Lecture 2

Overview of Wireless Systems (1)

Wireless Systems are Different!

- Physical layer is not really "physical"
  - High error rates compared to copper/fibre
- End devices are not fixed
  - Mobility makes protocols more complicated
- Power is a big issue
  - Devices run on battery power, have small size, and limited capabilities

PHY Layer Issues

- The radio channel is harsh
  - Cables and wires have "predictable" and time-invariant transmission characteristics
  - The radio channel is dynamic and harsh (High error rates need mitigation)
  - Examples of problems
    - Fading
    - Multipath dispersion
    - Signal attenuation due to rain or snow
    - Interference (again!)
- Coverage
- Effect on protocols

Spectrum Regulation (1)

- Spectrum Regulation
  - The medium of transmission is air
  - The medium cannot be easily duplicated and it must be shared by ALL applications
    - Communications, broadcast, emergency services, television, military, etc.
- Sharing is achieved by allocating separate "bands" of spectrum to users of different applications
    - Broadcast radio: 520-1605.5 kHz – AM Radio
    - Broadcast radio: 87.5 – 108 MHz – FM Radio
  - A band of spectrum refers to a range of electromagnetic frequencies
- The FCC regulates the spectrum allocated to applications

Show spectrum allocation chart

Spectrum Regulation (2)

- There is LIMITED spectrum for different applications
- The frequency bands are not "contained" as in the case of wired transmissions
  - There is some interference between signals transmitted in one frequency band and another
  - Same thing is true if you choose to split the band for an application (think AM)
- Capacity is limited and we need novel methods to improve capacity
- SUMMARY
  - Spectrum and hence bandwidth is limited
  - Radio transmissions can cause interference

MAC layer Issues + Network Design & Deployment

- MAC layer issues
  - Shared "broadcast" medium
    - Need for a simple medium access mechanism
  - Performance
    - Throughput, delay and QoS
- Network design and deployment
  - No single type of wireless access is available everywhere
  - Spectrum is scarce
    - Coexistence, interference, planning
  - Frequency reuse and cellular topology

Radio Resource Management & Power Management

- Resource limitations
  - Radio resources – link "quality" varies substantially over time and space
  - Power:
    - A mobile device relies on battery power
    - Transmissions consume energy!
      - The transmission scheme MUST be efficient in terms of energy consumption
  - Computation: The device cannot perform complex operations like a wired device
- Radio resource and power management
  - Assignment of radio channels and transmit power
  - Admission control, power control and handoff decision

Mobility Management

- Wireless devices are popular because they do not need to be tethered to a place like wired devices
- Wireless devices are continuously changing locations
  - The connectivity changes
  - Devices may move out of coverage of a service
  - Someone should keep track of where the device is to deliver information to it
  - Someone should make sure that the connection is not broken as a wireless device moves
- In wired communications the "address" of the device identifies its location – this is no longer true with wireless devices
- A moving device will "see" a harsher channel!
- Mobility management
  - Location management
    - Tracking where a MS is
  - Handoff management
    - Routing calls/packets as a MS moves
  - Routing in ad hoc networks
  - Database issues

Operations and Security

- Management and Security
  - Mobile end host is no longer confined to the home network
  - Wireless links can be easily "tapped"
  - Fraud
    - Accounting and billing
  - Conflicts with other issues
- Network operations and management
  - Accounting and billing to charge subscribers correctly
  - Access to resources and services on the network
- Service discovery and data management
  - Sensors and RF-IDs
    - How is data maintained?
    - Where should data reside?
    - How can it be efficiently accessed?

Summary – I

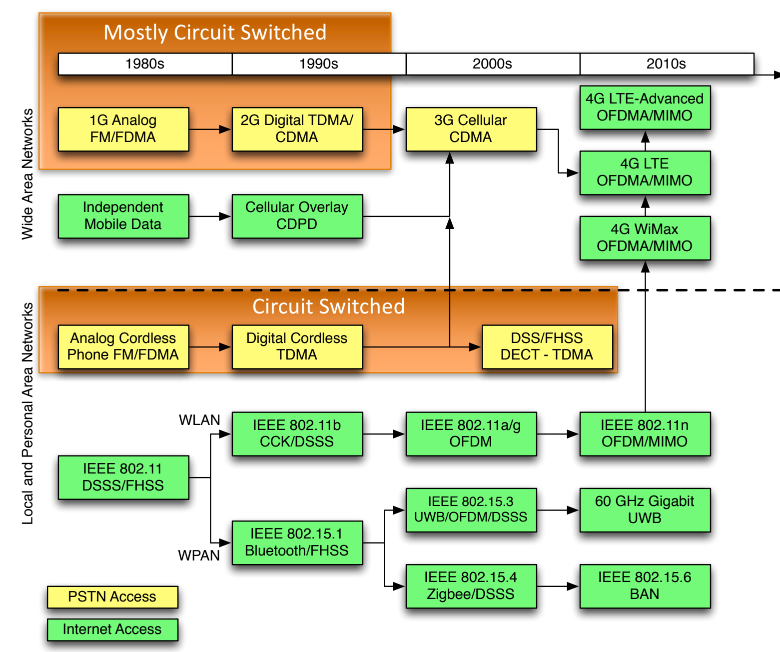
(Class Focus)

