# EECS 555: Digital Communications Theory

Winter 2005

Instructor: Prof. Wayne Stark
Course Time: Monday and Wednesday: 8:40-10:00
Sometimes we will meet Friday from 8:40-10:00 as a makeup for class due to travel.
Office Hours: Monday and Wednesday: 1:00-2:00 or by appointment. Office: 4242 EECS
Course Notes: Available
E-mail: stark@eecs.umich.edu
Grading will be based on homework, midterm exam, and a project.

| | |
|---|---|
| Homework | 30% |
| Midterm Exam | 35 % |
| Project | 35 % |
| Total | 100 % |





# JANUARY 2005

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| December<br>Su M Tu W Th F Sa<br>1 2 3 4<br>5 6 7 8 9 10 11<br>12 13 14 15 16 17 18<br>19 20 21 22 23 24 25<br>26 27 28 29 30 31 | February<br>Su M Tu W Th F Sa<br>1 2 3 4 5<br>6 7 8 9 10 11 12<br>13 14 15 16 17 18 19<br>20 21 22 23 24 25 26<br>27 28 | | | | | 1 |
| 2 | 3 | 4 | 5<br>Class 1 | 6 | 7 | 8 |
| 9 | 10<br>Class 2 | 11 | 12 | 13 | 14<br>Class 3 | 15 |
| 16 | 17<br>MLK Day | 18 | 19<br>Class 4 | 20 | 21 | 22 |
| 23 | 24<br>Class 5 | 25 | 26 | 27 | 28<br>Class 6 | 29 |
| 30 | 31<br>Class 7 | | | | | |



# FEBRUARY 2005

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| January<br>Su M Tu W Th F Sa<br>1<br>2 3 4 5 6 7 8<br>9 10 11 12 13 14 15<br>16 17 18 19 20 21 22<br>23 24 25 26 27 28 29<br>30 31 | March<br>Su M Tu W Th F Sa<br>1 2 3 4 5<br>6 7 8 9 10 11 12<br>13 14 15 16 17 18 19<br>20 21 22 23 24 25 26<br>27 28 29 30 31 | 1 | 2<br>Class 8 | 3 | 4 | 5 |
| 6 | 7<br>Class 9 | 8 | 9 | 10 | 11<br>Class 10 | 12 |
| 13 | 14<br>Class 11 | 15 | 16<br>Class 12 | 17 | 18<br>Class 13 | 19 |
| 20 | 21<br>Class 14 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28<br>— Spring | | Break — | | | |
| | | | | | | |



# MARCH 2005

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| February<br>Su M Tu W Th F Sa<br>1 2 3 4 5 6<br>7 8 9 10 11 12 13<br>14 15 16 17 18 19 20<br>21 22 23 24 25 26 27<br>28 | April<br>Su M Tu W Th F Sa<br>1 2<br>3 4 5 6 7 8 9<br>10 11 12 13 14 15 16<br>17 18 19 20 21 22 23<br>24 25 26 27 28 29 30 | 1<br>Spring | 2 | 3<br>Break | 4<br>— | 5 |
| 6 | 7<br>Class 15 | 8 | 9 | 10 | 11<br>Class 16 | 12 |
| 13 | 14<br>Class 17 | 15 | 16<br>Class 18 | 17 | 18 | 19 |
| 20 | 21<br>Class 19 | 22 | 23 | 24 | 25<br>Class 20 | 26 |
| 27 | 28<br>Class 21 | 29 | 30<br>Class 22 | 31 | | |
| | | | | | | |

# APRIL 2005

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| March | May | | | | 1 | 2 |
| 3<br>Begin DST | 4<br>Class 23 | 5 | 6<br>Class 24 | 7 | 8 | 8 |
| 10 | 11<br>Class 25 | 12 | 13 | 14 | 15<br>Class 26 | 16 |
| 17 | 18<br>Class 27 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| | | | | | | |

March

| Su | M | Tu | W | Th | F | Sa |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 29 | 30 | 31 | | |

May

| Su | M | Tu | W | Th | F | Sa |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 29 | 30 | 31 | | | | |



# Course Goals

- Obtain an understanding of the fundamental tradeoffs in the performance of a communication system.
  - Be able to analyze the performance of a given communication system
  - Be able to determine the optimal receiver for a communication system and channel characteristic.
  - Be able to find communication system design with low complexity but near optimal performance.
- For a few standardized communication system obtain an understanding of why the design choices were made.



