EECS 455:

Digital Communications Signals and Systems

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EECS 455

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- Office Hours: Monday 3:40-4:30pm, Tuesday 11:00-12:00am, Friday 3:40-4:30pm.
- Grading: 25 % for Exams 1 and 2, 15 % for Homework, 35 % for Final
- No late homework accepted (lowest homework grade will be dropped).
- Text: Proakis and Salehi: Communications Systems Engineering

Course Schedule

- First day of Classes: (today)
- “Fall Break:” October 18-19.
- Midterm Exam: Wednesday, October 29th (in class).
- Last day of Classes: Wed. Dec. 14th.
- Final Exam: Wednesday, December 17th from 10:30am-12:30pm.

September

Sun.	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.
			1	2	3	4
5	6	7	8 Class 1	9	10 Class 2	11
12	13 Class 3	14	15 Class 4	16	17 Class 5	18
19	20 Class 6	21	22 Class 7	23	24 Class 8	25
26	27 Class 9	28	29 Class 10	30		

October

Sun.	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.
					1 Class 11	2
3	4 Class 12	5	6 Class 13	7	8 Class 14	9
10	11 Class 15	12	13 Class 16	14	15 Class 17	16
17	18 -Break-	19	20 Class 18	21	22 Class 19	23
24	25 Class 20	26	27 Class 21	28	29 Class 22	30

November

Sun.	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.
	1 Class 23	2	3 Class 24	4	5 Class 25	6
7	8 Class 26	9	10 Class 27	11	12 Class 28	13
14	15 Class 29	16	17 Class 30	18	19 Class 31	20
21	22 Class 32	23	24 Class 33	25 Thanksgiving	26	27
28	29 Class 34	30				

December

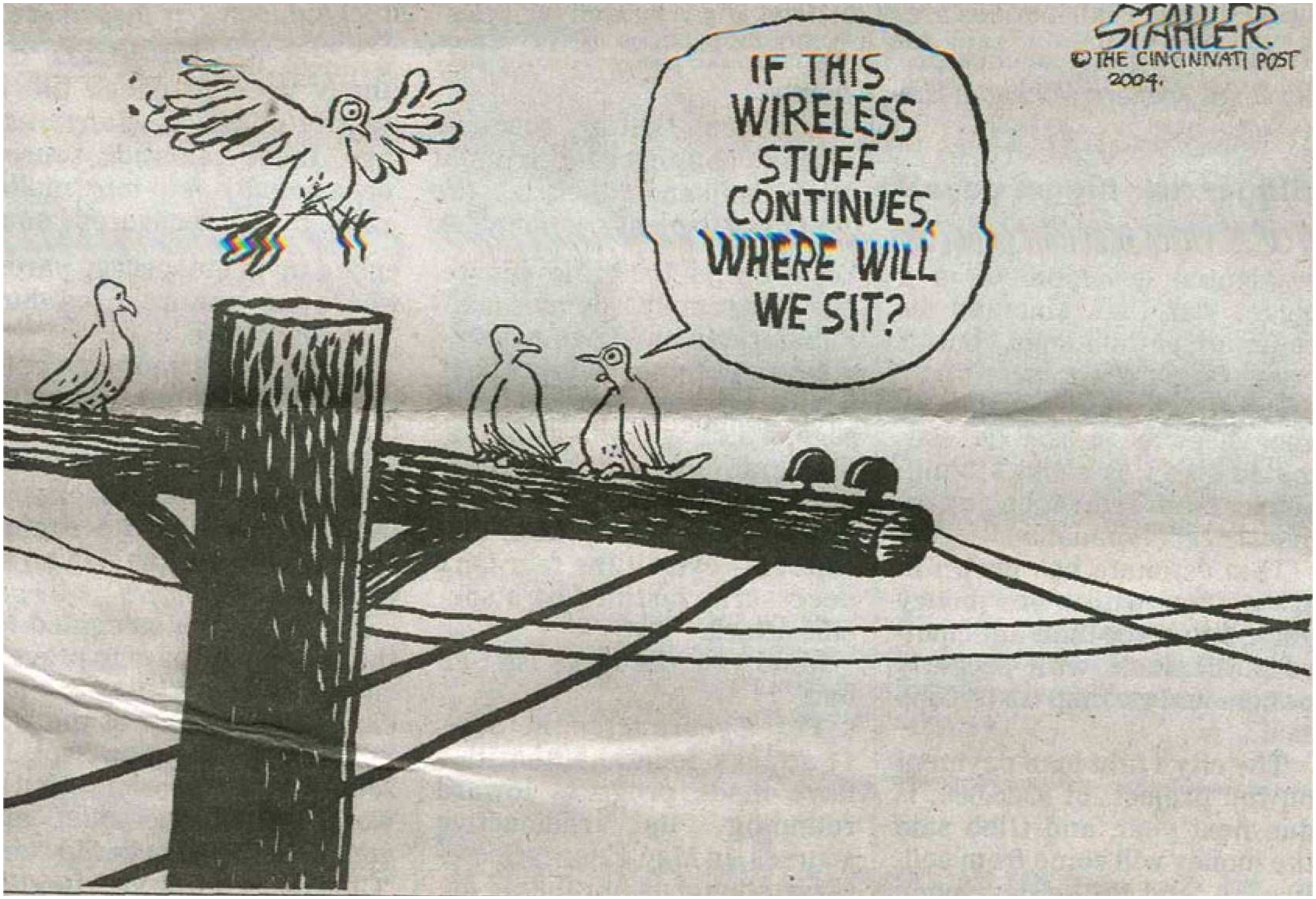
Sun.	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.
			1 Class 35	2	3 Class 36	4
5	6 Class 37	7	8 Class 38	9	10 Class 39	11
12	13 Class 40	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28				