- Spectrum is scarce
  - We need to squeeze as many data bits as possible in a given bandwidth
  - The more data bits you squeeze in the more stringent are the system requirements
    - Example: Squeezing in more data => larger signal to noise ratio requirement => larger transmit power => lower battery life
    - Example: multipath dispersion is not a problem at low data rates
    - Example: complex processing can result in large form factor

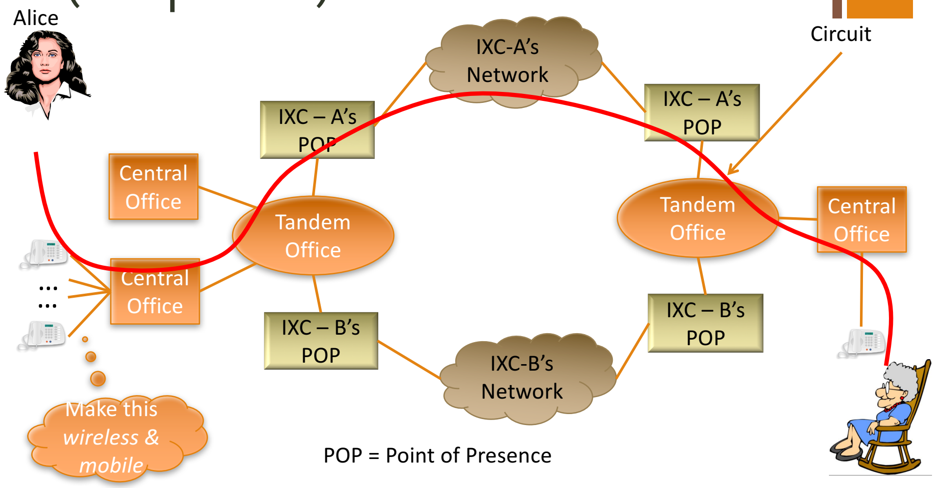
Summary - II

(Class Focus)

- Physical layer makes wireless communications unreliable and erroneous
  - Contributes greatly to the complexity of the system
  - Impacts all other aspects of a wireless system
- Fundamentally different from wired networks
  - Resource issues
  - Mobility issues
  - Network design issues

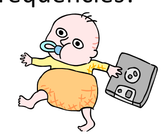


Circuit switched voice call (simplified)



First Generation Cellular Systems

- Goal: Provide basic voice service to mobile users over large area
- 1 G Systems developed late 70's early 80's, deployed in 80's
  - Advanced Mobile Phone System (AMPS) - USA
  - Total Access Communications Systems (TACS) - UK
  - Nordic Mobile Telephone (NMT) System – Scandinavian PTTs
  - C450 - W. Germany
  - NTT System - Nippon Telephone & Telegraph (NTT) – Japan
- Incompatible systems using different frequencies!
  - Have similar characteristics though



OR

1G Cellular (voice) Standards

Show RF Spectrum Allocation Chart

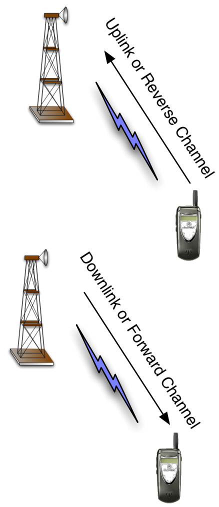
Standard	Downlink (MHz)	Uplink (MHz)	Channel Spacing	Multiple Access	Region	Comments
AMPS	869-894	824-849	30 kHz	FDMA	USA	FM & FSK Modulation
TACS	935-960	890-915	25 kHz	FDMA	EC	Later, bands allocated to GSM
ETACS	917-950	872-905	25 kHz	FDMA	UK	
NMT-450	463-467.5	453-457.5	25 kHz	FDMA	EC	
NMT-900	935-960	890-915	12.5 kHz	FDMA	EC	
JTACS	860-870 & others	915-925 +	25/12.5 kHz	FDMA	Japan	

Duplexing Modes

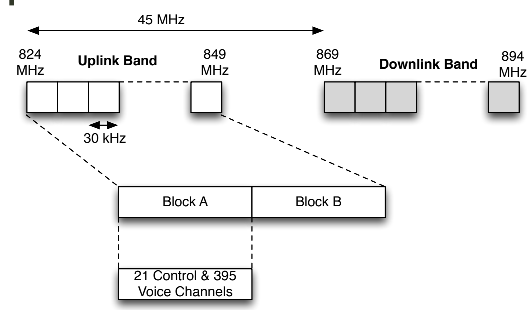
- Simplex – one way communication (e.g., broadcast AM)
- Duplex – two way communication
  - TDD – time division duplex
    - Users take turns on the frequency channel
  - FDD – frequency division duplex
    - Users get two channels – one for each direction of communication
      - For example one frequency channel for uplink (mobile to base station) another frequency channel for downlink (base station to mobile)
  - Half-duplex
    - As in 802.11, a device cannot simultaneously be transmitting and receiving