# Lecture 1: Wireless Communication Systems

There are a number of different wireless communication systems. These include the following.

- Analog Cellular
- Analog Cordless Phones
- Paging
- Digital Cordless Phones
- Digital Cellular
- Packet Radio
- Wireless Local Area Networks
- Low Earth Orbit Satellites



# Analog Cellular

The analog cellular systems are in widespread use. The different frequency bands are shown below for different countries. From [1]. All of these systems used FM (frequency modulation) with FDMA (frequency division multiple access).

# Analog Cellular Systems

Analog Cellular (Speech)

| Standard | Frequencies Mobile/Base | Channel Spacing | Number of Channels | Region |
|---|---|---|---|---|
| AMPS | 824-849/869-894 | 30kHz | 832 | US |
| TACS | 890-915/935-960 | 25kHz | 1000 | Europe |
| ETACS | 872-905/917-950 | 25kHz | 1240 | United Kingdom |
| NMT 450 | 453-457.5/463-467.5 | 25kHz | 180 | Europe |
| NMT 900 | 890-915/935-960 | 12.5kHz | 1999 | Europe |
| C-450 | 450-455.74/460-465.74 | 10kHz | 573 | Germany Portugal |
| RTMS | 450-455/460-465 | 25kHz | 200 | Italy |
| Radiocom 2000 | 192.5-199.5/200.5-207.5 | 12.5 | 560 | France |
| | 215.5-233.5/207.5-215.5 | | 640 | |
| | 162.5-168.4/169.8-173 | | 256 | |
| | 414.8-418/424.8-428 | | 256 | |
| NTT | 925-940/870-885 | 25 | 600 | Japan |
| JTACS/NTACS | 915-925/860-870 | 25 | 400 | Japan |



# Digital Cellular

| Standard | IS-54 | IS-95 | GSM | JDC |
|---|---|---|---|---|
| Frequencies | | | | |
| Downlink (MHz) | 869-894 | 869-894 | 935-960 | 810-826 |
| Uplink (MHz) | 824-849 | 824-849 | 890-915 | 940-956 |
| Country | U.S.A. | U.S.A. | Europe | Japan |
| Multiple-Access | TDMA/FDMA | CDMA/FDMA | TDMA/FDMA | TDMA/FDMA |
| Data Rate | 8 | 1.2-9.6 | 13 | 8 |
| RF Channel Spacing | 30kHz | 1.25MHz | 200kHz | 25kHz |
| Modulation | $\pi/4$ DQPSK | BPSK | GMSK | $\pi/4$ DQPSK |
| Coding | Convolutional | Convolutional | Convolutional | Convolutional |
| | CRC | Orthogonal | CRC | CRC |
| Channel Rate | 48.6kbps | 1.2288Mcps | 270.833kbps | 42kbps |
| Frame Duration | 40ms | 20ms | 4.615ms | 29ms |
| Power | 600mW | 600mW | 1W | |
| Max/Avg. | 200mW | | 125mW | |

From [2, 3].



# Personal Communications Systems (PCS)

| Frequency Band | Designation | Auction Type | Bandwidth | Auction Date |
|---|---|---|---|---|
| 1850-1865MHz | A | MTA | 15MHz | 12/6/94-3/13/95 |
| 1865-1870MHz | D | BTA | 5MHz | |
| 1870-1885MHz | B | MTA | 15MHz | 12/6/94-3/13/95 |
| 1885-1890MHz | E | BTA | 5MHz | |
| 1890-1995MHz | F | BTA | 5MHz | |
| 1995-1910MHz | C | MTA | 15MHz | 8/29/95 |
| 1910-1920MHz | Unlicensed Data | MTA | 10MHz | |
| 1920-1930MHz | Unlicensed Voice | MTA | 15MHz | |
| 1930-1945MHz | A | MTA | 15MHz | 12/6/94-3/13/95 |
| 1945-1950MHz | D | BTA | 5MHz | |
| 1950-1965MHz | B | MTA | 15MHz | 12/6/94-3/13/95 |
| 1965-1970MHz | E | BTA | 5MHz | |
| 1970-1975MHz | F | BTA | 5MHz | |
| 1975-1990MHz | C | MTA | 15MHz | 8/29/95 |

