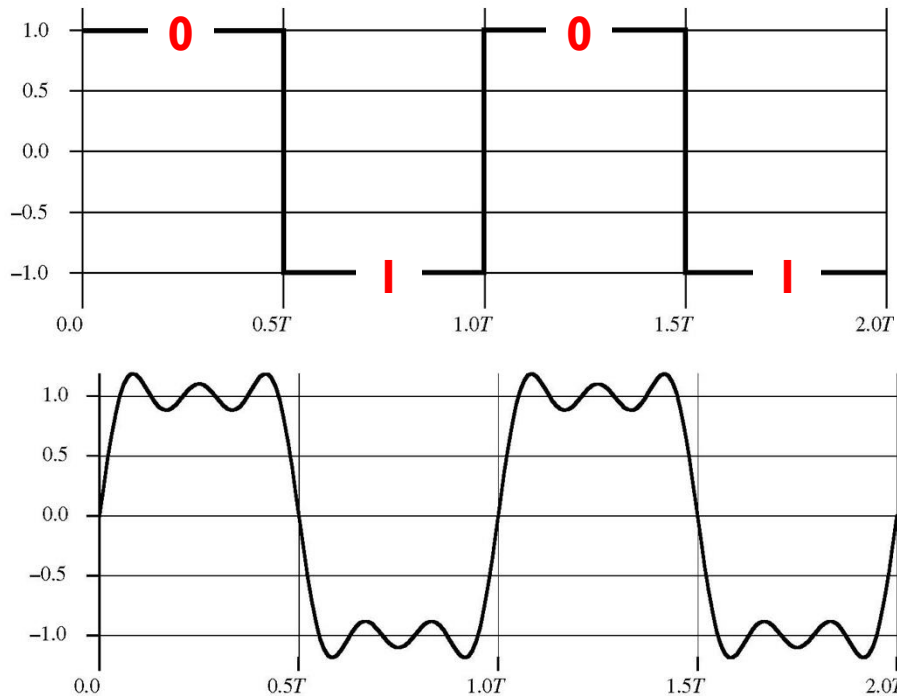
Data rate



Close enough to square wave to distinguish 0 and 1

- ▶ Available bandwidth of bandwidth of 4MHz
- ▶ If $f = 10^6$ cycles/sec = 1MHz
 - ▶ Signal bandwidth = 4MHz
 - ▶ $T = 1 \text{ bit}/0.5 \mu\text{sec}$
 - ▶ Data rate = 2 Mbps

Data rate



Close enough to square wave to distinguish 0 and 1

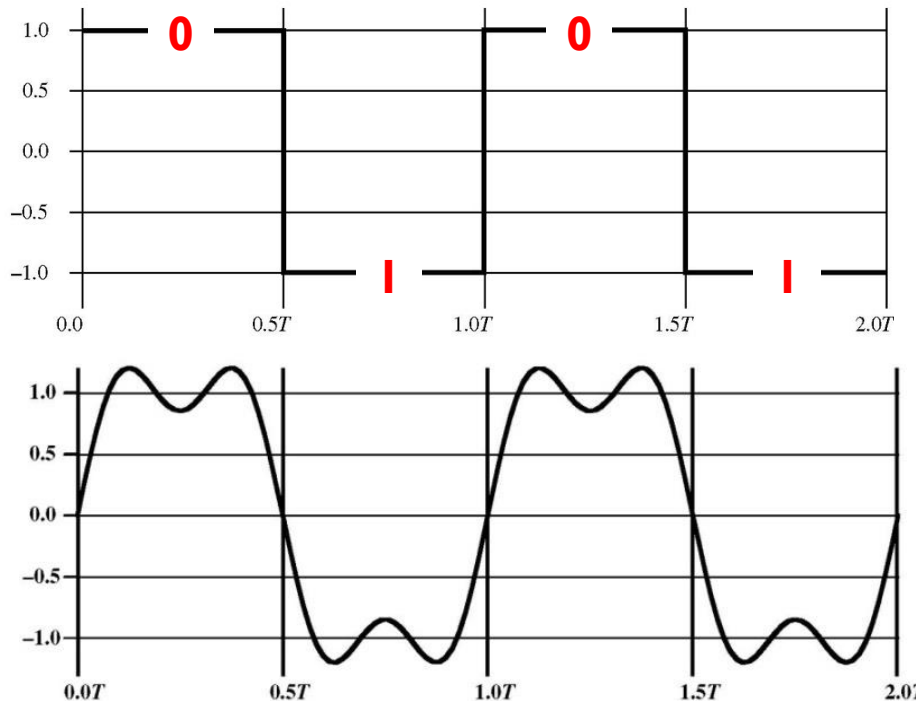
► Available bandwidth of bandwidth of 8MHz

► If $f = 2\text{MHz}$

- Signal bandwidth = 8MHz
- $T = 1 \text{ bit}/0.25 \mu\text{sec}$
- Data rate = 4 Mbps

2X BW = 2X data rate

Data rate



What if this is good enough?

► Available bandwidth of bandwidth of 4MHz

► If $f = 2\text{MHz}$

- Signal bandwidth = 4MHz
- $T = 1 \text{ bit}/0.25 \mu\text{sec}$
- Data rate = 4 Mbps

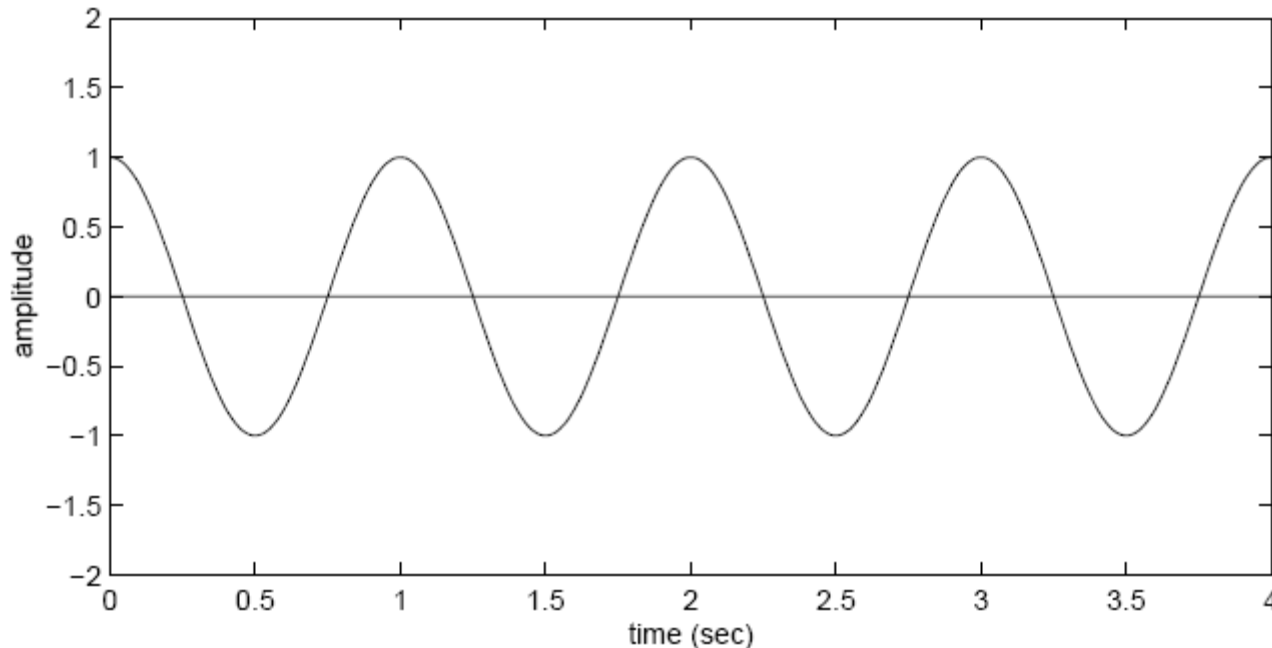
IF the receiver can distinguish between 0 and 1!