Lecture1

Goals:

- Know the difference between analog and digital communications
- Know the basic block diagram of a digital communications system.
- Know the fundamental tradeoff between data rate, bandwidth, signal power and noise power
- Understand different applications of digital communications.

Wireless vs. Wireline



Digital vs. Analog

Digital Communication differs from analog communications in that in any finite time interval there is a finite number of possible transmitted waveforms. Based on the received signal the receiver needs to decide which of the finite number of transmitted signals was sent. Because of this the performance measure for digital communication systems is usually the probability of making an error in deciding which waveform was transmitted.

The advantages of digital communications over analog communications include:

- ease of regeneration of signals in a series of regenerative repeaters,
- the flexibility of circuitry available for processing digital signals (DSPs, LSI),
- the ability to store information in digital format in various media (e.g. DVD, CD, RAM, Hard Disk),
- many source are digital (e.g. data files).

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

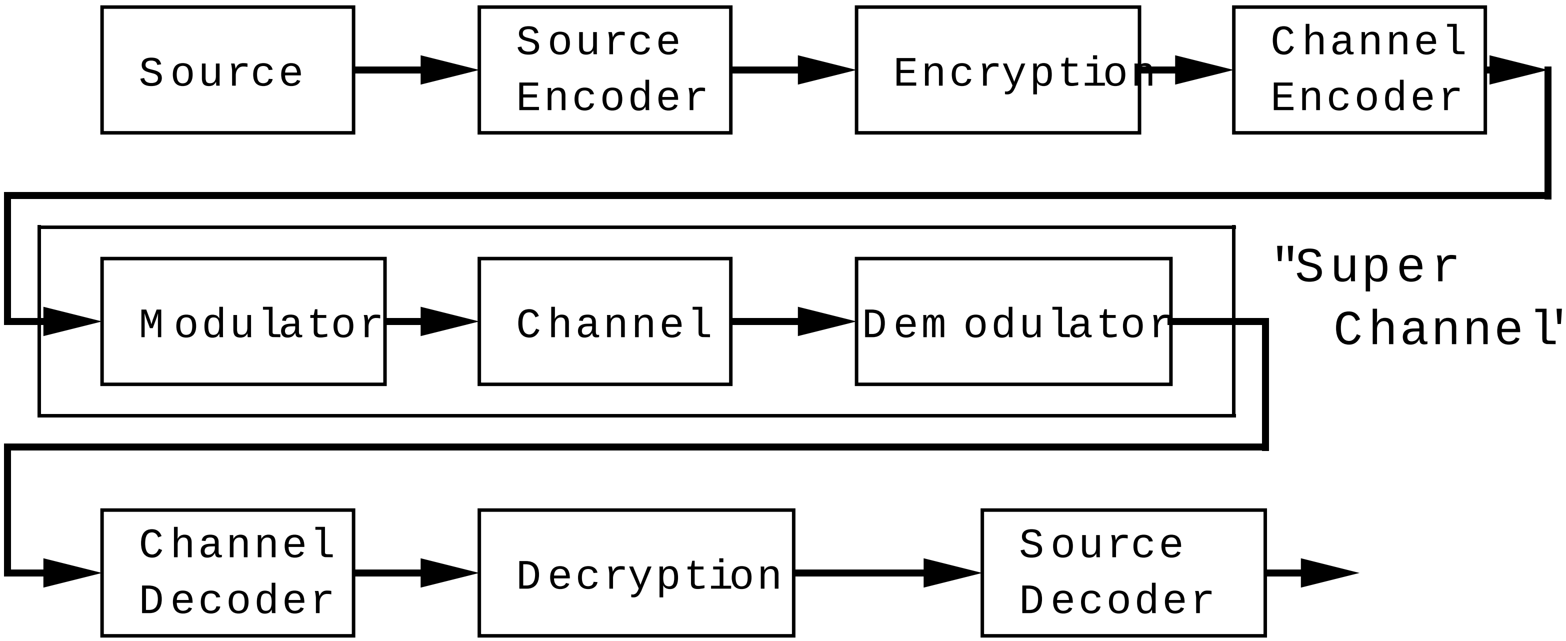


Figure 1: Block Diagram of a Digital Communication System

- **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.

Important Parameters

The goal of communication systems is to transmit information from one location to another. This can be done in various ways which depends on certain resources. These include the energy, the noise, the channel conditions among others.

1. **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.

2. **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.

3. **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 independent fades across frequencies and thus better averaging is possible.

4. **Bit Error Probability:** Different sources require different error probabilities (also call bit error rates).

5. **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 minimum frequency separation such that the response at the two different

frequencies is independent.

6. **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.

7. **Delay Requirement** Larger delay requirements allow for larger number of fades to be averaged out.

8. **Complexity** More complexity usually implies better performance. The trick is to get the best for less.