MTA: Major Trading Area (51). BTA: Basic Trading Area (493)



# Auctions for Frequencies

The auction for the A and B bands generated $7,736,020,384 . WirelessCo, L.P., a partnership among Sprint, Tele-Communications, Inc., Cox Cable, and Comcast Telephony, placed high bids totaling $2,110,079,168 in 29 markets. AT&T Wireless PCS Inc. was the high bidder in 21 markets with $1,684,418,000 in bids.

The FCC requires broadband PCS licensees to make their services available to one-third of the population in their service area within five years and to two-thirds within 10 years.

WirelessCo uses CDMA technology for it's PCS system.

## Auctions for Frequencies

Below is a sample of the information provide on the world wide web concerning the auction. For further information see the FCC home page on the internet (http://www.fcc.gov).

| Market | Frequency Block | Round Number | Bid Amount | Bidder Number | Date | Time |
|---|---|---|---|---|---|---|
| B321 | C | 5 | $300000000 | 2224 | 1/5/96 | 12:58:51 |
| B184 | C | 5 | $6461552 | 2358 | 1/5/96 | 10:39:10 |
| B007 | C | 5 | $5770000 | 2326 | 1/5/96 | 10:08:51 |
| B318 | C | 5 | $5492000 | 2086 | 1/5/96 | 12:25:53 |
| B438 | C | 5 | $3955701 | 2010 | 1/5/96 | 10:06:42 |
| B010 | C | 5 | $2550011 | 2187 | 1/5/96 | 10:18:40 |
| B412 | C | 5 | $2442276 | 2146 | 1/5/96 | 10:30:27 |
| B361 | C | 5 | $1413361 | 2238 | 1/5/96 | 10:13:13 |
| B063 | C | 5 | $963103 | 2290 | 1/5/96 | 10:37:42 |
| B319 | C | 5 | $1292000 | 2086 | 1/5/96 | 12:25:53 |

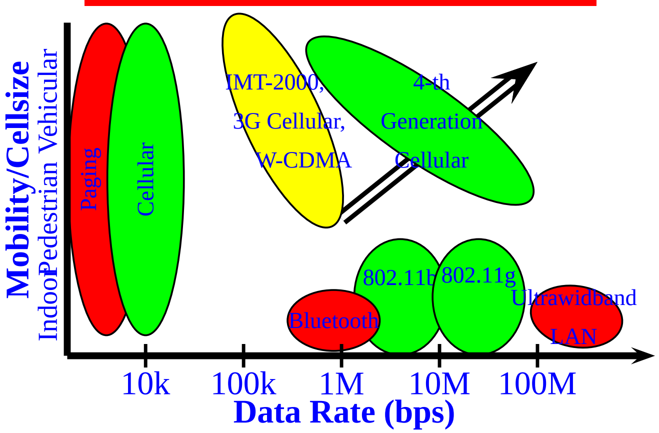


## Personal Communications Systems (PCS) Standards

| System | IS-136 derivative | PACS | IS-95 derivative | W-CDMA | GSM derivative | DECT | Omnipoint |
|---|---|---|---|---|---|---|---|
| Multiple-Access | TDMA FDMA | TDMA FDMA | DS-CDMA | DS-CDMA | TDMA | TDMA FDMA | TDMA FDMA CDMA |
| Data Rate | 8kbps | 32kbps | 8/13.3kbps | 32kbps | 13kbps | 32kbps | 8/32 kbps |
| Bandwidth | 30kHz | 300kHz | 1.25MHz | 5 MHz | 200kHz | 1.728MHz | 5MHz |
| Modulation | $\pi/4$ DQPSK | $\pi/4$ DQPSK | BPSK | QPSK | GMSK | GFSK | QCPM |
| Coding | FEC | Error Det. | FEC | FEC | FEC | None | None |
| Ave Power | 200mW | 25mW | 200mW | 200mW | 125mW | 20.8mW | 10mW |
| Peak Power | 600mW | 200mW | 200mW | 200mW | 1W | 250mW | 1W |
| Frame Dur. | 20ms | 2.5ms | 20ms | - | 4.62ms | 10ms | 20ms |
| Slot Dur. | 6.7ms | 0.3125ms | - | - | 0.58ms | 0.416ms | 0.625ms |