Channel Capacity

- ▶ **Data rate**
 - ▶ Rate at which data can be communicated (bps)
- ▶ **Channel Capacity**
 - ▶ Maximum rate at which data can be transmitted over a given channel, under given conditions
- ▶ **Bandwidth**
 - ▶ Bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- ▶ **Noise**
 - ▶ Average level of noise over the communications path
- ▶ **Error rate**
 - ▶ Rate at which errors occur
 - ▶ Error = transmit 1 and receive 0; transmit 0 and receive 1

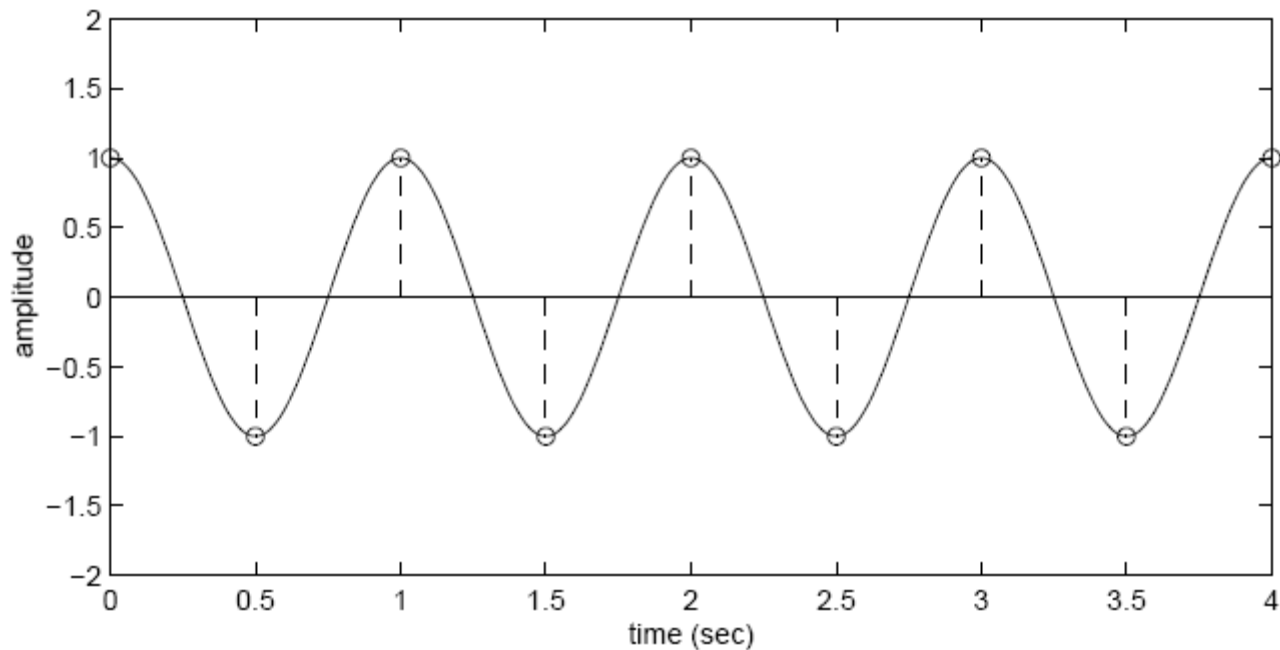


Sampling



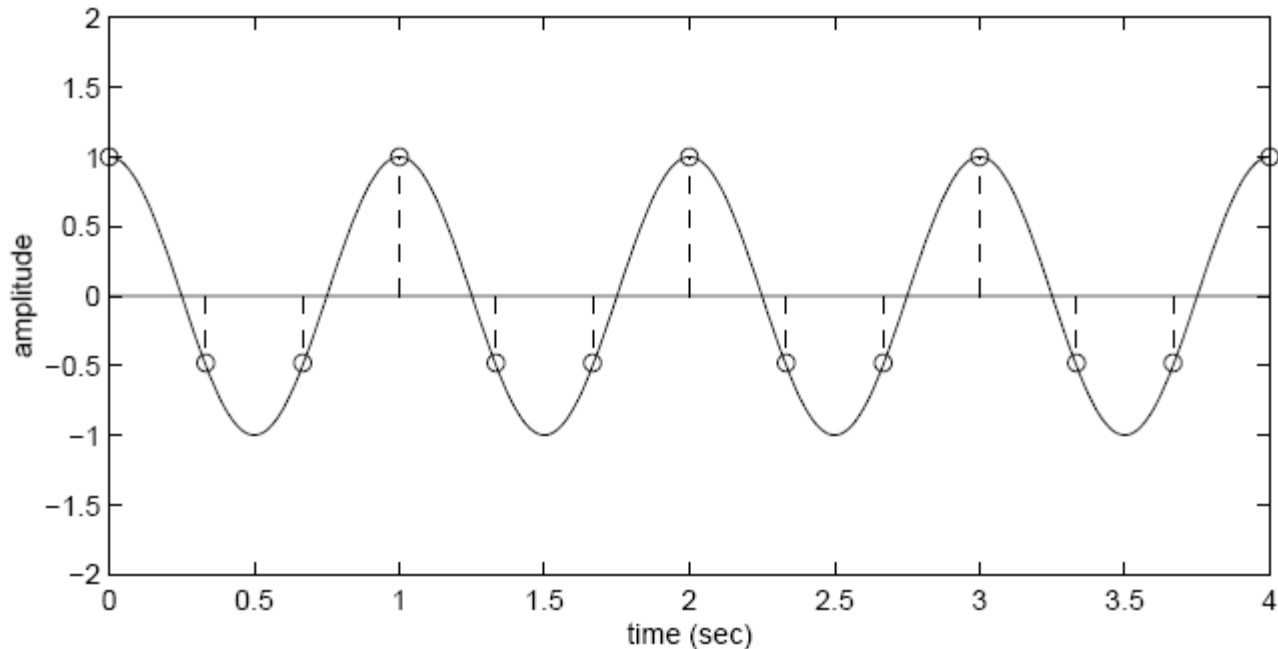
- ▶ Suppose you have the following 1 Hz signal being received
- ▶ How fast do you need to sample, to capture the signal?

Sampling



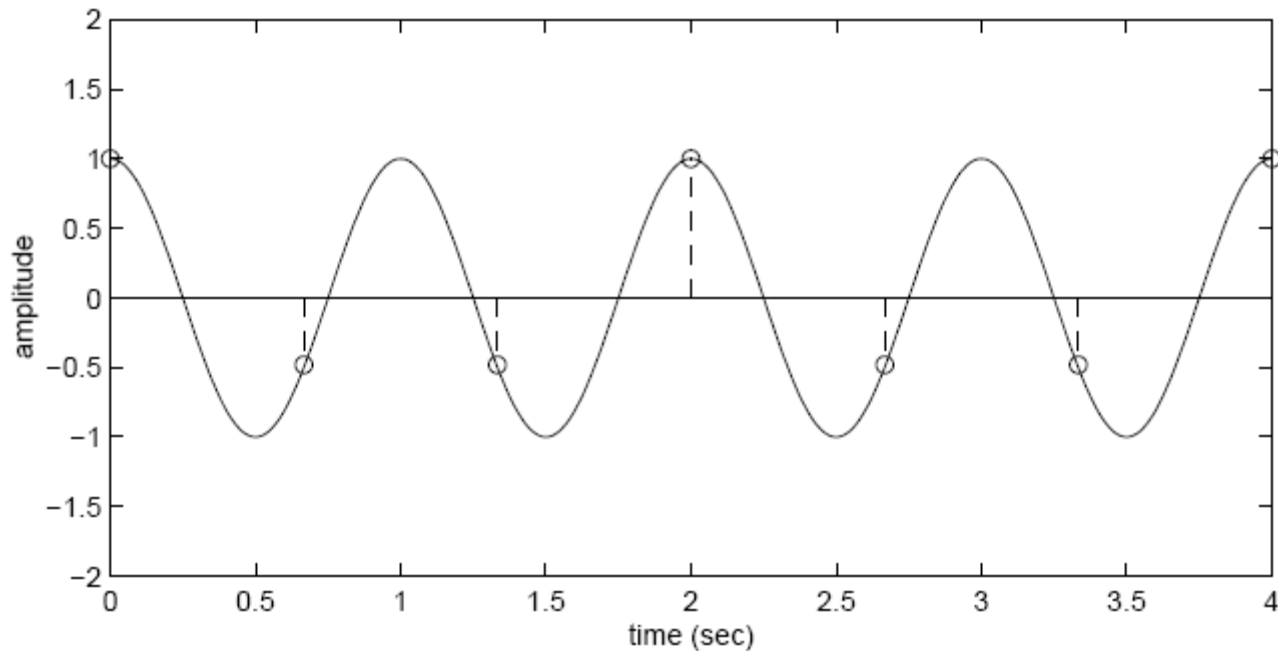
- ▶ Sampling a 1 Hz signal at 2 Hz is enough
 - ▶ Captures every peak and trough