Uplink and Downlink

- The link from the mobile to the tower is called the "uplink"
  - Sometimes called the "reverse" channel
- The link from the tower to the mobile is called the "downlink"
  - Sometimes called the "forward" channel



Example: AMPS

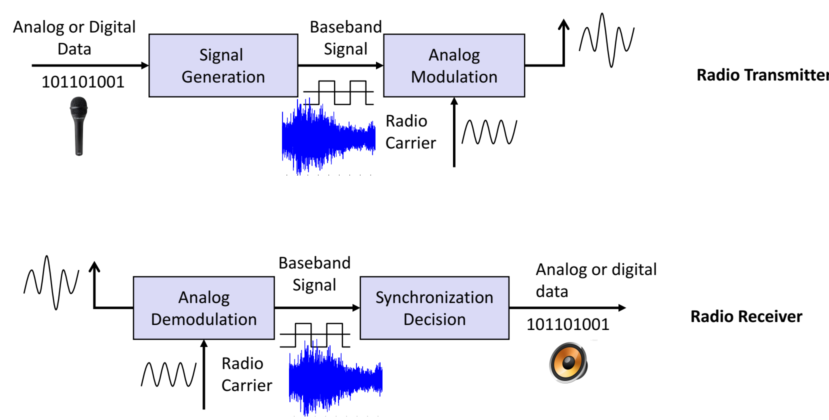


- Voice channels occupy 30 kHz and use frequency modulation (FM)
- 25 MHz is allocated to the uplink and 25 MHz for the downlink
- 12.5 MHz is allocated to non-traditional telephone service providers (Block A)
- 12.5 MHz / 30 kHz = 416 channels
- 395 are dedicated for voice and 21 for control

What does "Channel Spacing" mean?

- A frequency carrier (**sinusoid**) with modulation has a certain "bandwidth"
  - This bandwidth varies across technologies and systems
  - Logically, you can think of it as a slice or chunk of spectrum occupied by a signal
  - **Physically, it is more complicated**
- Multiple carriers are used in all wireless systems
  - The "separation" between the frequencies of the carriers = "channel spacing
  - This is also **roughly** equal to the **bandwidth** of the signal

Modulation and demodulation: Pictorial View



What is Modulation?

- Basic Idea
  - Convert digital or analog information to a waveform
  - Waveform is suitable for transmission over a given medium
- Process
  - Involves varying some parameter of a carrier wave as a function of the "information"
  - Carrier = sinusoidal waveform at a given **frequency**
  - After modulation, signal has a **"bandwidth"**
- Information
  - Usually contained in a message signal at **baseband** that is either analog or digital
- General sinusoid

$A \cos(2\pi f_c t + \varphi)$

Amplitude

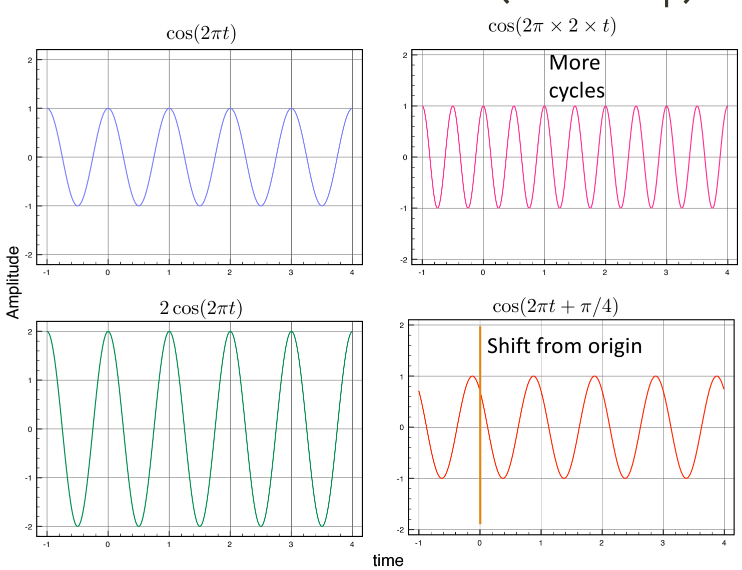
Frequency

Phase

Terminology - Sinusoid

- 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 the signal
- Wavelength (λ) - physical distance occupied by a single cycle of the signal
  - Or, the distance between two points of corresponding phase of two consecutive cycles
- For electromagnetic waves in air or free space, $\lambda = cT = c/f$ where c is the speed of light

The sinusoid – A cos(2πft +ϕ)



The sinusoid continued

- General sinusoid wave
  - $s(t) = A \cos(2\pi f t + \phi)$
- Previous slide shows the effect of varying each of the three parameters
  - $A = 1$, $f = 1$ Hz, $\phi = 0$ => $T = 1$s
  - Increased peak amplitude; $A=2$
  - Increased frequency; $f = 2$ => $T = 1/2$
  - Phase shift; $\phi = \pi/4$ radians (45°)
- Note: 2π radians = 360° = 1 period

Why Modulate?

