Wireless Communications
Chapter 9. Multiple Access

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If two nodes transmit in the same time and the same frequency band, their signal will collide. Signal becomes interference.

Multiaccess: to separate multiple signals.
Different Multiple Access Schemes

- **TDMA**: Separating in time domain
- **FDMA**: Separating in frequency domain
- **CDMA**: mixed in both time and frequency domains; separating by code
- **CSMA**: separated in time, but without scheduling
### Time Division Multiple Access

- The time slots have been allocated before data transmission.
- Synchronization, i.e. estimating timing information, is a key problem. Two types: decision-directed and non-decision directed.
Decision-directed Synchronization

- **Principle:** Assume the transmitted signal is known (e.g. pilot symbols);
- **Expected received signal**

\[ s(t; \tau) = \sum_k s(k)g(t - kT_s - \tau). \]

- **Likelihood function:**

\[ L(\tau) = \exp \left[ -\frac{1}{N_0} \int_{T_0} [r(t) - s(t; \tau)]^2 \right] \]
The time offset $\tau$ maximizing the likelihood satisfies

$$\sum_{k} s(k) \frac{d}{d\tau} z_k(\tau) = 0,$$

where

$$z_k(\tau) = \int_{T_0} r(t) g(t - kT_s - \tau) dt.$$
Need not know the original signal.
Principle: shift the time offset to match the correct one.
History of CDMA

Mother of CDMA

- Hedy Lamarr (1913-2000): a movie star in 1940s (six husbands). She has a star in the Hollywood Walk of Fame.

- On Aug. 11, 1942, US Patent 2,292,387 was issued to Hedy Lamarr and Antheil. This is the early version of frequency hopping communications.
Frequency hopping CDMA was widely used in World War II.

In each time slot, the transmit chooses one random frequency to transmit, for security.
IS-95 (Interim Standard 95) is the first CDMA based digital cellular standard, pioneered by Qualcomm.

Currently, there are two standards of CDMA systems: cdma2000 (3GPP2) and WCDMA (3GPP). Both are based on direct-sequence CDMA.
Each symbol contains $N$ chips in time. $N$ is called spreading gain, or processing gain. Each chip could be 1 or -1.

**Vector signal:** $\mathbf{r} = x_k \mathbf{s}_k$, where $x_k$ is scalar information symbol for user $k$ and $\mathbf{s}_k$ is an $N$-vector of the chips, called spreading code (or signature waveform).
Orthogonal Spreading Code

\[
\{s_1, s_2, s_3, s_4\} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}
\]

Check \(s_i^T s_j = 0\), if \(i \neq j\).
Received signal:

\[ r = \sum_{k=1}^{K} x_k s_k + n. \]

How to detect \( x_k \) from the superimposed signal?
For user \( k \), the scalar output of a correlation detector is given by

\[ z_k = s_k^T r = x_k + s_k^T n. \]
Compared with uncoded system, channel coding uses more time and energy to transmit one bit.

CDMA system uses the same time and power as a narrow band system to transmit one bit. There is no coding here.
Fundamentals of CDMA

Spectrum Spreading

- There are $N$ changes within a symbol period, therefore it requires approximately $N$ times bandwidth. CDMA is a wideband system.
- Better resolution of multiple paths.
- Larger channel capacity (recall Shannon's formula).
In most practical CDMA systems, the spreading codes are not orthogonal.

Reason:

- An orthogonal CDMA system can contain at most $N$ users. More users will break the orthogonality.
- When multiple path fading exists, the orthogonality is broken even if the spreading codes are orthogonal. (WHY?)
- The orthogonality is broken for asynchronous transmission. (WHY?)
Matched Filter

- Matched filter: for user $k$, we use
  \[ z_k = s_k^T r = x_k + s_k^T n. \]

- Multiple access interference (MAI):
  \[ I_k = \sum_{i \neq k} s_i^T s_k. \]

- Signal-to-interference-plus-noise ratio (SINR) is given by
  \[ SINR = \frac{E[|s_k|^4]}{E[|I_k|^2] + \sigma_n^2}. \]
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\]

Asymptotic case: as \( K, N \to \infty \)

\[
SINR \to \frac{1}{\beta + \sigma_n^2}.
\]

(Suppose all transmit powers are 1.)
Rake Receiver

Because of inter-user interference, the user far from the base station may be killed by a closer user.
The user closer to the base station should transmit with less power and the user farther away from the基站 station should transmit with larger power.