Sampling



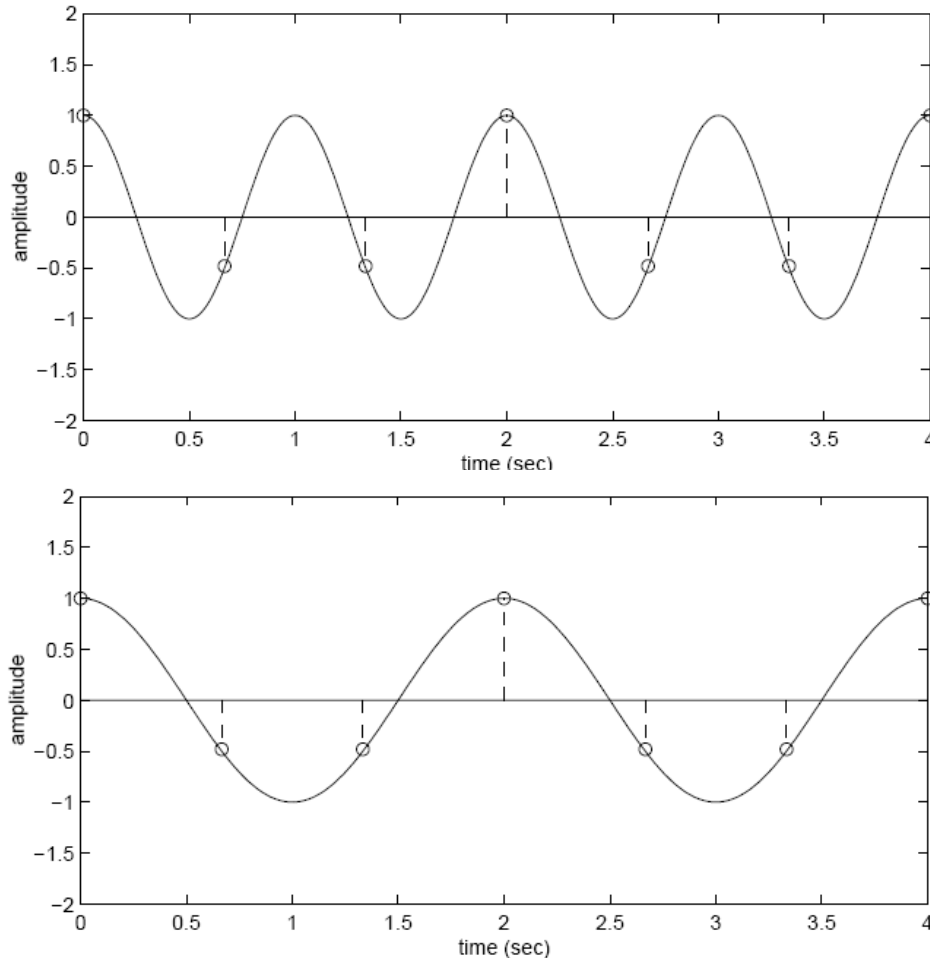
- ▶ Sampling a 1 Hz signal at 3 Hz is also enough
 - ▶ In fact, more than enough samples to capture variation in signal

Sampling



- ▶ Sampling a 1 Hz signal at 1.5 Hz is not enough
 - ▶ Why?

Sampling

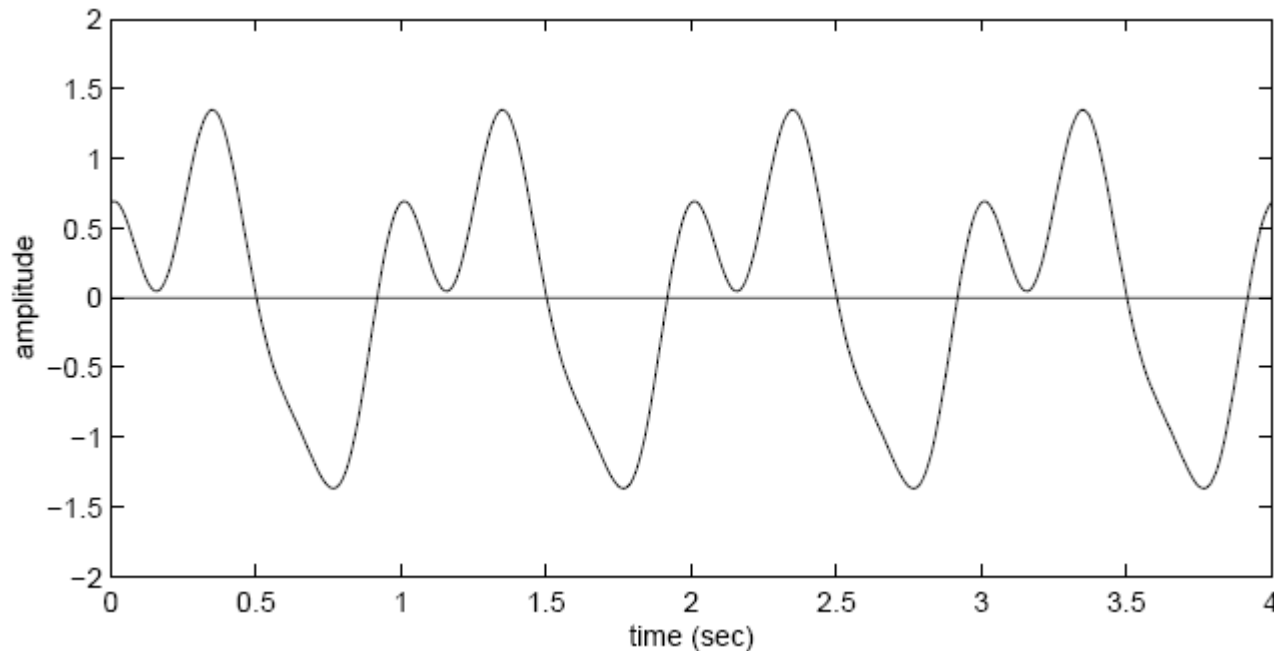


- ▶ Sampling a 1 Hz signal at 1.5 Hz is not enough
 - ▶ Can't distinguish between multiple possible signals
 - ▶ Problem known as **aliasing**

Aliasing

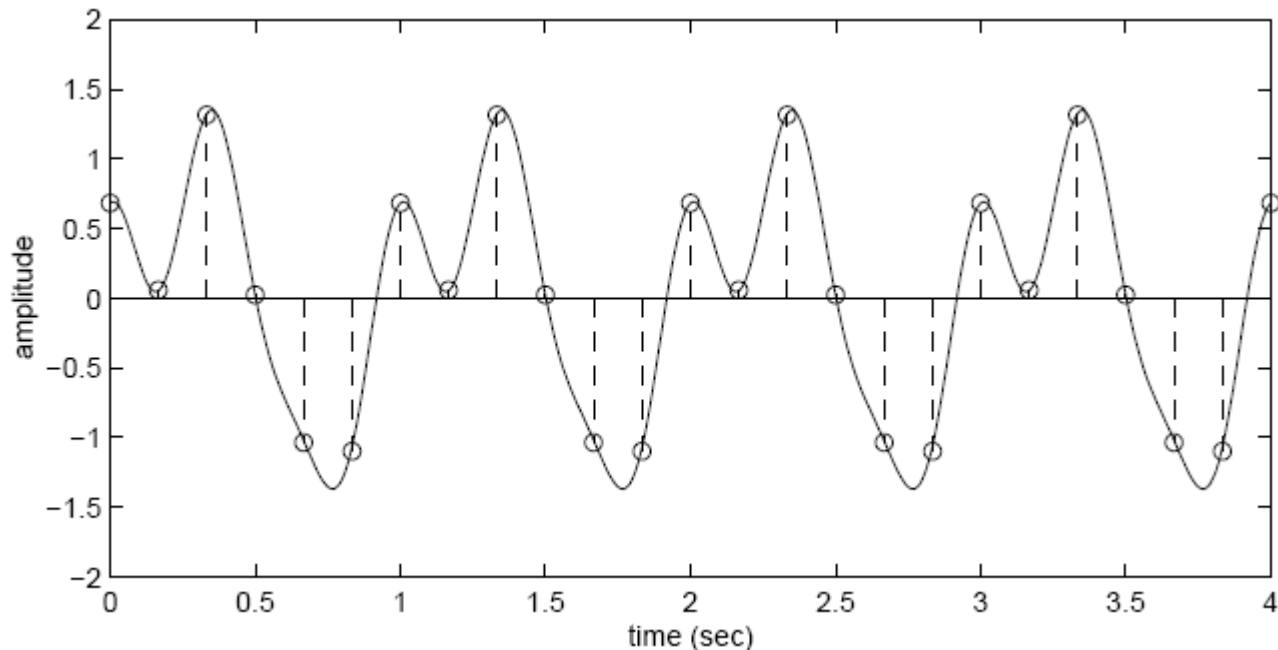


What about more complex signals?