- Support medium characteristics
- Antenna size
  - Usually the size of an antenna is proportional to the wavelength
    - Typical antenna size = $\lambda/4$
  - Smaller wavelengths => smaller antennas
- Example:
  - 3000 Hz baseband signal
  - $\lambda = 3 \times 10^8 / 3 \times 10^3 = 10^5$ m
  - Antenna is 100 km / 4 = 25 km = 15.6 miles long
- Example:
  - 900 MHz RF signal
  - $\lambda = 3 \times 10^8 / 9 \times 10^8 = 1/3$ m = 33.3 cm
  - Antenna is 33.3 / 4 = 8.3 cm long
- Interference rejection
  - Some modulation schemes are more robust than others in the presence of interference
  - Compare AM and FM
- Multiplexing
  - Signals can be moved to a different part of the spectrum
- Simplify circuitry

Analog Modulation

- Message signal (baseband) is analog: we have three types of modulation
  - Amplitude modulation (AM)
    - Vary the amplitude with the analog baseband signal
  - Frequency modulation (FM)
    - Vary the frequency with the analog baseband signal
  - Phase modulation (PM)
    - Vary the phase with the analog baseband signal

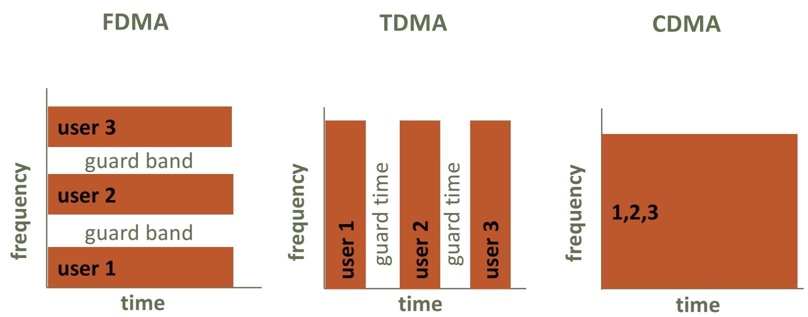
FM in Wireless Systems

- Frequency modulation was employed in 1G analog cellular telephone systems
  - AMPS (30 kHz channels)
  - JTACS (25 kHz channels)
  - NMT
- **One channel carried one voice call**
  - Uplink or downlink
- Reason for selecting FM
  - More robust to interference and fading compared to AM
  - Capture effect was useful and forms the basis for the original frequency reuse design

Centralized Multiple Access Techniques

- FDMA (frequency division multiple access)
  - Separate spectrum into non-overlapping frequency bands
  - Assign a certain frequency to a transmission channel between a sender and a receiver
  - Different users share use of the medium by transmitting on non-overlapping frequency bands at the *same time*
- TDMA (time division multiple access):
  - Assign a fixed frequency to a transmission channel between a sender and a receiver for a certain amount of time (users share a frequency channel in time slices)
- CDMA (code division multiple access):
  - Assign a user a unique code for transmission between sender and receiver, users transmit on the same frequency at the same time
- OFDMA (orthogonal frequency division multiple access):
  - Advanced form of FDMA/TDMA

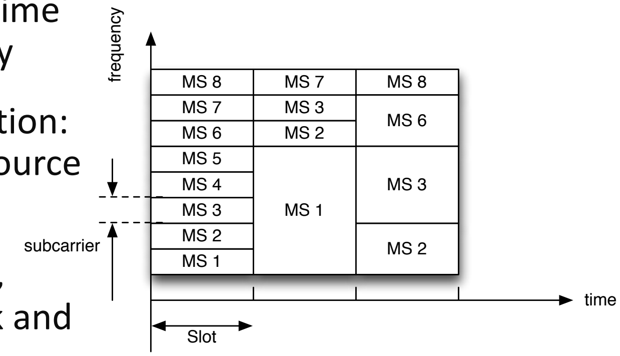
Multiple Access



Wireless systems often use a combination of schemes; GSM – FDD/FDMA/TDMA

OFDMA

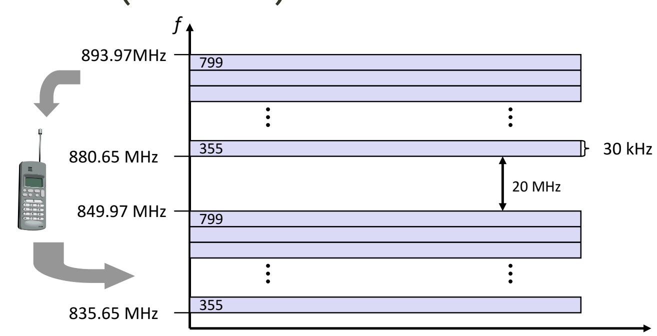
- Flexible resource allocation in time and frequency
- Unit of allocation: "Physical Resource Blocks"
- LTE Downlink, WiMax uplink and downlink



FDMA

- FDMA – simplest and oldest method
- Band of width *F* is divided into *T* non-overlapping frequency channels
  - Guard bands minimize interference between channels
  - Each station is assigned a different frequency
- Can be inefficient if more than *T* stations want to transmit or traffic is bursty
  - Results in unused bandwidth and delays
- Receiver requires high quality filters for adjacent channel rejection
- Used in First Generation Cellular (AMPS, NMT, TACS)

FDD/FDMA - general scheme, example AMPS (B block)