## Trends in Wirelss Communications






## Industrial Scientific and Medical(ISM) Bands

- Frequencies:
  - 902-928 MHz,
  - 2400-2483 MHz,
  - 5725-5850MHz
- There are no standards here. There are many systems currently available.
- The FCC requires the use of spread-spectrum communications so as to minimize the interference among users. Users are limited to 1 Watt transmission and must spread the bandwidth by a factor of 10 or more.
- The power radiated outside the band must be at least 20dB below the maximum power density within the band.
- There are many systems designed for the 902-928MHz band mostly using direct-sequence spreading. The systems for the 2.4GHz band mostly use frequency hopped spreading.
- The data rates vary from around 10 kbps to 1.5 Mbps.

## Other wireless systems

- CDPD: A overlay of existing cellular systems. Will share base stations with cellular. Modulation: GMSK. Coding: Reed-Solomon. Data Rate 19.2kbps. Currently being deployed.
- ARDIS (IBM/Motorola, 1983) Frequency: 800MHz. Data rate 4.8-19.2kbps. Modulation: GMSK. Power: 40W Base 4W Mobile. Range 10-15mi.



## DIGITAL MODULATION

- Narrowband (Bandwidth on the order of data rate).
- Wideband (Spread-spectrum, bandwidth much larger than data rate).



## NARROWBAND MODULATION

GOALS

- Maximize data rate given a limited portion of RF bandwidth
- Achieve low error probabilities
- Combat fading of the communication channel
- Deal with nonlinear amplifi ers
- Design a multiple-access scheme



## MAXIMIZING DATA RATE AND CONSTRAINING BANDWIDTH

- Send multiple bits per symbol (MPSK, QAM)
- Filter transmitted signal
- Adjust the shape of the basic transmitted pulse

## ACHIEVING LOW ERROR PROBABILITIES

- Increase transmitted power
- Choose a signal constellation with a large minimum distance
- Utilize channel error control coding techniques



## COMBATING FADING

- Increase transmitted power
- Choose a signal constellation with a large minimum distance
- Utilize channel error control coding techniques
- Increase the bandwidth of the signal
- Utilize spatial diversity with antenna arrays



## DEALING WITH NONLINEAR AMPLIFIERS

- Utilize constant-envelope signals
- Smooth phase transitions of transmitted signals
- Minimize peak-to-average envelope variations after filtering



## DESIGNING A MULTIPLE-ACCESS SCHEME

- Implement time-division multiple-access (TDMA)
- Implement frequency-division multiple-access (FDMA)
- Implement a random access scheme

