Lecture 1

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 in communicating binary information (bits) from a source to a destination
- Know the fundamental tradeoff between data rate, and distortion in representing a source signal in binary form (bits)
- Understand different applications of digital communications

Digital vs. Analog

- Digital communication differs from analog communications in that in a *digital* communication system during any finite time interval there is a *finite* number of possible transmitted waveforms.
- In an analog communication system during any finite time interval there are a potentially *infinite* number of possible waveforms transmitted.

Voice on cell phone : analog

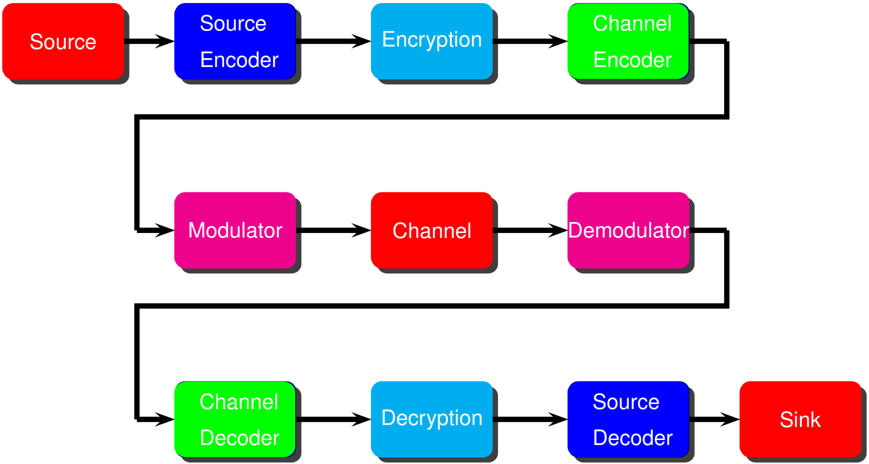
Digital vs. Analog

- In a digital communication system the receiver needs to *decide*, based on the received signal, which of the finite number of transmitted signals was sent.
- In an analog communication system the receiver needs to *estimate*, based on the received signal, what was the transmitted signal.
- The performance measure for *digital* communication systems is usually the probability of making an error in deciding which waveform was transmitted.

Advantages/Disadvantage of Digital Communications

- A: Ease of regeneration of signals in a series of regenerative repeaters,
- N: The flexibility of circuitry available for processing digital signals (DSPs, VLSI),
- A: The ability to store information in digital format in various media (e.g. DVD, CD, RAM, Hard Disk),
- A: Many sources are digital (e.g. data files).
- D: A receiver in a digital communication system needs to know when a bit starts and ends (synchronization).

Communication System Block Diagram



Functional Blocks

- **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.
  For example: Ths sntnc hs th rdndncy rmvd. (lol).
- **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).

Functional Blocks

- **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.

Functional Blocks

- **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 (AWGN). This is the classical channel. For example the deep space channel is well modeled as 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).

Functional Blocks

- **Channel:** Medium by which signal propagates from transmitter to receiver.
  Examples of communication channels (cont):
  - 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).
  - Quick Response (QR) channel (scratches, logos).

Functional Blocks

- **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.

Functional Blocks

- **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.

Functional Blocks

- **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.
- Parameters: Power/Energy, Data Rate, Bandwidth, Distortion, Bit Error Probability

Power

- The more power that is available the more reliable communication is possible.
- However, the goal is to reduce the required transmission power so that battery lifetime is maximized.
- Power levels of radios vary from less than a milliWatt (Bluetooth) to 1MWatt (Television, Radio).
- Performance generally depends on the received power (not the transmit power) which depends on how far apart the transmitter and receiver are located.

Data Rate

$P, R \propto \frac{1}{E}$

$R \uparrow \quad E \downarrow$

- The goal is large data rates.
- 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.

$R \uparrow, \quad E = PT$

$\quad\quad\quad \downarrow \quad\quad \downarrow$

Data Rate

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- 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.
- The data rate can be as low as several kbps to transmit speech to 10's of Gbps for data.