$f(c)$ = 825,000 + 30×(channel number) kHz <- uplink
$f(c)$ = f uplink + 45,000 kHz <- downlink

In general all systems use some form of FDMA

2G Cellular Systems (voice)

- Motivation for 2G Digital Cellular
  - Increase System Capacity
  - Add additional services/features
    - SMS, caller ID, etc.
  - Reduce Cost
  - Improve Security
  - Interoperability among components/systems
    - GSM only
- Main 2G Systems
  - North American TDMA (NA-TDMA) (IS-136)
  - Global System for Mobile (GSM)
  - IS-95 (cellular CDMA)

GSM: Global System of Mobile Communications

- A heterogeneous analog cellular implementation was observed in Europe in the 1980s
  - United Kingdom, Italy, Spain, Austria: TACS (900 MHz)
  - Scandinavia, Germany, The Netherlands, Spain: NMT (450 MHz, 900 MHz)
  - France: Radiocom
- 1987: 12 Member countries sign MOU for a common standard
- ETSI: European Telecommunications Standards Institute in 1989 took over the standardization of all cellular telephony in Europe
  - Strongly influenced by ISDN
  - Signaling System 7

2G Standards

System/Parameter	IS-54/IS-136	JDC	GSM	IS-95
Region	USA	Japan	Europe, Asia etc.	USA/Asia
Multiple access /duplex	TDMA/FDMA/FDD	TDMA/FDMA/FDD	TDMA/FDMA/FDD	CDMA/FDMA/FDD
Channels/carrier	3	3	8	Variable
Channel spacing	30 kHz	25 kHz	200 kHz	1.25 MHz
Uplink	824-849 MHz	810-826 MHz	890-915 MHz	824-849 MHz
Downlink	869-894 MHz	940-956 MHz	935-960 MHz	869-894 MHz
Channel bit rate	48.6 kbps	42 kbps	270.83 kbps	1.288 Mchips/s
Modulation Scheme	$\pi/4$ - DQPSK	$\pi/4$ - DQPSK	GMSK	QPSK/OQPSK
Spectral efficiency	1.62 bps/Hz	1.68 bps/Hz	1.35 bps/Hz	Variable
Frame duration	40 ms	20 ms	4.615 ms	20 ms
Peak power	0.6 W		1 W	
Data Service	9.6 kbps	9.6-14.4 kbps	9.6-14.4 kbps	9.6-115 kbps

Digital Modulation (1)

- Changing the parameters of a sinusoid is called “shift keying” if information is digital
- Types
  - Amplitude-shift keying (ASK)
    - Amplitude difference of carrier
  - Frequency-shift keying (FSK)
    - Frequency difference near carrier frequency
  - Phase-shift keying (PSK)
    - Phase of carrier signal shifted
  - Quadrature amplitude modulation (QAM)
    - Both amplitude and phase of the carrier carry data
- Bits/Symbol
  - Binary (one bit in one symbol => two symbols)
  - M-ary ($\log_2 M$ bits in one symbol => M symbols)

Digital Modulation (2)

- Binary
  - 2 symbols – 0 and 1
  - 1 bit per symbol
- M-ary
  - M symbols -- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \ldots, \alpha_M$
  - We have $k = \log_2 M$ bits/symbol
  - Usually $M = 2^k$
- Use amplitude, frequency or phase to carry the discrete information

Recap NRZ

'0' -> positive pulse
'1' -> negative pulse

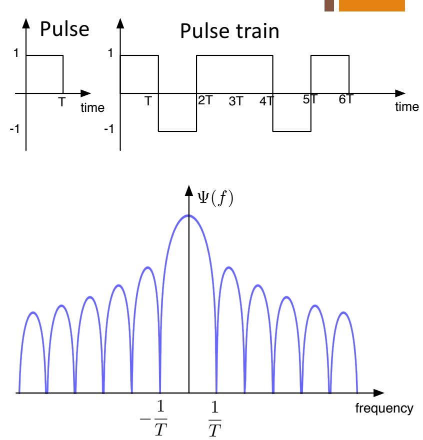
Line Codes

- Non Return-to-Zero (NRZ)
  - Each digital value is represented by a voltage pulse
  - The voltage value is constant for the entire symbol duration
- Return-to-Zero (RZ)
  - Voltage pulses have duty cycles
    - They do not last for the entire symbol duration
    - If the duty cycle is 100%, it becomes NRZ
- Unipolar
  - Signal values are 0V or some positive voltage
- Antipodal (or bipolar)
  - Both positive and negative voltage values (usually identical in magnitude) exist

