CDMA: An Introduction

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Motivation

- Why do we need CDMA?
- Which are its basic principles?
- What do we earn by using it?
Outline

- Introduction
- CDMA Basics
- CDMA Deeper
- CDMA Problems
- CDMA Benefits
- Conclusions
Why Multiple Access?

- Goal: Multiple use of a shared medium.
- Multiplex channels in three dimensions:
  - Time (t)
  - Frequency (f)
  - Code (c)
Frequency Division Multiple Access (FDMA)

- Cocktail Party Analogy: People create teams and discuss. There is a distance among them.
- Requires guard band between channels
- Waste of bandwidth if traffic is distributed unevenly
- Example: broadcast radio
Time Division Multiple Access (TDMA)

- Cocktail Party Analogy: People have access to the same room but each of them waits for his turn to speak.
- (-) Precise synchronization necessary
Time and Frequency Division Multiple Access

- Precise coordination required
- Example: GSM
Code Division Multiple Access (CDMA)

- Cocktail Party Analogy: All people are in the same room together. They can all be talking the same time!
- Example: UMTS
Spread Spectrum

- PN: Pseudo-Noise code sequence \(\rightarrow\) spread/despread the signal.
- Modulation:
  - FSK \(\rightarrow\) Frequency hopped (FH) multiple access
  - PSK \(\rightarrow\) Direct sequence (DS) multiple access
FHMA

- Bandwidth divides in non overlapping bands.
- Signal shifts from band to band in predefined intervals.
- Receiver is synchronized with the transmitter
- (+) less interference
- Use: Bluetooth
CDMA Basics (1)

- Each station is assigned a unique \( m \)-bit code (chip sequence).
- To send bit 1, station sends chip sequence.
- To send bit 0, station sends the complement.
- Example: 1 MHz band with 100 stations.
- FDMA
  - Each station a 10kHz band
  - Rate:10 kbps (Assume that you can send 1bit/Hz)
- CDMA
  - Each station uses the whole 1MHz band \( \rightarrow 10^6 \) cps.
  - If <100 chips per bit \( \rightarrow \) Rate >10 kbps
CDMA Basics (2)

- Let \( A: 00011011 \) or \( A: (-1 -1 -1 +1 +1 -1 +1 +1) \)
  - \( B: 00101110 \) or \( B: (-1 -1 +1 -1 +1 +1 -1 -1) \)
  - \( C: 01011100 \) or \( C: (-1 +1 -1 +1 +1 -1 -1 -1) \)
  - \( D: 01000010 \) or \( D: (-1 +1 -1 -1 -1 +1 -1 -1) \)

- Compare any pair of these sequences-vectors...
- Multiply any pair of these sequences-vectors...
- Two chips \( S, T \) are orthogonal IFF \( S \cdot T = 0 \)
- \[ S \cdot T = \frac{1}{m} \sum_{i=1}^{m} S_i T_i = 0 \]
  - \[ S \cdot S = \frac{1}{m} \sum_{i=1}^{m} S_i S_i = \frac{1}{m} \sum_{i=1}^{m} S_i^2 = \frac{1}{m} \sum_{i=1}^{m} (\pm 1)^2 = 1 \]
  - \[ S \cdot \bar{T} = \frac{1}{m} \sum_{i=1}^{m} S_i \bar{T_i} = \frac{1}{m} \sum_{i=1}^{m} (-1) = \frac{1}{m} (-m) = -1 \]
CDMA Basics (3)

- Let A, B, C, D transmit correspondingly bit 1, 0, 1, __.
  
  A: (-1 -1 -1 +1 +1 -1 +1 +1)
  B: (-1 -1 +1 -1 +1 +1 +1 -1)
  C: (-1 +1 -1 +1 +1 +1 -1 -1)
  D: (-1 +1 -1 -1 -1 -1 +1 -1)

- Assume that:
  - All stations are perfectly synchronous.
  - All codes are pair wise orthogonal (aren’t they?).
  - If two or more stations transmit simultaneously, the bipolar signals add up linearly.

- Receiver “understands” \( S = A + \overline{B} + C = (-1 +1 -3 +3 +1 -1 -1) \)
- How can the receiver “understand” what bit station C send?
Let’s compute the normalized inner product $S \cdot C$

$$S \cdot C = \frac{1}{8}(-1 +1 -3 +3 +1 -1 -1 +1)(-1 +1 -1 +1 +1 +1 -1 -1) =$$
$$= \frac{1}{8}(1+1+3+3+1-1+1-1) = \frac{1}{8}8 = 1$$

Right!
By accident??

$$S \cdot C = (A + \bar{B} + C) \cdot C = A \cdot C + \bar{B} \cdot C + C \cdot C = 0 + 0 + 1 = 1$$

Remember: All codes are pair wise orthogonal!
CDMA Basics (5)

- Reverse way...
- Think that each chip sequence arrives separately
- Receiver separately computes each inner product

\[ A \cdot C = 0 \quad (1) \]
\[ B \cdot C = 0 \quad (2) \]
\[ C \cdot C = 1 \quad (3) \]
\[ S = 0 + 0 + 1 = 1 \]

- It keeps only the non-orthogonal pair, i.e. the right bit
CDMA Deeper (1)

- More advanced analysis...
- Sender:
  
  \[ s_d(t) = A \cos(2\pi f_c t + \theta(t)) \]
  
  \[ \theta(t) \in \{0, +\pi\} \]
  
  \[ c(t) \in \{-1, +1\} \]
  
  \[ s(t) = A \cos(2\pi f_c t + \theta(t))c(t) \]

- Receiver:

  \[ s(t)c(t) = A \cos(2\pi f_c t + \theta(t))c(t)c(t) = A \cos(2\pi f_c t + \theta(t)) = s_d(t) \]
With orthogonal codes, we can safely decode the coding signals.