Bandwidth

- The bandwidth is the amount of frequency spectrum available for use.
- Generally the Federal Communications Commission (FCC) in the US 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.
- The available bandwidth might be 3kHz for voice-band telephone lines and as high as 10’s of GHz.

Noise Level

- Noise is present in virtually all communications systems.
- Thermal noise (due to motion of electrons in receivers) is often modeled as white Gaussian noise that is added to the desired received signal.
- The noise level depends on the temperature of the receiver.
- The noise at the front end of the receiver (before the signal has been amplified) is the most important noise.
- A low noise amplifier (LNA) as the first stage in a receiver is typical.
- Wide bandwidths increase the total noise level.

Distortion

- For analog sources such as speech or video the distortion between the original source and the reproduction of the original signal at the destination is often a performance measure of interest.
- The mean-squared error is one often used performance measure for distortion.

Bit Error Probability

- Different sources require different error probabilities.
- The bit error probability is also called the bit error rates (BER).
- A packet or frame or block is a set of bits (e.g. 100 bits).
- The bit error probability is also called the bit error rates (BER).
- The packet error probability is also called the packet error rate (FER) or block error rate (BLER) or frame error rate (FER).
- Bit error rates vary between 10^{-2} and 10^{-8}
- Packet error rates might be between 10^{-1} and 10^{-4}.

Channel Parameters

- **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.
- **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.

System Parameters

- **Delay Requirement** Larger delay requirements allow for larger number of fades to be averaged out. However, for a two way conversation delays that are too large become annoying.
- **Complexity** More complexity usually implies better performance. The trick is to get the best performance for least complexity.

Wireless Applications

- Paging
- Digital Cordless Phones
- Digital Cellular
- Packet Radio
- Wireless Local Area Networks
- Low Earth Orbit (LEO) Satellites
- Medium Earth Orbit (e.g. GPS)
- Geosynchronous Earth Orbit (GEO)
- Dedicated Short Range Communications (DSRC: V2V, V2X, X2V).
- C-V2X (Cellular Vehicle to Infrastructure,
- Automatic Dependent Surveillance-Broadcast (ADSB)
- Bluetooth

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

Wired Applications

- Telephone Modems
- DSL (Digital Subscriber Loop)
- Cable Modems
- Ethernet
- Optical Fiber
- USB

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

Analog Cellular

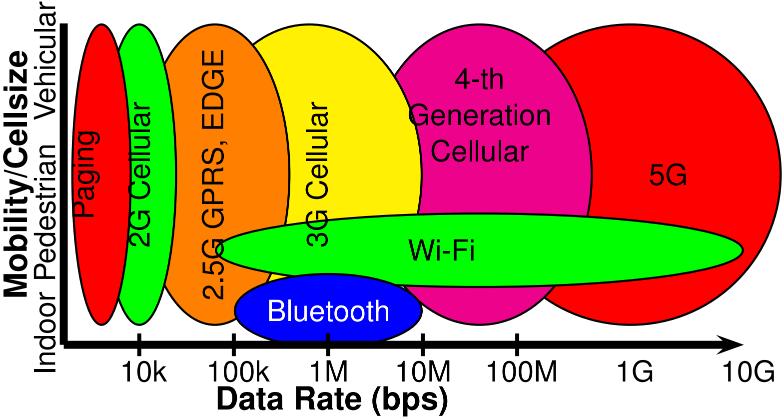
- Analog cellular systems were in widespread use from the early 1980's to the mid 1990's. but are not being used anymore (in the US).
- All of these systems used FM (frequency modulation) with FDMA (frequency division multiple access).
- The different frequency bands are shown below for different countries.

