Code Division Multiple Access for Wireless Communications

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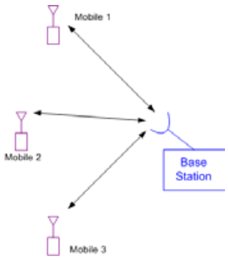
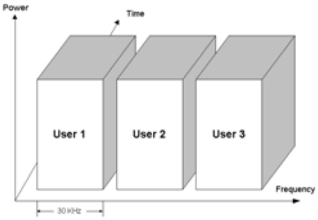
What is Multiple Access?

- Multiple users want to communicate in a common geographic area
- Cellular Example: Many people want to talk on their cell phones. Each phone must communicate with a base station.
- Imagine if only one person could talk on their cell phone at a time!
- **Problem**: How should we share our resources so that as many users as possible can communicate simultaneously?



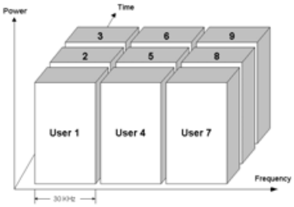
Freq. Division Multiple Access (FDMA)

- AMPS (analog), the First Generation (1G) used 30 KHz for each user.
- **Pros**
  - Very Simple to design
  - Narrowband (no ISI)
  - Synchronization is easy
  - No interference among users in a cell
- **Cons**
  - Narrowband interference
  - Static spectrum allocation
  - Freq. reuse is a problem
  - High Q analog filters or large guard band required



Time Division Multiple Access (TDMA)

- Can also partition time: users take turns using the channel
- IS-54 (2G) used same 30 KHz channels, but with three users sharing them (3 slots)
- GSM has 8 slots/270 KHz
- **Pros**
  - Better suited for digital
  - Often gets higher capacity (3 times higher here)
  - Relaxes need for high Q filters
- **Cons**
  - Strict synchronization and guard time needed
  - Still susceptible to jamming, other-cell interference
  - Often requires equalizer



Alternative to FDMA and TDMA?

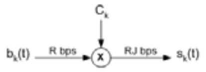
- What if we could allow users to share time and frequency?
  - Eliminates need for tight synchronization among many different users
  - Eliminates need for expensive analog filters
  - May have favorable impact on capacity (?)
- But:
  - How do we separate the users?
  - Won't they interfere with each other?

Code Division Multiple Access (CDMA)

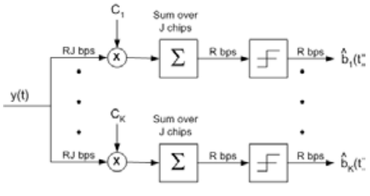
$b_k(t)$: bits for user *k*
C_k: spreading code
J: "spreading factor"
$s_k(t)$: transmitted signal for user k
$y(t)$: received signal for all users

$$y(t)=\sum_{k=1}^{K} h_k(t) * s_k(t)+n(t)$$

$h_k(t)$: channel impulse response for user *k*
$n(t)$: noise



The Basic CDMA Transmitter (User k)



The Basic CDMA Receiver (K Users)

Spreading Codes

- The spreading code C_k must be unique for each user.
- Ideally, they are orthogonal to one another, i.e.

  $<C_i, C_k> = 0$, unless i = k
  $<C_i, C_k> = J$, if i = k

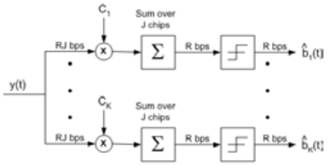
- Example: Walsh Codes
  - For a spreading factor *J*=4, there are 4 Walsh codes
  - In general there are always *J* Walsh codes, as long as *J* = 2, 4, 8, 16, 32, 64, 128, …

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix}=\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

4-Ary Walsh Codes

How Walsh Codes Work

- Assume a noiseless channel with unity gain
- Walsh codes allow four users to be transmitted *at the same time and frequency* using four times the number of bits



