CDMA and TDMA Cellular Communication

Abstract The objective of this project is to investigate how the cellular technologies of Time-Division Multiple Access and Code-Division Multiple Access allow users to communicate, investigate how a man named Shannon discovered it was possible to achieve reliable transmissions over a channel, and how different coding schemes and techniques such as direct sequence and frequency hopping allows Shannon’s discovery to become a reality today.
Introduction

Communications can be defined as the task of conveying information from one point to another. An information source produces a time-varying electrical signal, which has to be transferred flawlessly to the receiving end. This signal can either be analog (a time-continuous signal which can take on any value within a range) or digital (a quantized signal taking on a discrete number of values). In the early stages of development, communications involved all analog stages in both the transmitter and receiver. Advances in miniaturization as well as in the development in digital signal processing (DSP) allowed a gradual shift into digital systems. The advantages of digital systems are overwhelming, many present-day approaches such as error-correcting coding, multiple access techniques, multi-user detection, data compression and encryption can be implemented almost exclusively in digital communication systems. Cellular systems based on Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA) are multi-user applications. CDMA makes use of spread spectrum communication, a technique by which energy generated in a particular bandwidth is spread in the frequency domain. TDMA allows the users to share the same frequency channel by dividing the signal into different time slots. Each user takes turn in a round robin fashion for transmitting and receiving over the channel. Unlike TDMA, in CDMA several users can transmit over the channel at the same time.

The Shannon challenge

In 1498, Claude E. Shannon demonstrated that, for any transmission rate less than or equal to a parameter called channel capacity, there exists a coding scheme that achieves an arbitrarily small probability of error, and hence can make transmission over a channel perfectly reliable. Shannon’s proof of his capacity theorem was non-constructive, and hence gave no guidance as to how to find an actual coding scheme achieving the ultimate performance. The cornerstone of the proof was the fact that if we pick a long code at random, then its average probability of error will be satisfactorily low, and that there exists at least one code whose performance is at least as good as the average. Direct implementation of random coding, however, leads to a decoding complexity that prevents its actual use, as there is no practical encoding or decoding algorithm.

Fig.1 below summarizes some of Shannon’s finding on the limits of transmission at a given rate $p$ allowed on the additive white Gaussian noise channel with a given bit-error rate (BER).
Fig. 1: Admissible region for the pair BER, $E_b / N_0$. For a given code rate $p$, only the region above the curve labeled $p$ is admissible. (CWC p. 9)

Figure 1 shows the ratio $E_b / N_0$, where $E_b$ is the energy spent for transmitting one bit of information at a given BER over an additive white Gaussian noise channel and $N_0 / 2$ is the power spectral density of the channel noise, which must exceed a certain quantity.

Because all users transmit on the same frequency in multi-access systems, internal interference generated by the system is the most significant factor in determining system capacity and call quality. The transmit power for each user must be reduced to limit interference, however, the power should be enough to maintain the required $E_b / N_0$ (signal to noise ratio) for a satisfactory call quality. Maximum capacity is achieved when $E_b / N_0$ of every user is at the minimum level needed for the acceptable channel performance.

Since 1948, people have been trying hard to develop practically implementable coding schemes in attempt to approach channel capacity. The problem was eventually solved in the early 1990s, which led to technology such as CDMA and TDMA to be developed.

CDMA

During the last decade the development and applications of spread-spectrum (SS) based systems such as CDMA has increased with a previously unseen pace. Undoubtedly, research on the subject grew with the same rate. The role of spread spectrum technology in modern communications is indisputable. Since an important part of spread-spectrum applications lies in the area of CDMA.

CDMA is one of many types of spread spectrum. To be considered a spread spectrum system, the system must satisfy two criteria: (DACS p. 358)
1. The bandwidth of the transmitted signal \( s(t) \) needs to be much greater than that of the message \( m(t) \);
2. The relatively wide bandwidth of \( s(t) \) must be caused by an independent modulating waveform \( m(t) \), called the spreading signal, and this signal must be known by the receiver in order for the message signal, \( m(t) \) to be detected.

CDMA communications in general is distinguished between three key elements:
1. The signal occupies a bandwidth much greater than necessary to send the information. This results in many benefits such as immunity to interference and jamming and multi-user access;
2. The bandwidth is spread by means of a code which is data independent.
3. The receiver synchronizes to the code to recover the data. The use of independent code and synchronous reception allows multiple users to access the same frequency band at the same time.