- ▶ Fourier's theorem
 - ▶ Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- ▶ Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
 - ▶ How fast to sample?

What about more complex signals?



- ▶ Fourier's theorem
 - ▶ Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- ▶ Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
 - ▶ How fast to sample? --> **answer: 6 Hz**

Generalizing the Examples

- ▶ What data rate can a channel sustain?
- ▶ How is data rate related to bandwidth?
- ▶ How does noise affect these bounds?
- ▶ What else can limit maximum data rate?



What Data Rate can a Channel Sustain?

How is Data Rate Related to Bandwidth?

- ▶ Transmitting **N** distinct signals over a noiseless channel with bandwidth **B**, we can achieve at most a data rate of

Number of signals per second $\longrightarrow$ $2B \log_2 N$ $\longleftarrow$ Number of bits per signal

- ▶ ex.: a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
- ▶ Nyquist's Sampling Theorem (H. Nyquist, 1920's)

What Data Rate can a Channel Sustain?

How is Data Rate Related to Bandwidth?

- ▶ Transmitting **N** distinct signals over a noiseless channel with bandwidth **B**, we can achieve at most a data rate of

$$\begin{array}{ccc} \text{Number of signals} & \longrightarrow & \boxed{2B} \boxed{\log_2 N} \longleftarrow \text{Number of bits per} \\ \text{per second} & & \text{signal} \end{array}$$

Baud rate

Number of **physical symbols** transmitted per second

rate of at most

- ▶ ex.: a 3000
6000 bits/s

Bit rate

Actual number of **data bits** transmitted per second

- ▶ Nyquist's Relationship

Depends on the number of **bits** encoded in each **symbol**

(20's)

Noiseless Capacity

- ▶ Nyquist's theorem: $2B \log_2 N$
- ▶ Example 1: sampling rate of a phone line
 - ▶ $B = 4000$ Hz
 - ▶ $2B = 8000$ samples/sec.
 - ▶ sample every 125 microseconds



Noiseless Capacity

- ▶ Nyquist's theorem: $2B \log_2 N$
- ▶ Example 2: noiseless capacity
 - ▶ $B = 1200 \text{ Hz}$
 - ▶ $N =$ each pulse encodes 16 symbols
 - ▶ $C = 2B \log_2 (N) = D \times \log_2 (N)$
 $= 2400 \times 4 = 9600 \text{ bps}$



How does Noise affect these Bounds?

► Noise

- Blurs the symbols, reducing the number of symbols that can be reliably distinguished

► Claude Shannon (1948)

- Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

$$\text{channel capacity } C = B \log_2 (1 + S/N)$$

where

C is the maximum supportable bit rate

B is the channel bandwidth

S/N is the ratio between signal power
and in-band noise power

↖
N is noise

How does Noise affect these Bounds?

- ▶ **Noise**

- ▶ Blurs the symbols, reducing the number of symbols that can be reliably distinguished

- ▶ **Claude Shannon (1948)**

- ▶ Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

$$\text{channel capacity } C = B \log_2 (1 + S/N)$$

- ▶ **Represents error free capacity**

- ▶ also used to calculate the noise that can be tolerated to achieve a certain rate through a channel

- ▶ **Result is based on many assumptions**

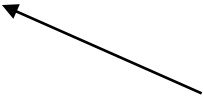
- ▶ Formula assumes white noise (thermal noise)
 - ▶ Impulse noise is not accounted for
 - ▶ Various types of distortion are also not accounted for



Noisy Capacity

- ▶ Telephone channel

- ▶ 3400 Hz at 40 dB SNR


$$\text{SNR(dB)} = 10 \log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{noise}}} \right)$$

decibels (dB) is a **logarithmic** unit of measurement that expresses the magnitude of a physical quantity (usually power or intensity) relative to a specified or implied reference level

Decibels

- ▶ A ratio between signal powers is expressed in decibels

$$\text{decibels (db)} = 10\log_{10}(P_1 / P_2)$$

- ▶ Used in many contexts
 - ▶ The loss of a wireless channel
 - ▶ The gain of an amplifier
- ▶ Note that dB is a relative value
 - ▶ Can be made absolute by picking a reference point
 - ▶ Decibel-Watt – power relative to 1W
 - ▶ Decibel-milliwatt – power relative to 1 milliwatt



Signal-to-Noise Ratio

- ▶ Signal-to-noise ratio (SNR, or S/N)
 - ▶ Ratio of
 - ▶ the power in a signal
 - to
 - ▶ the power contained in the noise
 - ▶ Typically measured at a receiver

- ▶ A high SNR
 - ▶ High-quality signal
- ▶ Low SNR
 - ▶ May be hard to “extract” the signal from the noise
- ▶ SNR sets upper bound on achievable data rate

$$(SNR)_{\text{dB}} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}}$$



Noisy Capacity

▶ Telephone channel

▶ 3400 Hz at 40 dB SNR

▶ $C = B \log_2 (1 + S/N)$ bits/s

▶ SNR = 40 dB

$$\text{SNR(dB)} = 10 \log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{noise}}} \right)$$


$$40 = 10 \log_{10} (S/N)$$

$$S/N = 10,000$$

▶ $C = 3400 \log_2 (10001) = 45.2 \text{ kbps}$



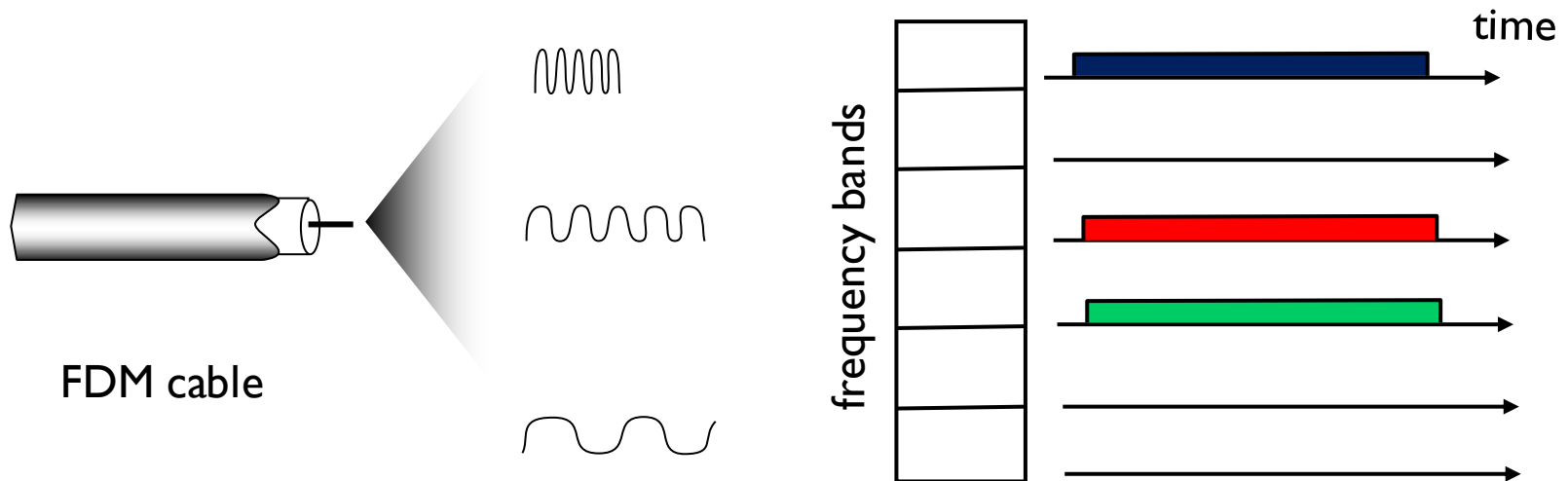
Multiplexing

- ▶ **Capacity of transmission medium**
 - ▶ May exceed capacity required for transmission of a single signal
- ▶ **Multiplexing**
 - ▶ Carrying multiple signals on a single medium
 - ▶ More efficient use of transmission medium