Comparison of Four Combinations

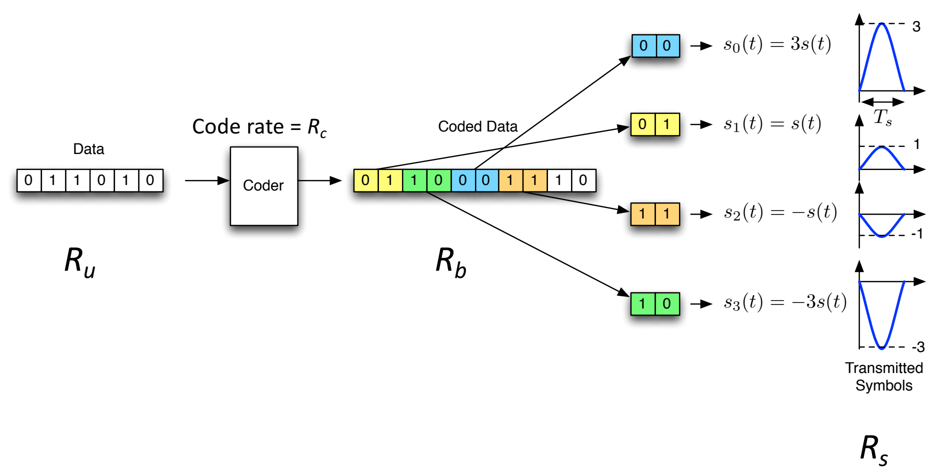
Bandwidth of a rectangular pulse

- Combinations
  - Unipolar RZ, NRZ and Bipolar RZ, NRZ
  - Assume RZ has 50% duty cycle
- Signal Power
  - Peak and average
- Bandwidth
  - RZ needs more bandwidth (why?)
- Sampling threshold for discrimination
  - Antipodal has a zero threshold for binary
- Transitions
  - RZ has more transitions, but no difference between unipolar and antipodal



Spectrum
(Power Spectral Density)

Example of 4-Ary digital transmission scheme



Symbol Rate, Bit Rate, Code Rate

- R_s is the symbol rate (how many pulses per second)
  - Symbol duration is $T_s = 1/R_s$
  - Often we will simply use R and T
- Bit rate is R_b which is R_s × (Number of Bits/Symbol)
  - If the scheme is M-ary, there are $k = \log_2 M$ bits/symbol
- "Code rate" is R_c which tells you what is the fraction of "actual data"
  - Code rate is usually less than or equal to 1

BW ≈ $1/T_s$

For most practical purposes

Example

- Consider an 8-ary scheme (there are 8 different symbols)
  - Each symbol carries 3 bits
- Let the symbol duration be 1 µs - one symbol is transmitted every microsecond
  - Symbol rate is 1 Msps ($R_s = 1/T_s$)
  - Raw bit rate is 3 Mbps ($R_b = 3 \times R_s$)
  - What is the approximate BW of the signal?
- Let the code rate R_c be 1/3
  - This means, one out of every 3 bits is the actual data
  - 2 out of 3 bits are redundant
  - Actual (useful) data rate is 1 Mbps ($R_u = R_c \times R_b$)

Why Digital Modulation?

- Analog cell phone systems migrated to digital in the 1990s
- Some main reasons
  - Increase System Capacity
    - Squeeze more channels in a given bandwidth
    - Example: Employ TDMA (3 channels in 30 kHz in NA-TDMA)
    - Voice compression
  - Efficient transmission
    - Error control coding, equalizers, etc. => lower power needed
    - More resistant to interference
- More reasons
  - Add additional services/features
    - SMS, caller ID, etc.
  - Reduce cost and size of mobile devices
  - Improve Security (encryption possible)
  - Data service and voice treated same (4G systems)
- Note: Still analog signals carrying digital data

What is Spectral Efficiency?

- It is defined as the raw bit rate supported in 1 Hz of bandwidth

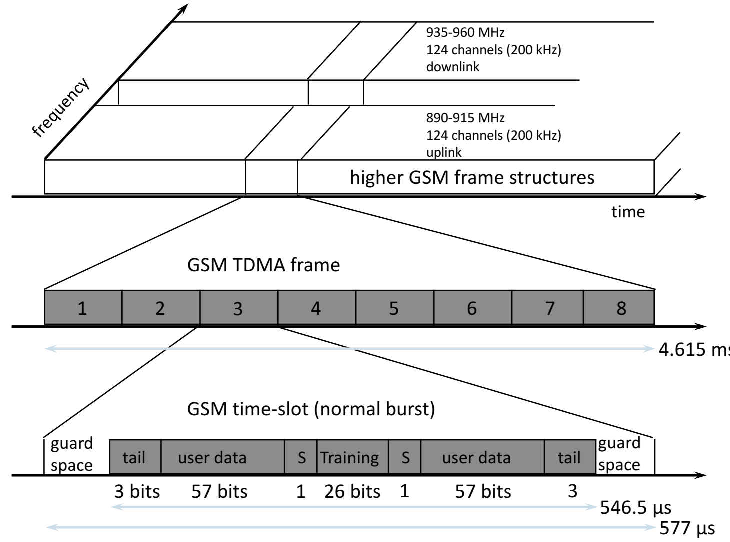
$$\eta = \text{bit rate/bandwidth}$$

- Example: Compute the spectral efficiency of GSM
- Answer:
  - The channel spacing or bandwidth is 200 kHz and the raw data rate is 270.83 kbps. So the spectral efficiency is 270.83/200 = 1.35 bps/Hz
- Compute the spectral efficiency on Slide 35