The Basic CDMA Receiver (K Users)

$$y[n]=C_1[n]b_1+C_2[n]b_2+C_3[n]b_3+C_4[n]b_4, \qquad \hat{b}_1=\operatorname{sgn}\left(\sum_{n=1}^{J} C_1[n]y[n]\right)$$

$$\Rightarrow \hat{b}_1=\operatorname{sgn}\left(\sum_{n=1}^{J} \underbrace{C_1[n]C_1[n]}_{=J}b_1+\underbrace{C_1[n]C_2[n]}_{=0}b_2+\underbrace{C_1[n]C_3[n]}_{=0}b_3+\underbrace{C_1[n]C_4[n]}_{=0}b_4\right)$$

$$=\operatorname{sgn}(Jb_1)=b_1$$

A numerical example

$$\text{Bits}: \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ -1 \\ 1 \end{bmatrix}, \quad \text{Spreading Codes}: \ \mathbf{C} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

$$\text{Received signal}: \ y[n] = C_1[n]b_1 + C_2[n]b_2 + C_3[n]b_3 + C_4[n]b_4$$

$$\begin{bmatrix} y[1] & y[2] & y[3] & y[4] \end{bmatrix} = \begin{bmatrix} 2 & -2 & 2 & 2 \end{bmatrix}$$

Decoded Bits:

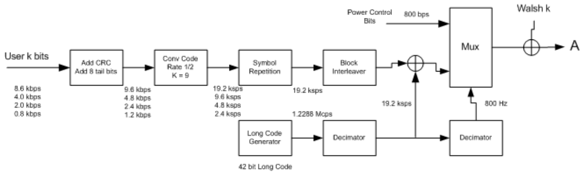
$$\hat{b}_1 = \operatorname{sgn}\left(\sum_{n=1}^{J} C_1[n]y[n]\right) = \operatorname{sgn}(4) = 1, \qquad \hat{b}_2 = \operatorname{sgn}\left(\sum_{n=1}^{J} C_2[n]y[n]\right) = \operatorname{sgn}(4) = 1$$

$$\hat{b}_3 = \operatorname{sgn}\left(\sum_{n=1}^{J} C_3[n]y[n]\right) = \operatorname{sgn}(-4) = -1, \qquad \hat{b}_4 = \operatorname{sgn}\left(\sum_{n=1}^{J} C_4[n]y[n]\right) = \operatorname{sgn}(4) = 1$$

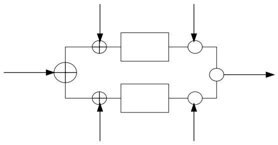
Properties of Walsh Codes

- There are some issues with Walsh Codes
  - Synchronization of all users is required
  - In a multipath channel, delayed copies may be received which are *not* orthogonal any longer!
  - Only J codes exist with a bandwidth expansion of J, so as far as capacity, we are right back where we started with TDMA and FDMA!
- Advantages relative to TDMA and FDMA
  - No guard bands or guard times are typically required
  - No equalizer is typically required, when a RAKE receiver is used

The IS-95 CDMA (2G) Forward Link



This transmitter structure is used in the base station by Sprint PCS, Verizon, and worldwide



Total spreading gain $J = 128$

The IS-95 Reverse Link

- The reverse link is quite different
  - Instead of Walsh Codes, “psuedorandom noise” (PN) codes
  - PN codes are deterministic Bernoulli sequences of {-1,+1}
  - While not orthogonal, they have low *cross-correlation,* e.g.

$$< C_i, C_k > \approx 1, \text{ unless } i = k$$
$$< C_i, C_k > = J, \quad \text{if } i = k$$

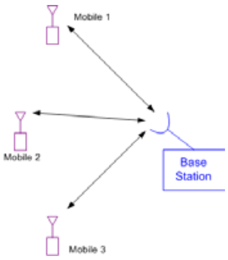
  - These codes have good properties even when not synchronized
  - Very strong error correcting codes make up the difference

The Near-Far Problem

- Users may be received with very different powers:
  - Users near the base station are received with high power
  - Users far from the base station are received with low power
  - For a path loss exponent of 4 and a cell size of 1 km, example:

$$\frac{P_2}{P_1} = \left(\frac{1000}{50}\right)^4 = 160{,}000 = 52dB!$$

  - Nearby users will completely swamp far away users
- Solution: **Power Control**

