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

### Spreading Codes

- The spreading code $C_k$ must be unique for each user.
- Ideally, they are orthogonal to one another, i.e.
  $$ <C_i, C_k> = 0, \text{ unless } i = k $$
  $$ <C_i, C_k> = J, \text{ if } i = k $$

- 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 $J = 2, 4, 8, 16, 32, 64, 128, ...$

### 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

$$ y(t) = \sum_{k=1}^{4} h_k(t) * s_k(t) + n(t) $$

$$ h_k(t) = \text{channel impulse response for user } k $$
$$ n(t) = \text{noise} $$
A numerical example

Bits: \( \mathbf{b} = [ b_0 \ b_1 \ b_2 ] \)

Spreading Codes: \( \mathbf{C} = [ C_0 \ C_1 \ C_2 ] = [ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ -1 \ -1 \ -1 \ -1 ] \)

Received signal: \( y(t) = C_0 x(t) + C_1 x(t) + C_2 x(t) + C_3 x(t) + C_4 x(t) + \ldots \)

\( y[t] = [ y[2] \ y[3] \ y[4] ] = [ 2 \ -2 \ 2 \ 2 ] \)

Decoded Bits:
\[
\begin{align*}
\hat{b}_0 &= \text{sgn} \left( \sum_{n} C_0[n] y[n] \right) - \text{sgn}(4) - 1 \\
\hat{b}_1 &= \text{sgn} \left( \sum_{n} C_1[n] y[n] \right) - \text{sgn}(4) - 1 \\
\hat{b}_2 &= \text{sgn} \left( \sum_{n} C_2[n] y[n] \right) - \text{sgn}(4) - 1 \\
\end{align*}
\]
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:
    \[ \frac{P_1}{P_2} = \left( \frac{1000}{50} \right)^4 = 160,000 = 52 \text{ dB} \]
  - 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 sneer 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. Interference 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:
3. The Qualcomm capacity paper
4. The definitive text (theoretical):