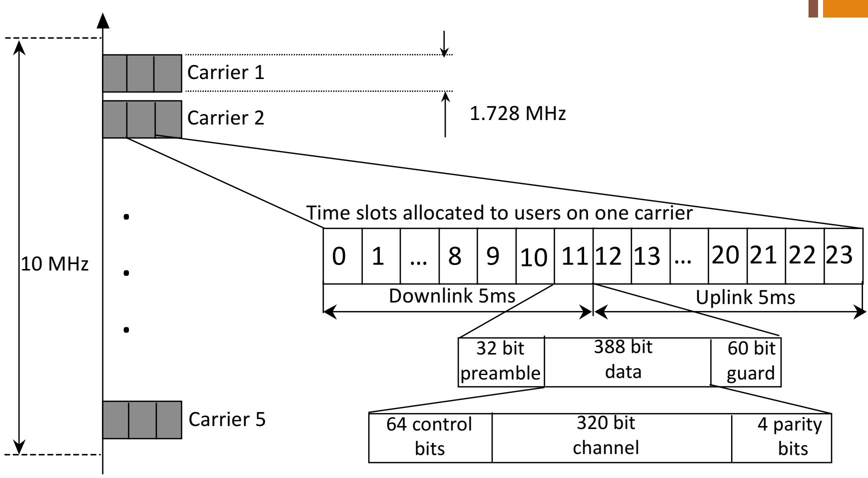
TDMA

- Users share same frequency band in non-overlapping time intervals,
  - E.g. Round robin
- Receiver filters are just windows instead of bandpass filters (as in FDMA)
- Guard time can be as small as the synchronization of the network permits
  - All users must be synchronized with base station to within a fraction of guard time
  - Guard time of 30-50 µs common in TDMA
- Used in GSM, NA-TDMA, (PDC) Pacific Digital Cellular

2G GSM - TDMA/FDMA/FDD



TDMA/FDMA/TDD – example of DECT



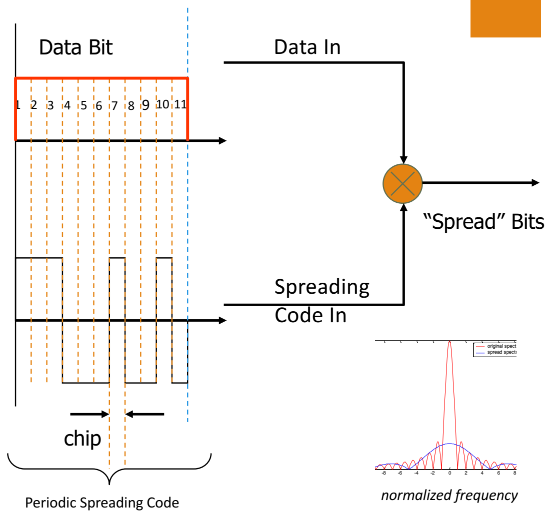
CDMA

- Narrowband message signal is multiplied by very large bandwidth spreading signal using direct sequence spread spectrum
- All users can use same carrier frequency and may transmit simultaneously
- Each user has own unique access spreading codeword which is approximately orthogonal to other users codewords
- Receiver performs time correlation operation to detect only specific codeword, other users codewords appear as noise due to decorrelation
- Cocktail party example

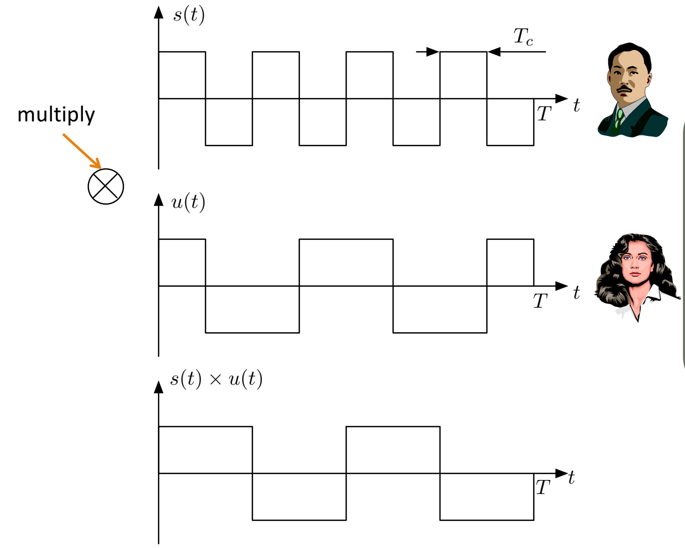
Direct Sequence Spread Spectrum

- The original data stream is "chipped" up into a pattern of pulses of smaller duration
- Good **autocorrelation** properties
- Good **cross-correlation** properties with other patterns
- Each pattern is called a spread spectrum code or spread spectrum sequence
  - E.g. Walsh

PN Codes (Later)



Orthogonality



Vector notation:
[1 -1 1 -1 1 -1 1 -1]
×
[1 -1 -1 1 1 -1 -1 1]
=
[1 1 -1 -1 1 1 -1 -1]

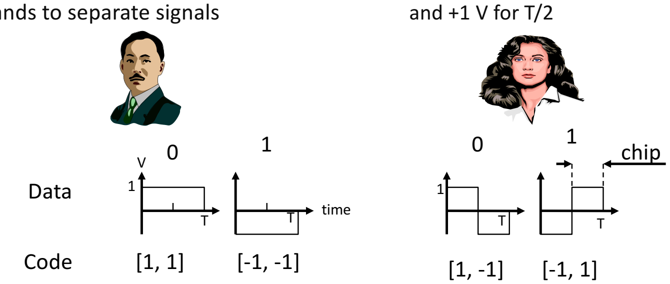
Sum the elements in the product => 0

Area under the product is ZERO!