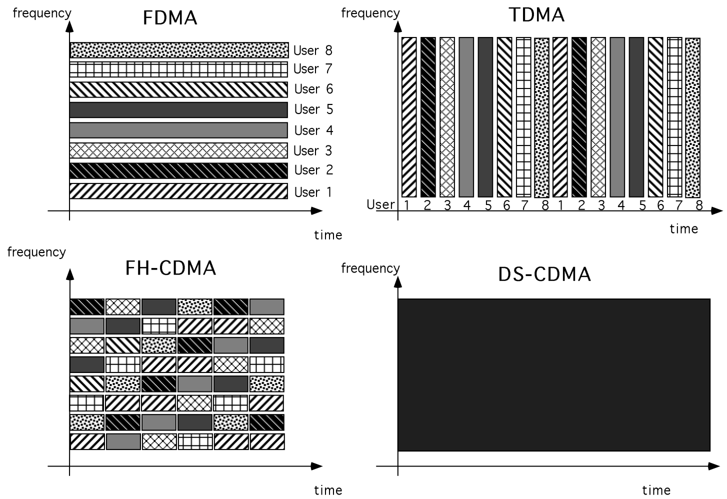



Figure 1: Multiple-Access Techniques



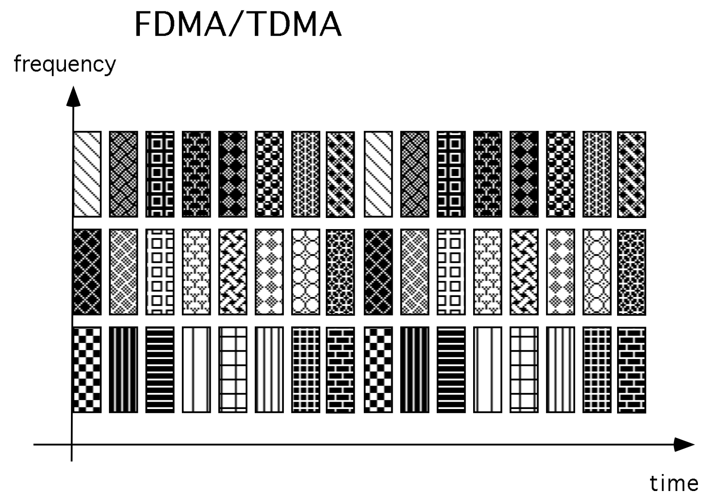



Figure 2: Time/Frequency Multiple-Access



## Spread-Spectrum

Spread-spectrum is a form of modulation that uses considerably more bandwidth than that usually required to transmit at a certain data rate over simple channels (additive Gaussian noise channel).

Spread-spectrum was originally developed for communication in a hostile jamming environment but in the last decade been considered for environments such as fading channels, multipath channels, and multiple-access channels.

**Commercial Applications**

- Satellite Communications
- Indoor Wireless Communication (Bluetooth)
- Urban Radio (Cellular Radio)
- Power Line Transmission
- Optical Fiber



## Spread-Spectrum (cont.)

The basic idea of spread-spectrum is that since the available bandwidth is much larger than necessary to transmit the data, the signal can be hidden in the large bandwidth available.

More insight into this is gained by viewing signals as points in a space of time-limited and bandwidth limited signals. The number of dimensions in this space is proportional to the time bandwidth product.

| | Time Bandwidth Product |
|---|---|
| Unspread System | 1 |
| Spread System | 30-10000 |

## Spread-Spectrum (cont.)

If the spread signal can occupy any of many thousand dimensions, an interferer would not know in which dimension to concentrate his noise. As such, his signal must be spread over a all dimensions thus reducing the power level in any one of the dimensions (in particular, the one where the signal is hidden).



## Spread-Spectrum (cont.)

There are several different techniques for spreading a signal. These include:

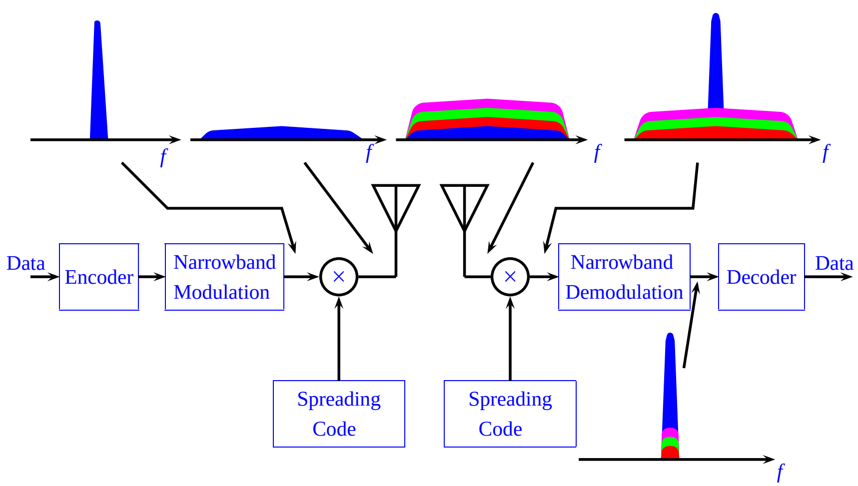
- Frequency Hopping (FH)
- Direct-Sequence (DS)
- Time-Hopping (TH)
- Chirp
- Hybrid combinations of the above.