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

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

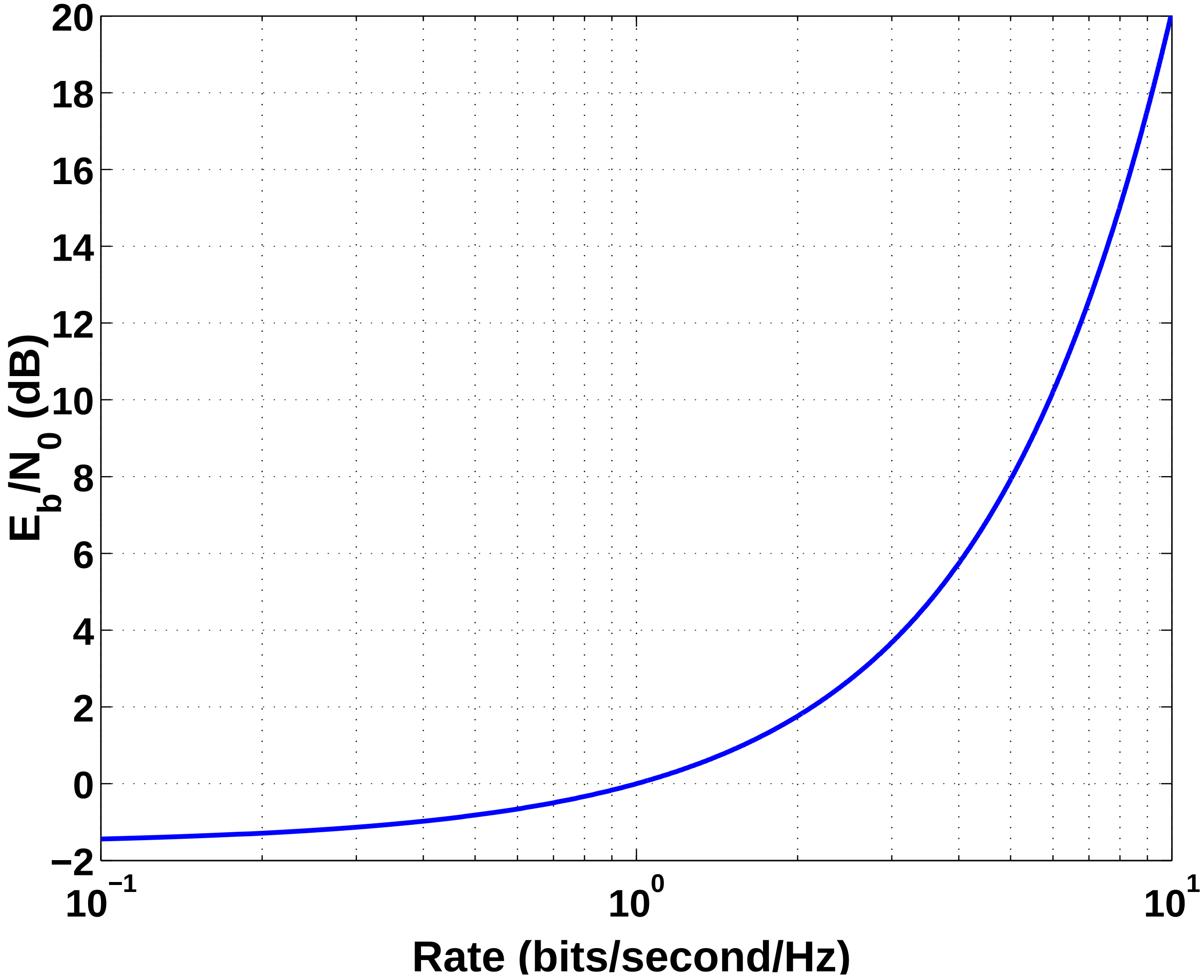
Inverting this we obtain

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

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 2: Claude Elwood Shannon

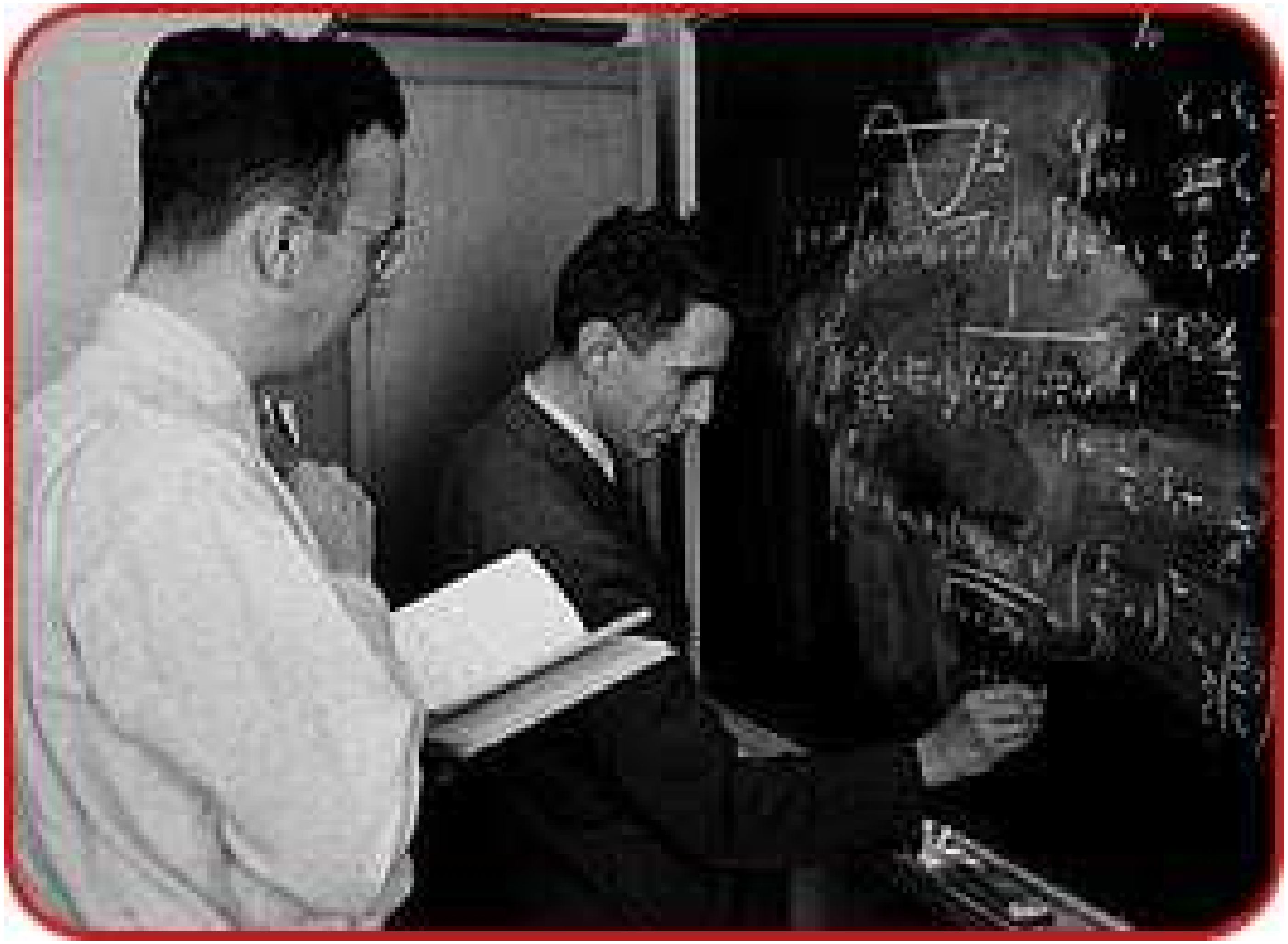


Figure 3: Claude Elwood Shannon

Figure 4: Claude Elwood Shannon

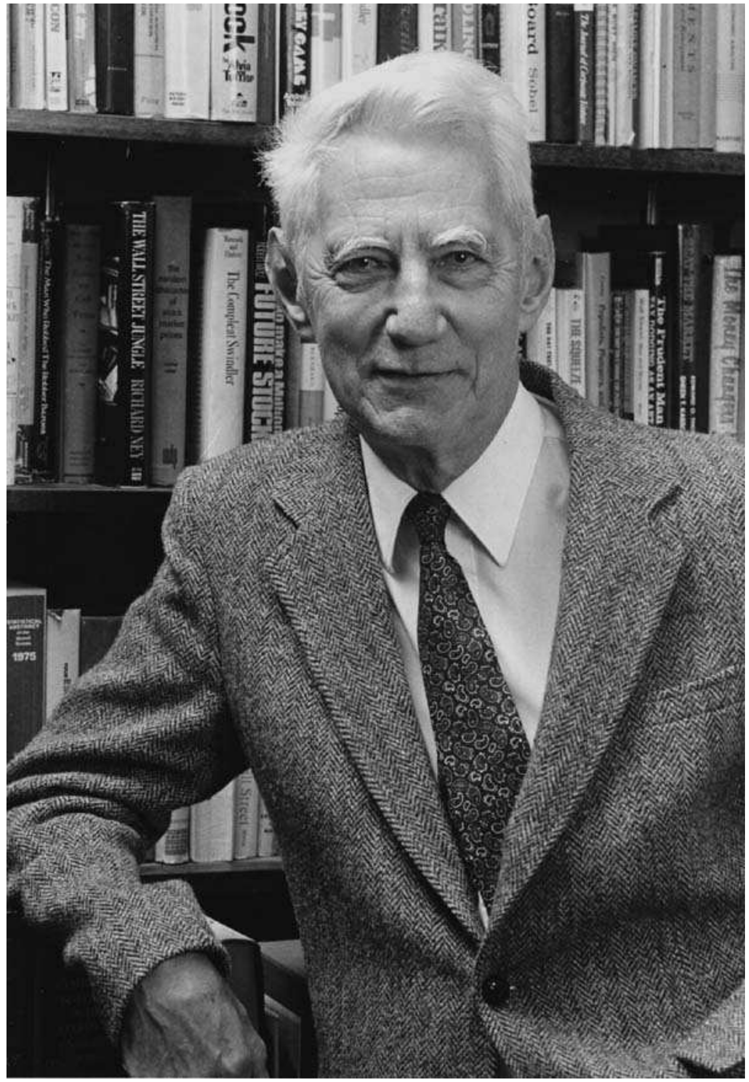


Figure 5: Claude Elwood Shannon

Figure 6: Claude Elwood Shannon

Applications

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

Generally these systems are power or energy limited rather than bandwidth limited in that they must operate on batteries.

Wired Applications

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

- Telephone Modems
- DSL (Digital Subscriber Loop)
- Cable Modems
- Ethernet

Generally these systems are bandwidth limited rather than power or energy limited since they are typically powered from an AC power source.

Analog Cellular

The analog cellular systems are in widespread use. The different frequency bands are shown below for different countries. 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	192.5-199.5/200.5-207.5 215.5-233.5/207.5-215.5 162.5-168.4/169.8-173 414.8-418/424.8-428	12.5	560 640 256 256	France
NTT JTACS/NTACS	925-940/870-885 915-925/860-870	25 25	600 400	Japan Japan

Digital Cellular

Standard	IS-54	IS-95	GSM	JDC
Frequencies Downlink (MHz) Uplink (MHz) Country	 869-894 824-849 U.S.A.	 869-894 824-849 U.S.A.	 935-960 890-915 Europe	 810-826 940-956 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 Max/Avg.	600mW 200mW	600mW	1W 125mW	

Personal Communications Systems (PCS)

Frequency Band	Designation	Autction 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)

Auction for Frequencies

The auction for the A and B bands generated $7,736,020,384 . Wireless CO, 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.