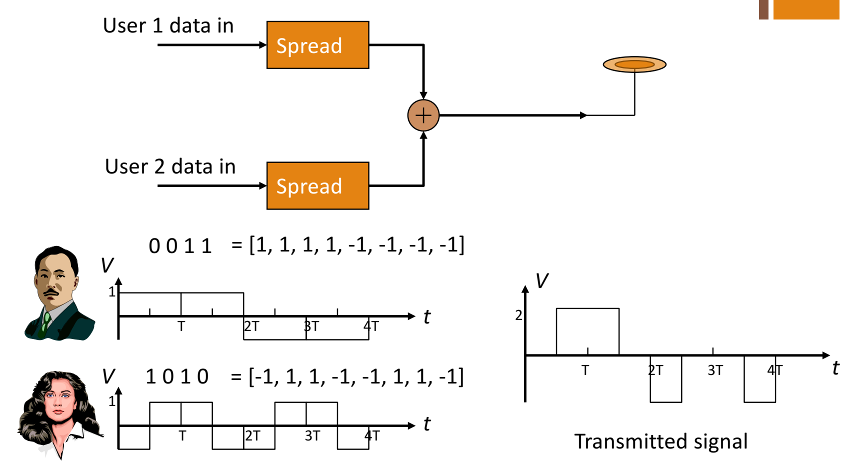
Simple example illustrating CDMA

- **Traditional**
- To send a 0, send +1 V for T seconds
- To send a 1, send -1 V for T seconds
- Use separate time slots or frequency bands to separate signals

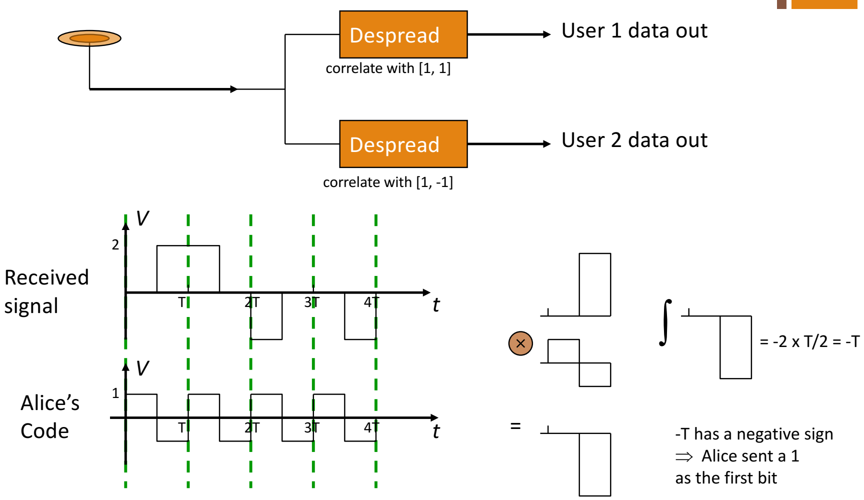
- **Simple CDMA**
- To send a 0, Bob sends +1 V for T seconds; Alice sends +1 V for T/2 seconds and -1 V for T/2 seconds
- To send a 1, Bob sends -1 V for T seconds; Alice sends -1 V for T/2 seconds and +1 V for T/2



Simple CDMA Transmitter



Simple CDMA Receiver



Simple CDMA continued

- Proceeding in this fashion for each "bit", the information transmitted by Alice can be recovered
- To recover the information transmitted by Bob, the received signal is correlated bit-by-bit with Bob's code [1,1]
- Such codes are "orthogonal"
  - Multiply the codes element-wise
    - [1,1] × [1,-1] = [1,-1]
  - Add the elements of the resulting product
    - 1 + (-1) = 0 => the codes are orthogonal
- CDMA used in IS-95 standard and both 3G standards: UMTS, cdma2000
- CDMA has big capacity advantage as frequency reuse cluster size = 1

Old Wide Area Data Systems

Can be considered 1G Mobile Data, GPRS is 2G Mobile Data

System	ARDIS	Mobitex	CDPD	GPRS	Tetra
Frequency band (MHz)	Bands around 800 MHz	935-940 896-901	869-894 824-849	890-915 935-960	380-383 390-393
Channel bit rate (kbps)	4.8 - 19.2	8.0 – 19.2	19.2	160	36
RF channel spacing	25 kHz	12.5 kHz	30 kHz	200 kHz	25 kHz
Channel & Multi-user Access	FDMA/DSMA	FDMA/Dyn. Slotted ALOHA	FDMA/DSMA	FDMA/ TDMA/ Reservation	FDMA/DSMA
Modulation Technique	4-FSK	GMSK	GMSK	GMSK	π/4-DQPSK