Analog Cellular Systems

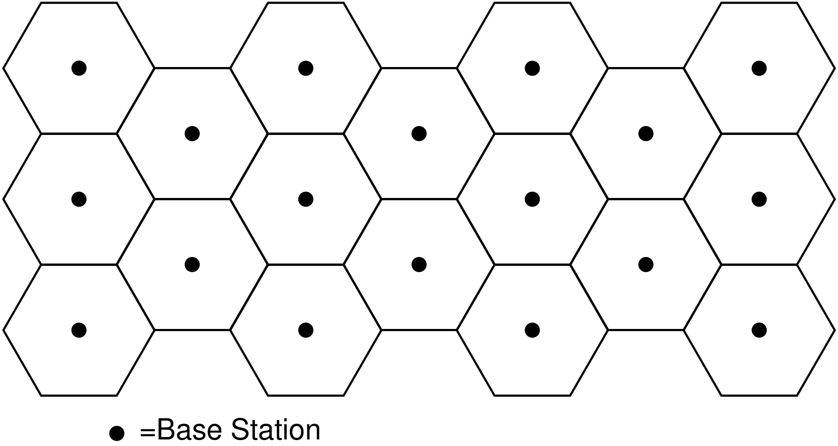
Analog Cellular (Speech) (1G)

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
Radiocomm 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

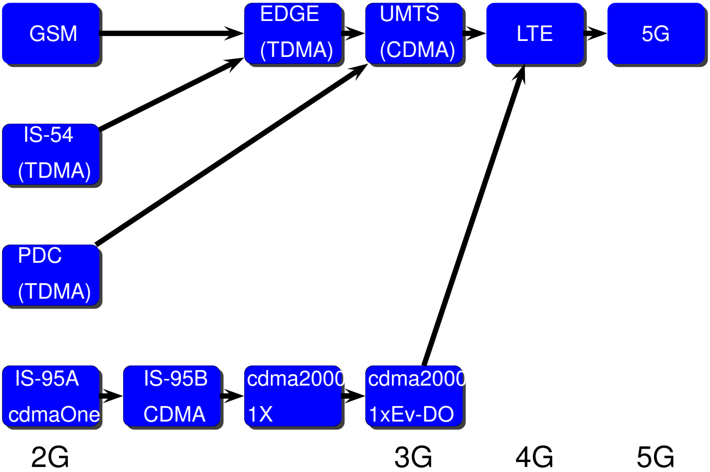
Trends in Wireless Communications



Cellular Communications



Evolution of Cellular Communications



Digital Cellular Evolution

Generation	Standard	Download Speed	Upload Speed
2G	GPRS	0.1 Mbps	$<$ 0.1 Mbps
2G	EDGE	0.3 Mbps	0.1 Mbps
3G	WCDMA	0.3 Mbps	0.1 Mbps
3G	HSPA	7.2 Mbps	1.5 Mbps
3G	HSPA+	21 Mbps	4 Mbps
3G	DC-HSPA+	42 Mbps	8 Mbps
4G	LTE Cat 6	150 Mbps	15 Mbps
4G	LTE-A Cat 9	450 Mbps	45 Mbps
4G	LTE-A Cat 12	600 Mbps	60 Mbps
4G	LET-A Cat 16	979 Mbps	90 Mbps
5G	5G (NR)	1-10 Gbps	150-200 Mbps

Cellular Evolution: First Generation, 1980

- Called Advanced Mobile Phone System (AMPS) in the US
- Used analog modulation (FM)
- Frequency division multiple access (FDMA)
- For making voice calls
- Circuit switched
- Poor batter life
- Poor security
- Frequencies: 800-900 MHz

Cellular Evolution: 2G (1990):

- Global System for Mobile (GSM) in Europe, Digital AMPS and cdmaOne (IS-95) in US , Japanese Digital Cellular (JDC) in Japan
- CDMA,TDMA/FDMA
- Used digital modulation
- Used data compression (voice to data)
- Used error control coding to lower energy needed
- Mainly for voice calls but also some data (e.g. dial up modem)
- Circuit switched
- Much improved security due to digital nature of calls
- Internet just starting to be developed
- Limited data 50kbps (GPRS)-384 kbps (EDGE)
- Frequency 850-1900 MHz (GSM), 800-900 MHz (cdmaOne).