Requirement of power control is usually expressed as (R. Yate, 1995)

\[ \mathbf{p} \geq \mathbf{l}(\mathbf{p}), \]

where \( \mathbf{p} = (p_1, \ldots, p_K) \) is the vector of transmit power of \( K \) users, \( \mathbf{l}(\mathbf{p}) \) represents the vector of effective interference.
We consider $K$ users and 1 base station. The channel gain from user $k$ to base station is denoted by $h_k$ and the noise power at base station $m$ is denoted by $\sigma_n^2$.

The SINR of user $k$ is given by $p_k \mu_k$, where

$$\mu_k = \frac{h_k}{\sum_{i \neq k} P_i h_i + \sigma_n^2}.$$  

When the required SINR is $\gamma_k$ for user $k$, the effective interference can be written as

$$I(p)_k = \frac{\gamma_k}{\mu_k}.$$
Power Control

Power Control Algorithm

- The power control is carried out in an iterative way (proposed by R. Yates)\(^1\)

\[ p(t + 1) = l(p(t)) \]

- Theorem: If \( l(p) \) is feasible, for any initial power configuration, the power control algorithm converges to a unique fixed point.

OFDM: Orthogonal Frequency Division Multiplexing

- OFDM was born in 1960s in Bell Labs.
- Life begins at forty (John Lenon).
- Now OFDM is the fundamental signaling technique for 4G cellular systems (UWB, LTE, WiMAX).
The data is divided into many streams and transmitted on many subcarriers (also called tones).
Features of OFDM

- No need for equalization (no ISI). Each tone looks like a scalar channel. High speed.
- Good structure for resource allocation.
Transceiver of OFDM

Transmitter
Receiver

Tranceiver of OFDM

Diagram showing the process of receiving OFDM signals.
Each OFDM symbol (in time) transmits a block of information bits. It contains $N$ chips (in time) (similar to CDMA).
Suppose the transmitted signal is $x(n)$ ($n$ is time index) and channel response is $h(n)$. The received signal is

$$y(n) = (x \bigotimes h)(n)$$

$\bigotimes$ means circular convolution:

$$(x \bigotimes h)(n) = \sum_{k=0}^{N-1} x(k)h(n - k)_N,$$

where $h(k)_N = h(\text{mod}(k, N))$. 
Recall that circular convolution in time means multiplication in frequency domain (please check your textbook of digital communications)

\[ y = (x \otimes h) \] means \[ Y_i = X_i H_i \], where \( Y, X, H \) are the Discrete Fourier Transform of \( y, x, h \).
Recall that circular convolution in time means multiplication in frequency domain (please check your textbook of digital communications)

\[ y = (x \otimes h) \text{ means } Y_i = X_i H_i, \text{ where } Y, X, H \text{ are the Discrete Fourier Transform of } y, x, h. \]
Why Use Frequency Domain?

- If the information symbols are in time domain, how to recover $x$ from $y = x \otimes h$? Need complicated equalization.
- If the information symbols are in frequency domain, it is very easy to recover $X$ from $Y$: $X_i = \frac{Y_i}{H_i}$. 
Tranceiver of OFDM

Information Flow

Transmitter:
- \( \{X_i\}_{i=0,...,N-1} \)
- IDFT

Receiver:
- \( \{y_i\}_{i=0,...,N-1} \)
- DFT
- \( \{Y_i\}_{i=0,...,N-1} \)
- PS

Channel

\( S-P \)
Due to delay spread in the channel, there exists interference across different OFDM symbols (ISI).

We set a portion of the OFDM symbol as prefix, whose length is larger than the delay spread. (suppose the length of prefix is \( L \).)

The prefix should be the same as the end of the OFDM symbol, thus forming a circulation:

\[
\mathbf{x} = (x_{N-L}, \ldots, x_{N-1}, x_0, x_1, \ldots, x_{N-L}, \ldots, x_{N-1}).
\]
Why Use Random Access?