Wireless CO uses CDMA technology for it's PCS system.

Auctions for Frequencies

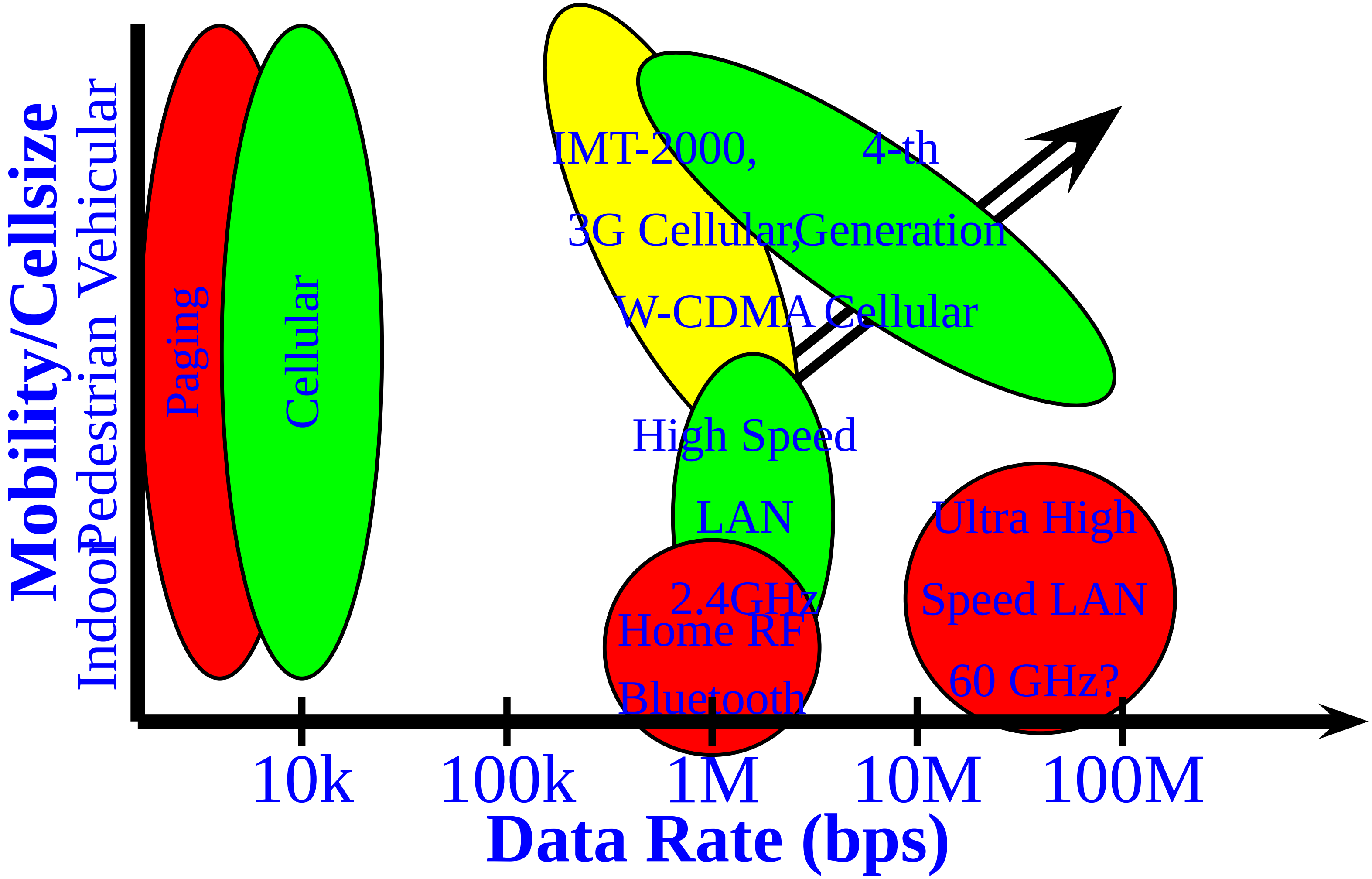
Below is a sample of the information provide on the world wide web concerning the auction. For further information see the FCC home page on the internet (http://www.fcc.gov).

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 Wireless 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

- GPRS
- 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.