Multiplexing

- ▶ **FDM: Frequency Division Multiplexing**
 - ▶ Channel spectrum divided into frequency bands
 - ▶ Each assigned fixed frequency band/reduced rate
 - ▶ Unused transmission time in frequency bands go idle
 - ▶ Example: 6-station LAN, 1,3,4 transmit, frequency bands 2,5,6 idle



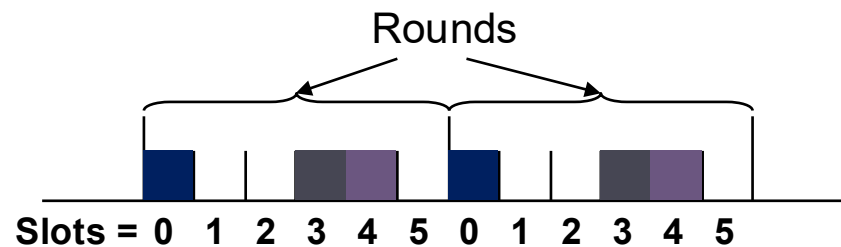
FDM Example: AMPS

- ▶ US analog cellular system in early 80's
- ▶ Each call uses an up and down link channel
 - ▶ Channels are 30 KHz
- ▶ About 12.5 + 12.5 MHz available for up and down link channels per operator
 - ▶ Supports 416 channels in each direction
 - ▶ 21 of the channels are used for data/control
 - ▶ Total capacity (across operators) is double of this



Multiplexing

- ▶ TDM: Time Division Multiplexing
 - ▶ Access in "rounds"
 - ▶ Each user/node/etc... gets fixed length slot in each round
 - ▶ Each user can sent at full speed some of the time
 - ▶ Unused slots go idle
 - ▶ Example: 6-slots with transmissions in slots 0, 3, and 4



TDM Example: GSM

- ▶ **Global System for Mobile communication**
 - ▶ First introduced in Europe in early 90s
- ▶ **Uses a combination of TDM and FDM**
- ▶ **25 MHz each for up and down links.**
- ▶ **Broken up in 200 KHz channels**
 - ▶ 125 channels in each direction
 - ▶ Each channel can carry about 270 kbs
- ▶ **Each channel is broken up in 8 time slots**
 - ▶ Slots are 0.577 msec long
 - ▶ Results in 1000 channels, each with about 25 kbs of useful data; can be used for voice, data, control
- ▶ **General Packet Radio Service (GPRS)**
 - ▶ Data service for GSM, e.g. 4 down and 1 up channel



Spread Spectrum

▶ Direct Sequence Spread Spectrum

- ▶ Spread the signal over a wider frequency band than required
- ▶ Originally designed to thwart jamming
- ▶ Original 802.11 uses 83 MHz in 2.4 GHz band

▶ Frequency-Hopped Spread Spectrum

- ▶ Uses 80 1MHz sub-bands in 2.4 GHz band
- ▶ Transmit over a random sequence of frequencies

Spread Spectrum

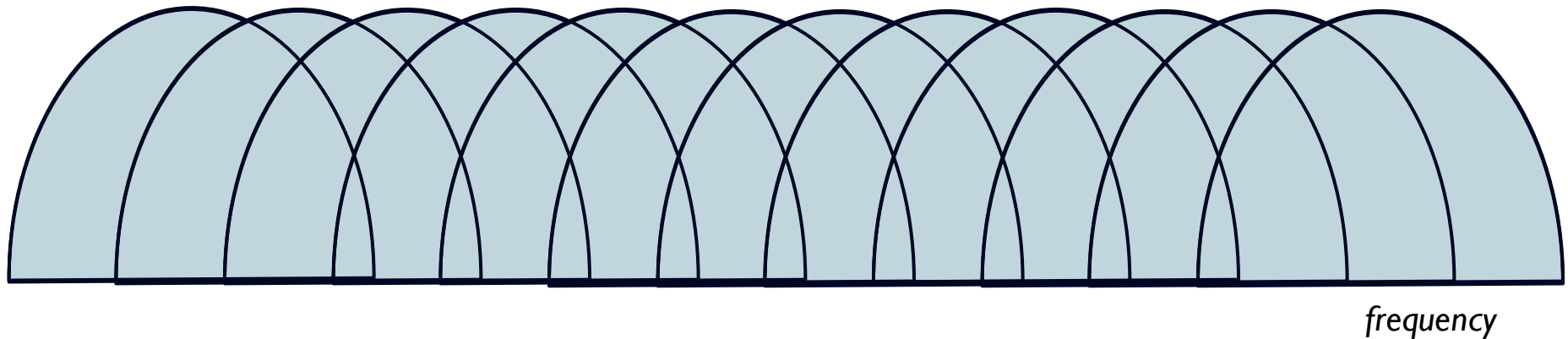
▶ Direct Sequence Spread Spectrum

- ▶ Spread the signal
- ▶ Originally used for military
- ▶ Original spread spectrum
- ▶ Frequency hopping
 - Frequency hopping had many inventors
 - 1942: actress Hedy Lamarr and composer George Antheil patented Secret Communications System
 - Piano-roll to change between 88 frequencies, and was intended to make radio-guided torpedoes harder for enemies to detect or to jam
 - The patent was rediscovered in the 1950s during patent searches when private companies independently developed Code Division Multiple Access, a civilian form of spread-spectrum
- ▶ Uses 80 channels
- ▶ Transmits data



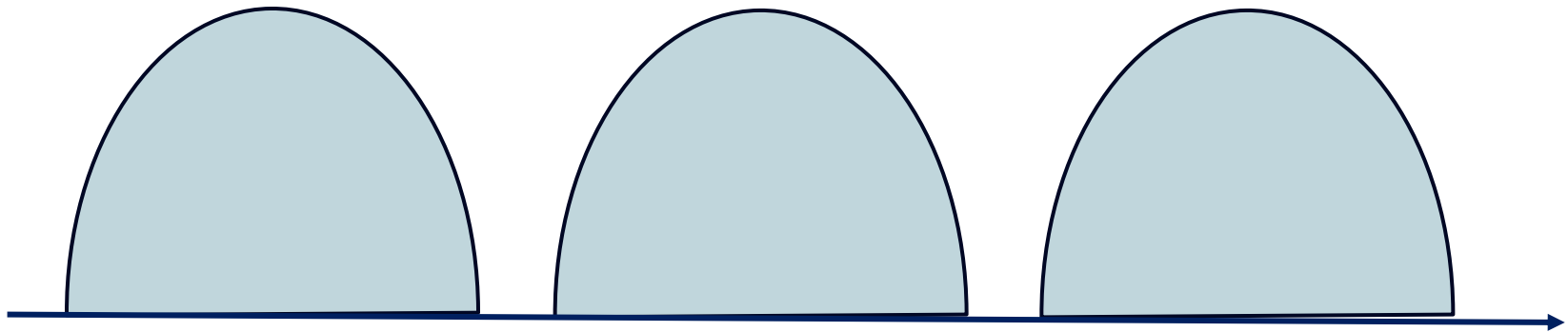
Why Not Just Use FDM?

- ▶ The example shows 12 channels using FDM
 - ▶ How many can we use?



Why Not Just Use FDM?