- In TDMA, CDMA or OFDMA, the channels (time slots for TDMA, spreading code for CDMA and subcarrier for OFDMA) need to be distributed to the transmitters by a center.
- In a general network, there is no center or the users may emerge or quit, it is different to schedule the transmission in a stationary way.
- In random access, there is no fixed channel assignment. The access is probabilistic and the signals are separated by probability.
  - Advantage: no channel scheduling;
  - Drawback: possible collision and less efficient; when throughput when the number of nodes is large.
Types of Random Access

- Aloha: the first technology of random access
- Carrier sensing multiple access with collision detection (CSMA-CD): used in Ethernet
- Carrier sensing multiple access with collision avoidance (CSMA-CA): used in WiFi (IEEE 802.11)
History of Aloha Aloha

- Proposed by Abramson in 1970 at the University of Hawaii.
- The idea was to use low-cost ham radio-like systems to create a computer network linking the far-flung campuses of the University.
- It can be categorized into pure and slotted Aloha systems.
Aloha

Basic Protocol of Pure Aloha

- Transmission: when a user has data, it transmits immediately. It is possible that some other user is transmitting.
- Random recession: if the transmission fails (due to transmission collision), the user waits for a random time $\tau$ and then retransmits. The random time $\tau$ satisfies the exponential distribution:

$$p(\tau) = \alpha e^{-\alpha \tau}$$
### Basic Protocol of Slotted Aloha

- The time is slotted. The transmissions can only begin at the head of each time slot.
- The waiting time is discrete, measured by time slots.
Let $T_p$ be the time required to send a packet. Then, if there is another packet transmitting within the vulnerable region ($2T_p$), the transmission will fail.
Assume that the arrival of packets satisfies a Poisson distribution and averagely $\lambda$ packets arrive within a unit time. The probability of $k$ packets arrives within time period $t$ is given by

$$P(k) = \frac{(\lambda t)^k e^{-\lambda t}}{k!}$$

The probability that there is no packet within a period of $2T_p$ is given by $e^{-2G}$, where $G = \lambda T_p$. This is also the probability of successful transmission.

The average number of successfully transmitted packets (throughput), $S$, is given by

$$S = Ge^{-2G}.$$
For slotted Aloha, the vulnerable time is $T_p$.

Using the same argument, for slotted Aloha, $S$ is given by

$$S = Ge^{-G}.$$ 

The maximum of $S$ is 0.368 when $G = 1$. 

Comparison of Pure and Slotted Aloha

- Slotted Aloha achieves better performance.
Carrier Sensing Multiple Access (CSMA)

- Principle of CSMA: sense the carrier before transmission; if finding some other transmitter is transmitting, it waits for a random time and then transmit. A transmitter transmits only when the channel is detected idle.

- Two versions:
  - collision detection (CD): a transmitter is able to detect signal collision;
  - collision avoidance (CA): use RTS and CTS to clear hidden node and exposed node (will explain later).
Rule of transmission (from Proakis’ book):

- If the channel is idle, the user transmits a packet;
- If the channel is sensed busy, the user schedules the packet transmission at a later time according to some delay distribution. At the end of the delay interval, the user again senses the channel and repeats.
1-persistent CSMA/CD

Rule of transmission (from Proakis’ book):
- If the channel is idle, the user transmits a packet;
- If the channel is sensed busy, the user schedules the packet transmission at a later time according to some delay distribution. At the end of the delay interval, the user transmits with probability 1.
$p$-persistent CSMA/CD

- Rule of transmission (from Proakis’ book):
  - If the channel is idle, the user transmits with probability $p$ or delay by $\tau$ seconds with probability $1 - p$;
  - If at time $\tau$, the channel is still sensed idle, the above is repeated. if a collision happens, the users reschedule retransmission of the packets according to some delay distribution;
  - If at time $\tau$, the channel is still busy, the user waits until it becomes idle and repeat the above steps.
0.01-persistent CSMA looks the best. (Then, why consider other types of CSMA?)
Hidden Node and Expose Node

- **Hidden node**: A is transmitting. C wants to transmit to B but is out of the sensing range for A, then C transmits and collides with A at B.

- **Expose node**: B is transmitting, then C dare not transmit, but D is actually out of the interference range of B.
When A wants to transmit, it sends a request-to-transmit (RTS) to B. Neighboring nodes then know A intends to transmit.

When B agrees to receive, it sends a clear-to-transmit (CTS) to A. Neighboring nodes will keep silent.
Interference Limited and Thermal Limited

- **Thermal limited:** noise is too strong and SNR is too small. Example: in a one-to-one communication system, the transmitter and receiver are too far away from each other; or in a multiuser system that has very little interference.

- **Interference limited:** noise is negligible and interference dominates; it is useless to simply increase transmit power. Example: CDMA system.
Two Approaches

- Interference Average: consider interference as noise and allow collision; but the interference is averaged. (we can also call it interference diversity). Example: symbol rate hopping OFDM
- Interference Avoidance: avoid collision. Example: CDMA/CA.