Cellular Evolution: 3G (2000)

- Called Universal Mobile Telecommunications System (UMTS) in Europe
- Called CDMA 2000 in US
- Air Interface is CDMA/WCDMA (Code division multiple access/Wideband Code division multiple access)
- For making voice calls
- For data (email, text messages, surfing internet)
- Circuit switched and packet switched (Internet Protocol)
- 2 Mbps
- Bandwidths of up to 5 MHz

Cellular Evolution: 4G (2010)

- Long Term Evolution (LTE), LTE-Advanced and WiMax
- Orthogonal frequency division multiple access (OFDMA)
- Exclusively packet switched (Internet Protocol , IP)
- Voice over IP (VOIP)
- Better error control coding (turbo codes)
- Multiple Input/multiple output (MIMO) Antennas

Cellular Evolution: 5G (2020)

- New Radio (NR)
- Orthogonal frequency division multiple access (OFDMA)
- Exclusively packet switched (Internet Protocol, IP)
- Voice over IP (VOIP)
- Massive MIMO
- Option for low latency (delay) communications
- Option for low energy operation
- Option for IoT operation
- Operation at higher frequencies possible including 28, 37, 39, 40, 64-71 GHz (mmwave frequencies)

WiFi Evolution

Name	Standard	System	Data rate	Frequency Band
-	802.11-1997	DSSS	1 or 2 Mbps	2.4 GHz
WiFi 1	802.11b (1999)	DSSS	11 Mbps	2.4 GHz
WiFi 2	802.11a (1999)	OFDM	54 Mbps	5 GHz
WiFi 3	802.11g (2003)	OFDM	54 Mbps	2.4GHz
WiFi 4	802.11n (2007)	OFDM	600 Mbps	2.4/5GHz
WiFi 5	802.11ac (2013)	OFDM	7 Gbps	5GHz
WiFi 6	802.11ax (2019)	OFDM	9.6 Gbps	2.4/5 GHz

- DSSS= Direct Sequence Spread Spectrum
- OFDM= Orthogonal Frequency Division Multiplexing
- MIMO=Multiple Input, Multiple Output (antennas)
- QAM=Quadrature Amplitude Modulation

Other systems

- GPS
- Bluetooth
- Wireless Microphones
- ZigBee
- Internet of Things (IoT)
- UWB
- Wireless USB
- StarLink (Space X): 12,000 satellites
- OneWeb: 48,000 satellites
- Kuiper (Amazon), 3,236 satellites

- Compact Disc (CD)
- Serdes (Serial-izer/Deserializer)
- Computer Memories
- Hard Drives
- QR Codes

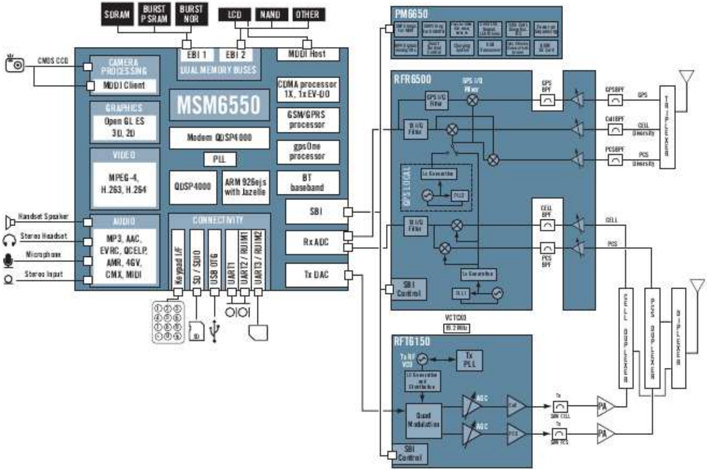
Example 1: GSM

- In Global System for Mobile Communications (GSM) systems the speech is sampled at 8000 samples per second and uniformly quantized to 13 bits (8192 levels).
- A group of 160 samples (20ms worth of speech), which is equivalent to 2080 bits, is compressed by the speech coder to 244 bits.
- The rate of information at the output of the speech encoder is 244bits/20ms=12.2kbps.
- Error correction coding is applied and redundant bits are added to these 244 informaiton bits to yield 456 coded bits.
- The rate at the output of the channel encoder is 22.8kbps.
- The bits at the ouput are modulated and transmitted in very short bursts with some extra bits added for synchronization. (More on this later).