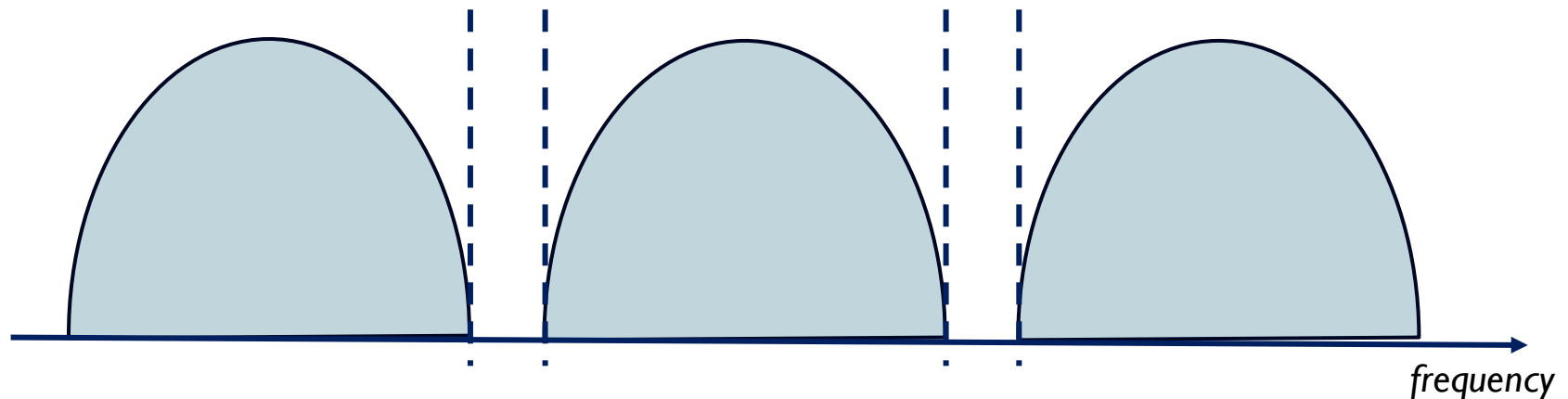
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Why Not Just Use FDM?

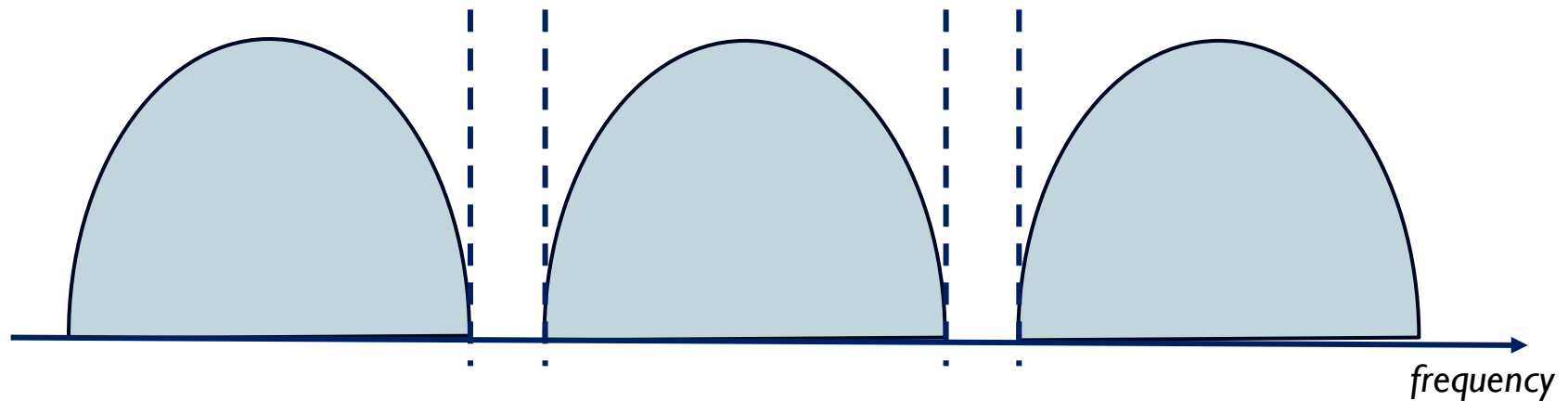
- ▶ Add guard bands

- ▶ Prevent overlap, but waste spectrum
- ▶ Each narrow band is still hit hard by multipath over a long symbol period
 - ▶ Indoor multipath delay spread $\sim 50\text{--}200$ ns
 - ▶ A wideband symbol lasting only tens of ns gets smeared across several symbols $\rightarrow$ inter-symbol interference (ISI)



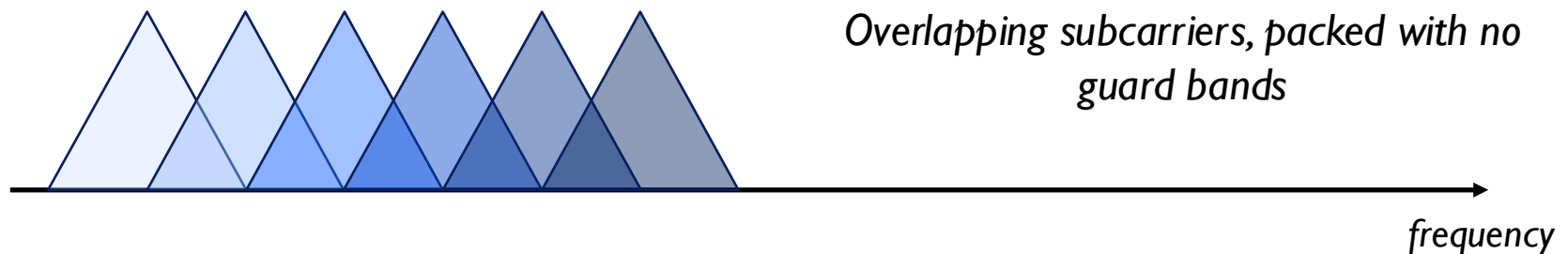
Why Not Just Use FDM?

- ▶ What if subcarriers could pack together with no gaps, and each one resist multipath too?



OFDM: Orthogonal Frequency Division Multiplexing

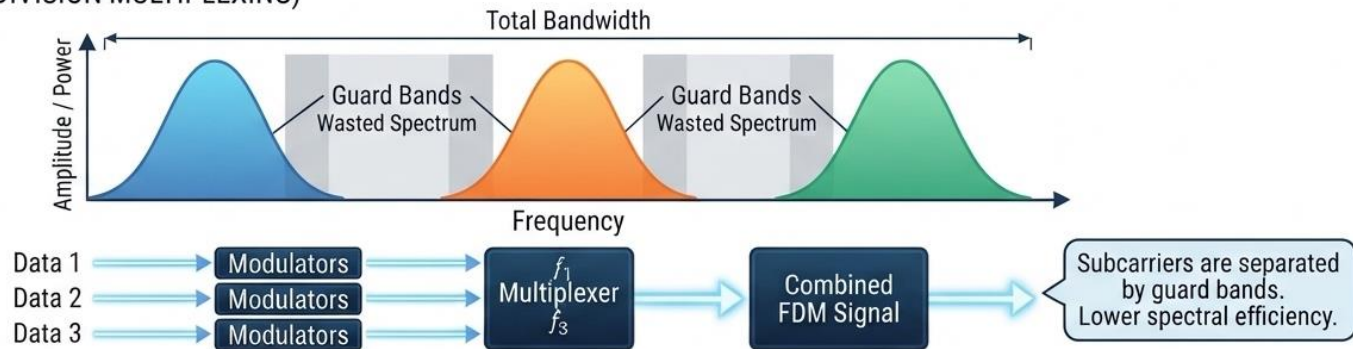
- ▶ Split one wide channel into many narrow, tightly-spaced subcarriers
 - ▶ Orthogonal = each subcarrier's peak lands exactly on its neighbors' nulls
 - ▶ Spacing: $\Delta f = 1/T$ (T = symbol duration) guarantees zero interference
- ▶ Long symbol duration per subcarrier
 - ▶ Far more resistant to multipath delay spread than one wideband signal
 - ▶ A guard interval (cyclic prefix) precedes each symbol, absorbing echoes and eliminating inter-symbol interference