We will only discuss FH and DS techniques.

Each of these techniques have advantages and disadvantages depending on the situation.

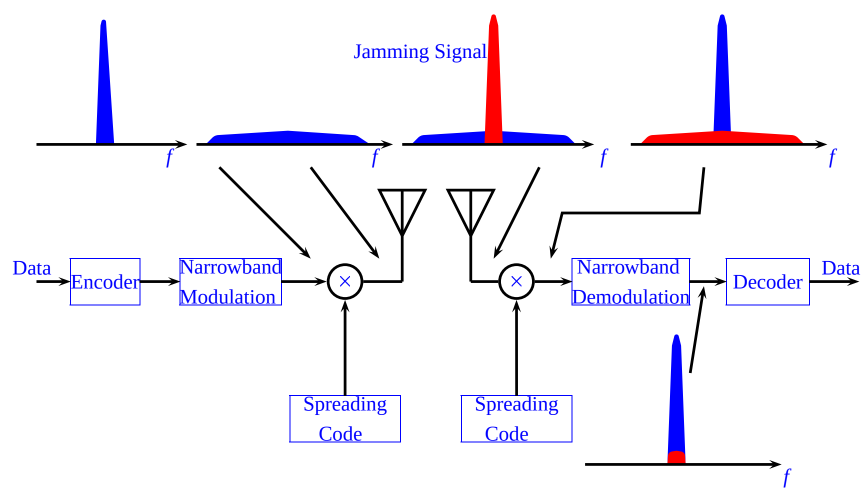


## Block Diagram of a DS-CDMA system






## Conceptual View of DS with Jamming



## Spread-Spectrum (cont.)

- **DS**
  - Suffers from the near-far problem (with conventional receivers).
  - Can usually be demodulated coherently.
  - Works well with multipath fading.
- **FH**
  - Difficult to coherently demodulate.
  - Able to cope with the near-far problem.
  - Less resistant to multipath fading.

Hybrid systems try to get the advantages of each of the component systems without the disadvantages.

JTIDS (Joint Tactical Information Distribution System) flown on AWACS planes uses a combination of FH, DS and TH (along with error correction coding).



## Spread-Spectrum (cont.)

There is a digital cellular telephone standard (IS-95) that is a form of DS with power control to eliminate the near-far problem.

There is a digital cellular telephone standard (GSM) that frequency hopped with coding to compensate for the fading problem.

Spread-Spectrum has been developed for indoor wireless data networks. Both DS and FH have been considered with the majority of the systems being DS.

In a packet radio network without base stations, power control is not possible so FH is a better candidate. The SINCGARS radio is a packet radio network utilizing FH spread-spectrum. The Blue tooth system is also a frequency hopped radio.



## Other Topics

- Ultrawideband radio
- Space Time Processing



## Important Parameters in a Wireless Communications System

- **Power or Energy:** Clearly the more power available the more reliable communication is possible. However, the goal is to reduce the required transmission power so that talk time is maximized.
- **Data Rate:** The goal is large data rates. However, for a fixed amount of power as the data rate increases the energy transmitted per bit will decrease because of decreased transmission time for each bit. In addition if the data rate increases then the amount of intersymbol interference will increase. A wireless channel typically has an impulse response with some delay spread. That is, the received signal is delayed by different amounts on different paths. The signal corresponding to a particular bit received with the longest delay with interfere with the signal corresponding to a different bit with the shortest delay. The larger the number bits that are interfered with the more difficult it is to correct for this interference.

## Important Parameters (cont.)

- **Bandwidth:** This is the amount of frequency spectrum available for use. Generally the FCC allocates spectrum and provides some type of mask for which the radios emissions must fall within. The larger the bandwidth the more indendent fades accross frequencies and thus better averaging is possible.
- **Error Probability:** Data communication requires smaller error probability than voice transmission. Usually we are interested in either bit error probability or packet error probability.