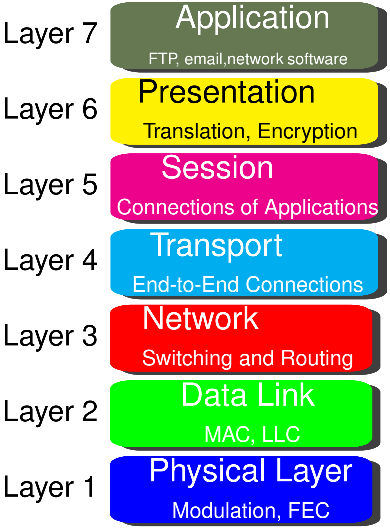
Example 2: Code Division Multiple-Access CDMA

Verizon and Sprint provided cellular service using “CDMA Technology” (2G). T-Mobile, Cingular use mainly GSM (2G). Many phones used by Sprint and Verizon use chips from Qualcomm. The following diagram shows how signals are processed in a Qualcomm chipset.

Qualcomm Chipset



Open Systems Interconnect (OSI) Model



OSI Model

- Network Layer: Routing packets from the source to the destination.
- Data Link Layer: Function is getting packets of information from one node to another node. Includes medium access control (MAC) sublayer which determines who transmits and when and the link layer control (LLC) providing error recovery (e.g. error detection).
- Physical Layer (Phy): Bits mapped to waveforms (modulation). Error control coding
- A breakdown of the different functions in a communication system is needed because of the complexity.
- Communication systems generally follow this but each one has unique features that might not be exactly the OSI model.

802.11 Model

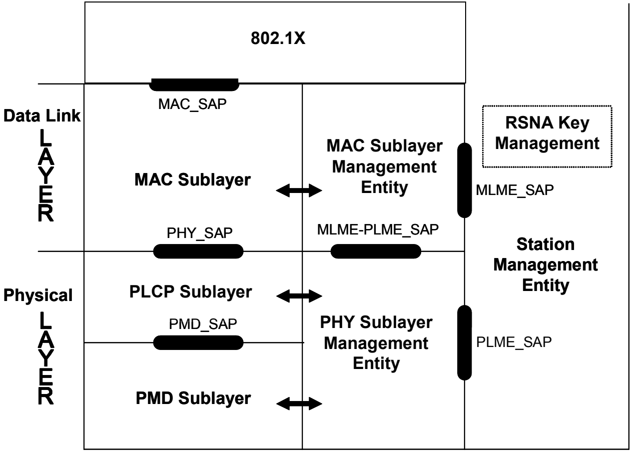


Figure 5-10—Portion of the ISO/IEC basic reference model covered in this standard

CDMA 1X Model

TIA/EIA/IS-2000.1-A

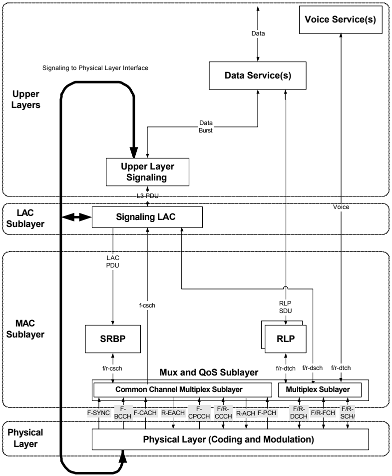


Figure 1. cdma2000 Architecture

Goals for this class

- Learn the different digital modulation techniques
- Learn optimum receiver design
- Learn how to analyze digital communication systems
- Understand the tradeoff between data rate, bandwidth, energy, noise
- Understand the fundamental limits of digital communications
- Understand the effects of propagation (link budget, intersymbol interference)
- Understand CDMA and OFDM
- Understand synchronization techniques such as for GPS
- Understand error coding techniques
- Understand some of the current digital systems (e.g. 5G, WiFi, GPS, DVB)

Prerequisites

- EECS 216
- EECS 301
- Matlab/Python coding

We will have a extended homework/mini project to demodulate a recorded GPS signal. You will need to find which satellites are being heard and what is the Doppler shift for each satellite.
We also have, for those interested, GNU Radio Companion and USRP radios so you can “play” with designing your own transmitter and receiver (in software).

QR Code