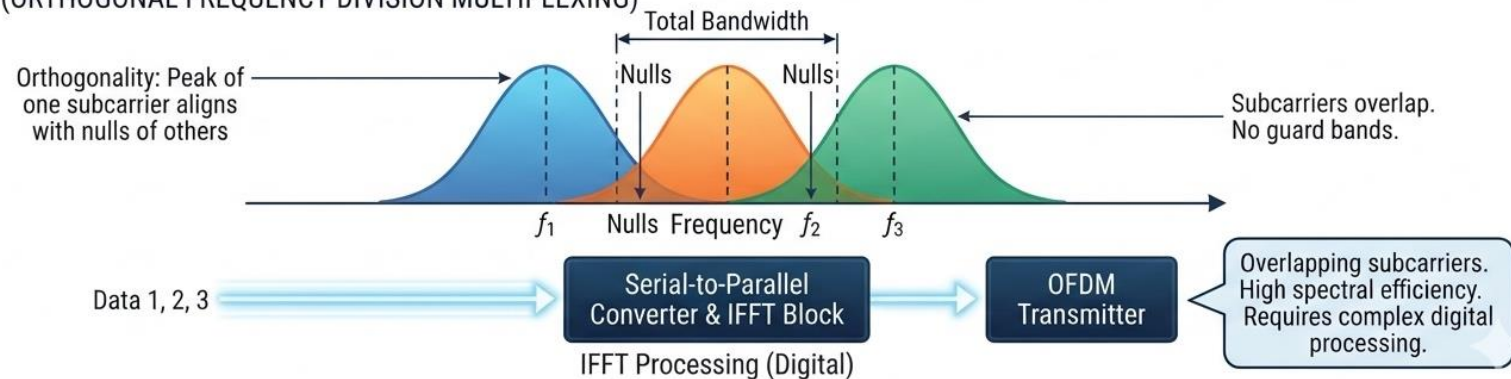
OFDM: Orthogonal Frequency Division Multiplexing

► FDM vs OFDM

FDM (FREQUENCY DIVISION MULTIPLEXING)



OFDM (ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING)



OFDM: Orthogonal Frequency Division Multiplexing

▶ The FDM Approach (Traditional Highway)

- ▶ Each truck gets its own designated lane.
- ▶ To ensure they don't crash into each other, leave a full empty lane between them as a safety buffer (the guard band).
- ▶ The Downside
 - ▶ Waste half of the highway's asphalt just keeping the trucks apart.
 - ▶ If you run out of lanes, you can't send more trucks.

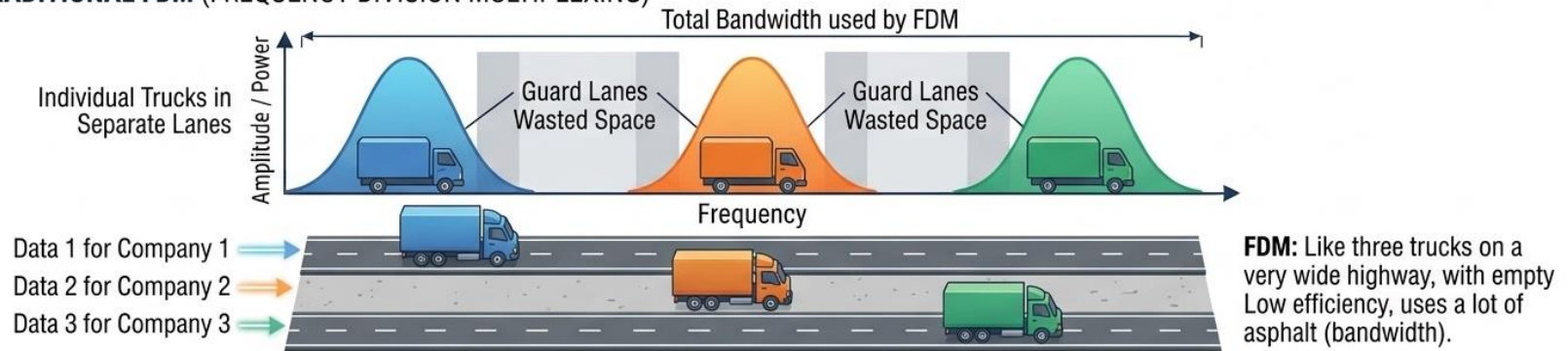
▶ The OFDM Approach (The "Ghost" Trucks)

- ▶ Through mathematical precision, the trucks are perfectly synchronized.
- ▶ They drive overlapping each other in the exact same space.
- ▶ The Magic
 - ▶ Because of orthogonality, at the exact moment Truck A hits its maximum width, Trucks B and C collapse to a width of zero.
 - ▶ They pass right through each other without touching.
- ▶ The Benefit
 - ▶ More trucks on the same highway without them ever colliding or requiring empty buffer lanes.

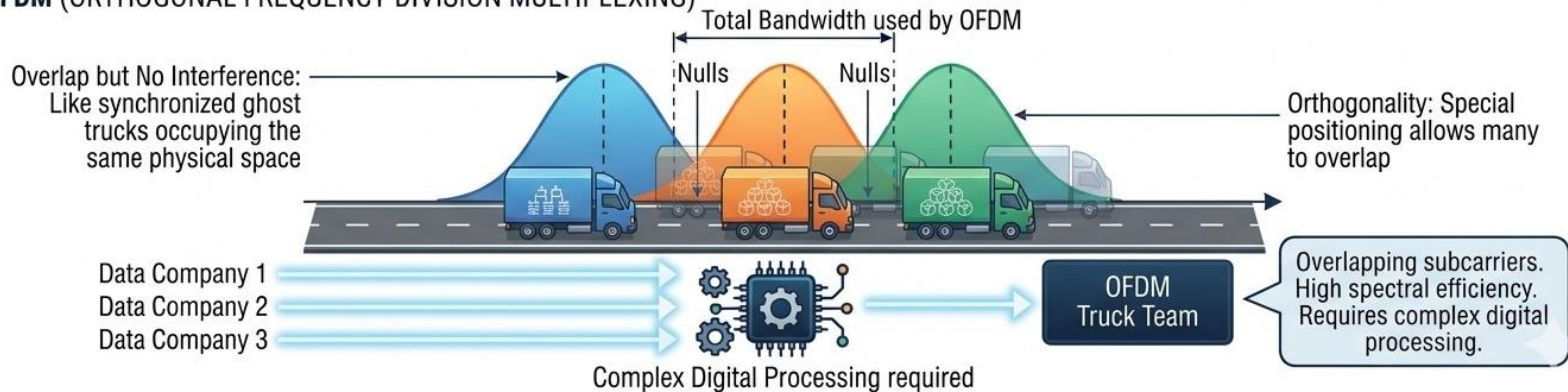
OFDM: Orthogonal Frequency Division Multiplexing

► FDM vs OFDM

TRADITIONAL FDM (FREQUENCY DIVISION MULTIPLEXING)



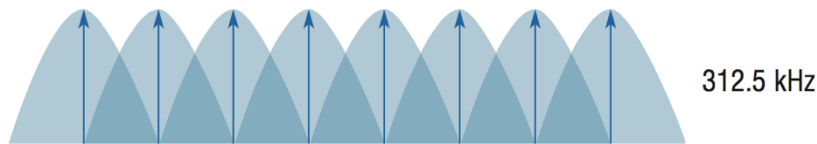
OFDM (ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING)



OFDM: Orthogonal Frequency Division Multiplexing

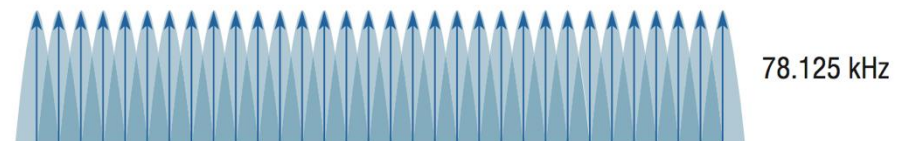
▶ 802.11a

- ▶ 20 MHz channel
- ▶ 64 subcarriers
- ▶ 312.5 kHz spacing
- ▶ 4 μ s symbol (3.2 μ s data + 800 ns cyclic prefix)
- ▶ Generated by IFFT at sender
- ▶ Decoded by FFT at receiver



▶ 802.11ax

- ▶ 20 MHz channel
- ▶ 242 subcarriers
- ▶ 78.125 kHz spacing
- ▶ 12.8 μ s symbol + a guard of 0.8, 1.6, or 3.2 μ s
 - ▶ Total symbol time of 13.6, 14.4, or 16 μ s

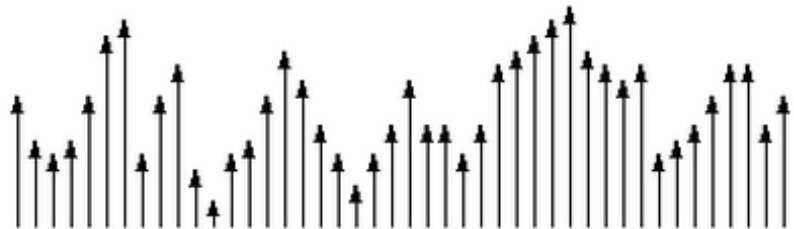


OFDM vs. Frequency-Selective Fading

- ▶ Real channels are often frequency-selective
- ▶ Different frequencies fade independently due to multipath
- ▶ Frequency selective fading causes Inter-Symbol Interference