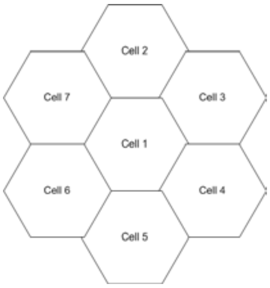


CDMA – Issues

- So far, CDMA looks like a step backwards:
  - Tight synchronization is required to use orthogonal codes, which then break in a multipath channel anyway
  - Quasi-orthogonal codes cause self-interference, which dominates the performance in most CDMA systems
  - Near-far problem is a serious hindrance, requiring fast and accurate power control (that uses up bits we could otherwise send information with)
  - And for all this, the required bandwidth is now J times larger than it was before, so there doesn't appear to be a capacity gain
  - How did Qualcomm convince people to use this stuff?

Interference Averaging

- It turns out there are serious advantages to CDMA in a multicell system
- Unlike FDMA and TDMA, CDMA does not rely on orthogonal frequency and time slots that are compromised by neighboring cells
- CDMA systems can reuse frequencies every cell! (FDMA and TDMA usually need *reuse factors* of 4 - 7)
- **Capacity increased 4-7 fold**

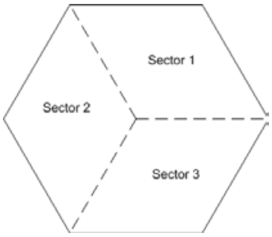


Voice Activity

- In TDMA and FDMA systems:
  - If a user doesn't have anything to send, the time/frequency slot allocated to them is wasted
  - It is typically very difficult to dynamically allocate time and frequency slots
- In CDMA systems:
  - If a user doesn't have anything to send, it causes less interference to other users of the system
  - Typically, each user needs to transmit less than half the time
  - Since interference-limited, this **doubles the capacity**

Sectorized Antennas

- Cells can use directional antennas to “sectorize” the cell
- At right, 120 degree antennas create 3-sector cells – very common
- For CDMA, this reduces the interference by a factor of three
  - **Capacity is increased by a factor of three!**
- FDMA/TDMA also use sectored antennas, but just to decrease reuse distance



Capacity Comparison

- Comparing the capacity of TDMA/FDMA/CDMA is very controversial
- In 1991, a famous (notorious?) Qualcomm paper claimed that due to voice activity, frequency reuse, and sectorization, CDMA increased capacity by:
  - Factor of 18 relative to AMPS
  - Factor of 6 relative to US TDMA (and similar for GSM)
- This turned out to be optimistic, about 1/3 of this gain actually happened (depends on who you ask)
- Still, twice as many users is nothing to snear at!
- **All 3G systems use CDMA for multiple access**

The Future of CDMA

- CDMA has overcome most cynicism to dominate the worldwide wireless voice market
- What about data services? Scheduling vs. Inteference Averaging
- CDMA appears to be an underdog for 4G, but still may win
- Ongoing research on CDMA
  - Increase capacity by joint decoding (multiuser detection & interference cancellation)
  - Applying CDMA to other applications: optical CDMA, ad hoc networks, dense wireless LANs
  - “MultiCDMA”: multiple antenna CDMA, multicarrier CDMA, multicode CDMA

Further Reading

1. Prof. Andrews’s CDMA webpage :
   - http://www.ece.utexas.edu/~jandrews/cdma.html
2. A tutorial:
   - R. Kohno, R. Meidan, and L. Milstein, “Spread spectrum access methods for wireless communications”, *IEEE Comm. Magazine*, Jan. 1995.
3. The Qualcomm capacity paper
   - K.S. Gilhousen et al, “On the capacity of a cellular CDMA system," *IEEE Trans. on Vehicular Tech.*, May 1991.
4. The definitive text (theoretical)
   - A. Viterbi, *CDMA: Principles of Spread Spectrum Communication*, Addison Wesley, 1995.