Noise?

$R' = R + N$, $N$: m-digit noise vector and $N = (\pm a \pm a \ldots \pm a)$

Decode … $R' \cdot S = (R + N) \cdot S = S \cdot S + (\text{orthogonal codes}) \cdot S + N \cdot S = 1 + 0 + ?$

No problem if chipping codes are balanced (same $\pm$)

$R' \cdot S = (R + N) \cdot S = S \cdot S + (\text{orthogonal codes}) \cdot S + N \cdot S = 1 + 0 + (a \ a \ a \ a)(+1+1-1-1)=1+0+0=1$
CDMA Deeper (3)

- How many codes can we construct with m chips?
- m (why?)
- If \( m=2^k \), Walsh-Hadamard codes can be constructed recursively!
- The set of codes of length 1 is \( C_0 = \{<+>\} \)
- For each code \( <c> \in C_k \) we have two codes \( \{<c> <c \bar{c}>\} \in C_{k+1} \)
- Code Tree:
  - \( C_0 = \{<+>\} \)
  - \( C_1 = \{<++>,<+->\} \)
  - \( C_2 = \{<+++>,<++->,<+-+>,<--->,<--+>,<++->,<+-+>\} \)
Correlation: Determines similarity between two sets of data.
- Possible values
  - 1 sequences are similar
  - 0 no relationship between them.
  - -1 one is the mirror of the other
Cross correlation: Compare two sequences from different sources
Auto correlation: Compare a sequence with itself after a time-interval
Walsh Codes: No cross correlation – Low auto correlation
PN sequences: Low cross correlation – Low auto Correlation
CDMA Deeper (5)

- We cannot have more than $m$ orthogonal codes.
- Let $m + k$ stations and $m$ chips...
- Idea: Use PN Sequences.

\[
R \cdot S = S \cdot S + (k \text{ random codes}) \cdot S + (m-1 \text{ orthogonal codes}) \cdot S =
\]

\[
1 + ? + 0
\]

- $?$: the sum of the $k$ random variables that are either 1 or -1.
- But PN Sequences = low cross correlation. $?$ should be 0.
- Experimental evaluation: For $k=m=128$, decoding is correct more than 80%.
CDMA Problems (1)

- All stations are received with the same power level...

- In reality… users may be received with very different powers!
- Near-far Problem
- Solutions:
  - Empirical rule: Each MS transmits with the reverse power that it receives from the BS
  - Power Control!
    - Open Loop
    - Fast Closed Loop
CDMA Problems (2)

- Bad Properties of Walsh Codes
- Perfect Synchronization of all users required.
- Impossible...
- …is nothing! Use a long enough known chip sequence.

- But…In a multipath channel, delayed copies may be received, which are not orthogonal any longer.
- Self-Interference.
CDMA Problems (3)

- So far...
- (-) tight synchronization
- (-) self-interference
- (-) Near-far problem
- (-) Higher complexity of sender/ receiver
- ...
- How did Qualcomm convince people to use this stuff??
CDMA Benefits (1)

- Unlike FDMA and TDMA, CDMA does not rely on orthogonal frequency and time slots!
CDMA Benefits (2)

- In TDMA and FDMA systems
  - Nothing to send $\Rightarrow$ time/frequency slot is wasted
  - Dynamic allocation is very difficult

- In CDMA systems
  - Nothing to send $\Rightarrow$ less interference
  - Transmit $\sim$half times $\Rightarrow$ doubles the capacity
CDMA Benefits (3)

- FDMA-TDMA use sectors to decrease the reuse distance
- CDMA use sectors to increase capacity (triple it)!
CDMA Benefits (4)

- Why handoff?
- Types
  - “Hard”
  - “Soft”
CDMA Benefits (5)

- Break-Before-Make
- Each MS communicates with only one BS each time
- (+) Reduced dropped calls
CDMA Benefits (6)

- Each MS communicates with more than one BS each time
- Use Signal Strength to decide where to connect.
- Make-Before-Break
- (+++) no dropped calls
CDMA Benefits (7)

- Capacity…
- TDMA-FDMA: bandwidth limited
- CDMA: interference limited
- CDMA’s capacity is bigger.
- How?
- Long Story…
Conclusions

- Back to the start…
- Why do we need CDMA?
  - Introduction
- Which are its basic principles?
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  - CDMA Deeper
- What do we earn by using it?
  - CDMA Problems
  - CDMA Benefits
Ευχαριστώ!