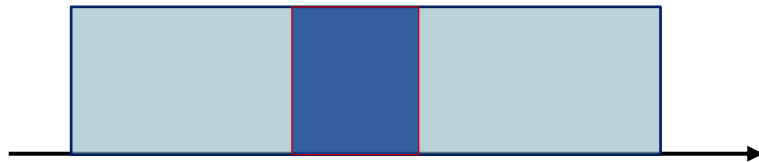


Carrier amplitude before fading



OFDM vs. Frequency-Selective Fading

- ▶ Real channels are often frequency-selective
- ▶ Different frequencies fade independently due to multipath
- ▶ Frequency selective fading causes Inter-Symbol Interference



Single wideband signal

One deep fade corrupts the whole signal

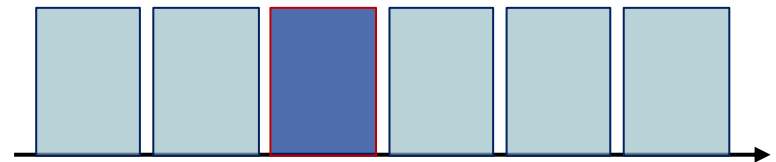
OFDM vs. Frequency-Selective Fading

- ▶ Split into many narrow
 - ▶ N nearly flat-fading channels
 - ▶ A deep fade (or narrowband interferer) wipes out only a handful of subcarriers, not the whole signal
 - ▶ Lost subcarriers are recovered with forward error-correcting codes
 - ▶ No complex per-symbol equalizer needed, unlike single-carrier high-rate signals



Single wideband signal

One deep fade corrupts the whole signal



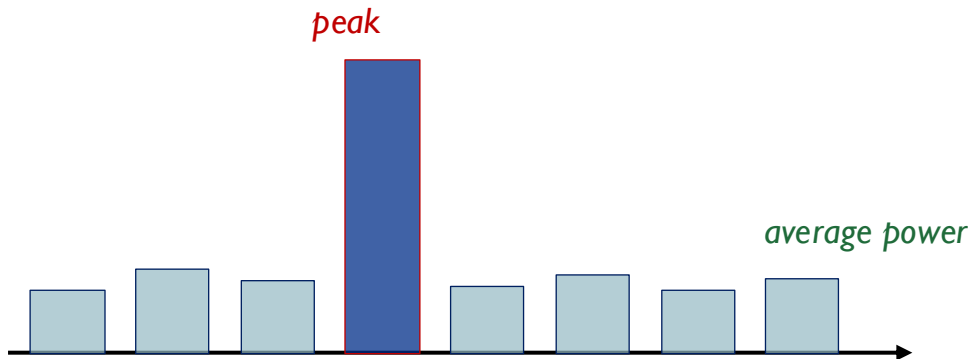
OFDM: many narrow subcarriers

Only 1–2 lost – recovered with FEC

OFDM Trade-offs

► Peak-to-Average Power Ratio (PAPR)

- Many subcarriers summed together can occasionally add up constructively
 - Very high instantaneous peaks relative to average power; PAPR grows with the number of subcarriers
 - Requires expensive, highly linear power amplifiers or else the signal clips and distorts at the peaks

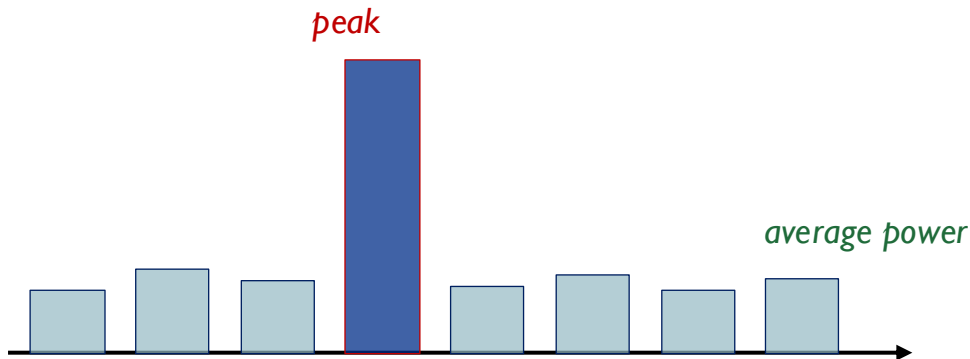


Instantaneous OFDM waveform amplitude, summed across subcarriers

OFDM Trade-offs

► Intercarrier Interference (ICI)

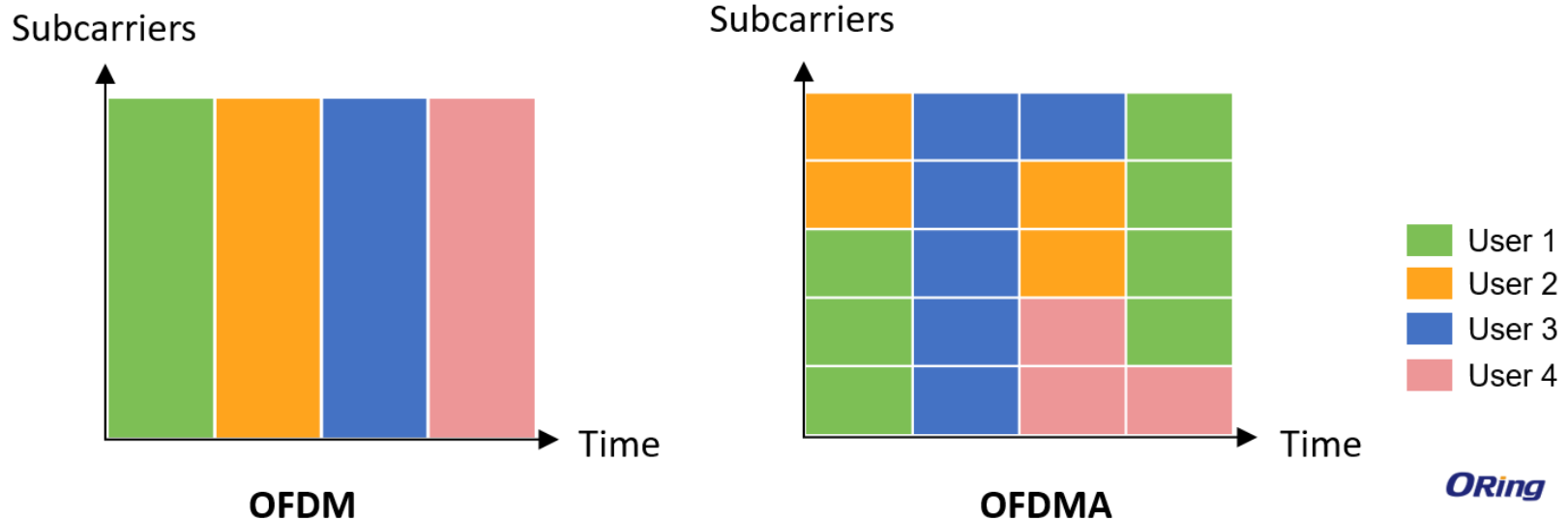
- Orthogonality requires precise frequency alignment
- Doppler shift/mismatched oscillators shift subcarriers slightly
 - No longer landing on each other's nulls
 - Subcarriers bleed into each other
- The cyclic prefix protects against multipath-caused ISI, but does not fix frequency-offset-caused ICI



*Instantaneous OFDM waveform
amplitude, summed across
subcarriers*

OFDM in Practice

- ▶ The dominant PHY technique in modern wireless
 - ▶ Wi-Fi (802.11a and later), 4G LTE, 5G NR
 - ▶ Also used on wires: DSL and cable (DOCSIS)
- ▶ Improvement: Multi-user OFDMA
 - ▶ Divides subcarriers among multiple simultaneous users



Frequency Reuse in Space

- ▶ Frequencies can be reused in space
 - ▶ Distance must be large enough
 - ▶ Example: radio stations
- ▶ Basis for “cellular” network architecture
- ▶ Set of “base stations” connected to the wired network support set of nearby clients
 - ▶ Star topology in each circle
 - ▶ Cell phones, 802.11, ...