## Important Parameters (cont.)

- **Delay Spread (Coherence Bandwidth)** The delay spread of a channel measures the differential delay between the longest significant path and the shortest significant path in a channel. The delay spread is inversely related to the coherence bandwidth which indicates the minimun frequency separation such that the response at the two different frequencies is independent.
- **Coherence Time (Doppler Spread)** This is related to the vehicular speed. The correlation time measures how fast the channel is changing. If the channel changes quickly it is hard to estimate the channel response. However a quickly changing channel also ensures that a deep fade does not last too long. The Doppler spread is the frequency characteristics of the channel impulse response and it is inversely related to the correlation time.



## Important Parameters (cont.)

- **Delay Requirement** Larger delay requirements allow for larger number of fades to be averaged out.
- **Complexity** More complexity usually implies better performance. The trick is to get the best for less.



## Communication System Coat of Arms

There are many different functions in a digital communication system. These are represented in the block diagram shown below.

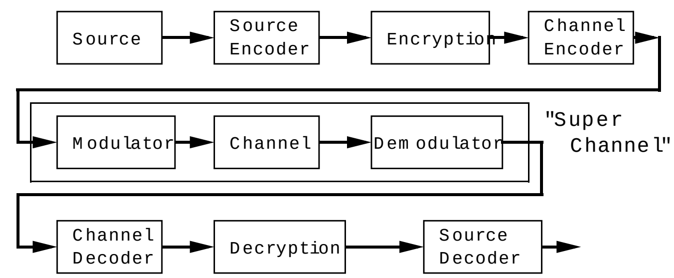



Figure 3: Block Diagram of a Digital Communication System

## Coat of Arms

- **Source Encoder:** Removes redundancy from the source data such that the output of the source encoder is a sequence of symbols from a finite alphabet. If the source produces symbols from an infinite alphabet than some distortion must be incurred in representing the source with a finite alphabet. If the rate at which the source produces symbols is below the "entropy" of the source than distortion must be incurred.
- **Encryption Device** Transforms input sequence $\{W_k\}$ into an output sequence $\{Z_n\}$ such that knowledge of $\{Z_n\}$ alone (without a key) makes calculation of $\{W_l\}$ extremely difficult (many years of CPU time on a fast computer).
- **Channel Encoder:** Introduces redundancy into data such that if there are some errors made over the channel they can be corrected.

  Note: The source encoder removes *unstructured* redundancy from the source data and may cause distortion or errors in a *controlled* fashion. The channel encoder adds redundancy in a structured fashion so that the channel decoder can correct some errors caused by the channel.
- **Modulator:** Maps a finite number of messages into a set of distinguishable signals so that at the channel output it is possible to determine which signal in the set was



transmitted.

- **Channel:** Medium by which signal propagates from transmitter to receiver

  Examples of communication channels:

  Noiseless channel (very good, but not interesting).

  Additive white Gaussian noise channel (classical, for example the deep space channel is essential an AWGN channel).

  Intersymbol interference channel (e.g. the telephone channel)

  Fading channel (mobile communication system when transmitters are behind buildings, Satellite systems when there is rain on the earth).

  Multiple-access interference (when several users access the same frequency at the same time).

  Hostile interference (jamming signals).

  Semiconductor memories (RAM's, errors due to alpha particle decay in packaging).

  Magnetic and Optical disks (Compact digital disks for audio and for read only memories, errors due to scratches and dust).
- **Demodulator:** Processes the channel output and produces an estimate of the message that caused the output.
- **Channel Decoder:** Reverses the operation of the channel encoder in the absence of any



channel noise. When the channel causes some errors to be made in the estimates of the transmitted messages the decoder corrects these errors.

- **Decryption Device:** With the aid of a secret key reverses the operation of the encryption device. With private key cryptography the key determines the method of encryption which is easily invertible to obtain the decryption. With public key cryptography there is a key which is made public. This key allows anyone to encrypt a message. However, even knowing this key it is not possible to reverse this operation (at least not easily) and recover the message from the encrypted message. There are some special properties of the encryption algorithm known only to the decryption device which makes this operation easy. This is known as a trap door. Since the encryption key need not be kept secret for the message to be kept secret this is called public key cryptography.
- **Source Decoder:** Reverse the operation of the source encoder to determine the most probable sequence that could have caused the output.

  Often the modulator-channel-demodulator are thought of as a *super channel* with a finite number of inputs and a finite or infinite number of outputs.



## Fundamental Tradeoffs

More than 50 years ago Claude Shannon (U of M EE/Math graduate) determined the tradeoff between data rate, bandwidth, signal power and noise power for reliable communications for an additive white Gaussian noise channel. Let $W$ be the bandwidth (in Hz), $R$ be the data rate (in bits per second), $P$ be the *received* signal power (in watts) and $N_0/2$ the noise power spectral density (in watts/Hz) then reliable communication is possible provided

$$R < W\log_2(1+\frac{P}{N_0 W}).$$

Let $E_b$ be the energy transmitted per bit of information. Then

$$E_b = P/R \quad \text{or} \quad P = E_b R.$$

Using this relation we can express the capacity formula as

$$R/W < \log_2(1 + \frac{E_b}{N_0}\frac{R}{W}).$$

Inverting this we obtain

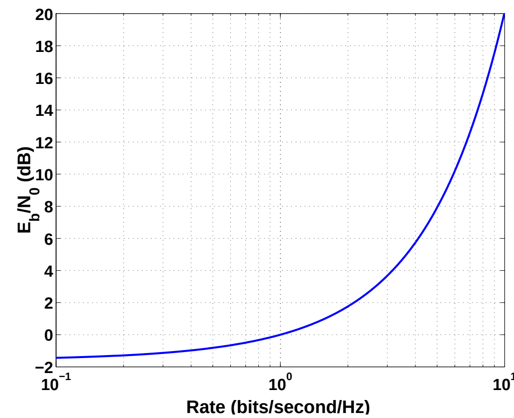
$$E_b/N_0 > \frac{2^{R/W} - 1}{R/W}.$$

The interpretation is that reliable communication is possible with *bandwidth efficiency* $R/W$ provided that the *signal-to-noise ratio* $E_b/N_0$ is larger than the right hand side of the above equation. Usually energy or power ratios are expressed in dB's. The conversion is

$$E_b/N_0(dB) = 10\log_{10}(E_b/N_0).$$



## Capacity






## Notes

The capacity formula only provides a tradeoff between energy efficiency and bandwidth efficiency. Complexity is essentially infinite, as is delay. The model of the channel is rather benign in that no signal fading is assumed to occur.

Figure 4: Claude Elwood Shannon



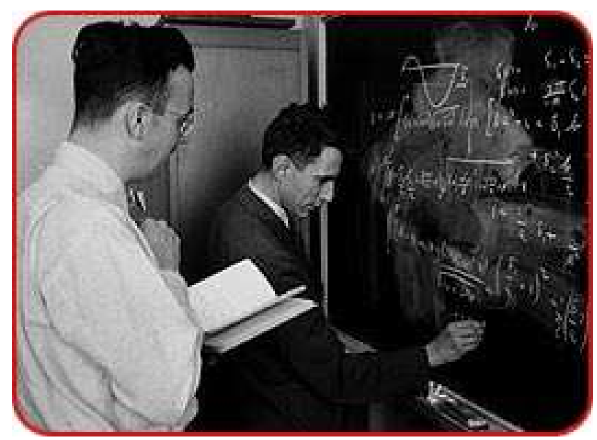


Figure 5: Claude Elwood Shannon

Figure 6: Claude Elwood Shannon



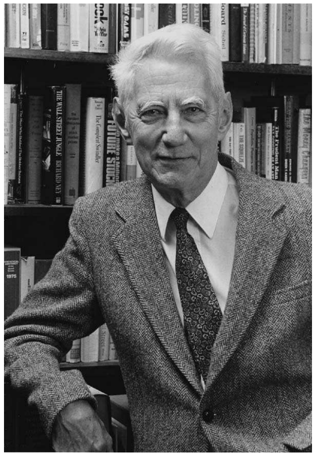


Figure 7: Claude Elwood Shannon



Figure 8: Claude Elwood Shannon