Two ways to spread the bandwidth of the signal to achieve maximum channel capacity are;

*Frequency hopping* (FH) - The signal is rapidly switched between different frequencies within the hopping bandwidth pseudo-randomly, and the receiver knows before hand where to find the signal at any given time. Here \( g \) is of the FM type where there are \( M = 2^k \) hop frequencies determined by the \( k \)-bit words obtained from the spreading code waveform, \( c(t) \).

*Direct sequence* (DS) - The digital data is directly coded at a much higher frequency. The code is generated pseudo-randomly, the receiver knows how to generate the same code, and correlates the received signal with that code to extract the data. Here a double-sideband suppressed carrier type of spreading modulation is used [i.e., \( g_c(t) = c(t) \)] and \( c(t) \) is a polar waveform.

**Direct Sequence** (DS)

Assume that the information waveform, \( m(t) \) comes from a digital source and that \( m(t) \) is a polar waveform having values of \(+1\). Also, let the case of the binary-phase-shift keyed data (BPSK) modulation where \( g_m(t) = A_c m(t) \), were \( A_c \) denotes the level of modulated signal of carrier frequency. Thus, for DS where \( g_c(t) = c(t) \) is used the spread spectrum signal becomes \( g(t) = A_c m(t)c(t) \).

The resulting \( s(t) = g(t)e^{jw_0t} \) is called a binary-phase-shift keyed data direct sequence spreading spread spectrum signal (BPSK-DS-SS), and \( c(t) \) is a polar spreading signal. The spreading process is done by directly combining the baseband information to high chip rate binary code. The Spreading Factor is the ratio of the chips to baseband information rate.

Also, let this spreading waveform be generated by using a Pseudo Noise (PN) code generator, as shown in Fig. 2, where the values of \( c(t) \) are \(+1\).
The pulse width of $c(t)$ is denoted by $T_c$ and is called the chip interval. The code generator uses a modulo 2 adder and $r$ shift register stages that are clocked every $T_c$ seconds. Furthermore, feedback taps from the stage of the shift registers and modulo 2 address is arranged so that the $c(t)$ waveform has a maximum-length sequence or $m$-sequence waveform.

Some properties of $m$-sequences are:
1. In one period the number of 1’s is always one more than the number of -1s.
2. The modulo 2 sum of any m-sequence when summed chip by chip with a shifted version of the same sequence produces another shifted version of the same sequence.
3. If a window of width $r$ (where $r$ is the number of stages in the shift register) is slid along the sequence for $N$ shifts, then all possible $r$-bit words will appear exactly once, except for the all -1 $r$ bit word.

**Frequency Hopping**

A frequency-hopped (FH) SS signal uses a complex envelope $g_c(t)$ that is of the FM type where there are $M = 2^k$ hop frequencies controlled by the spreading code where $k$ chip words are taken to determine each hop frequency. An FH-SS transmitter is shown in Fig. 3.
The source information is modulated using conventional Frequency Shift Keying (FSK) or Binary Phase Shift Keying (BPSK) to produce a signal. The frequency hopping is accomplished by using a mixer circuit where the Local Oscillator (LO) signal is provided by the output of a frequency synthesizer that is hopped by the PN code. The serial-to-parallel converter reads $k$ serial chips of the spreading code and outputs a $k$ chip parallel word to the programmable word to the frequency synthesizer. The $k$ chip word specifies one of the possible $M = 2^k$ hop frequencies $w_1, w_2, \ldots, w_M$.

The decoded FH signal is shown in Fig.4.

Here the receiver has the knowledge of the transmitter, $c(t)$ so that the frequency synthesizer in the receiver can be hopped in synchronism with that of the transmitter.
Coding

A CDMA spread spectrum system uses unique spreading codes to spread the data before transmission. Some examples of these codes are shown in table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Synchronization Codes</th>
<th>Channel Codes</th>
<th>Scrambling Codes, UL</th>
<th>Scrambling Codes, DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Gold Codes - Primary Synchronization Codes (PSC) and Secondary Synchronization Codes (SSC)</td>
<td>Orthogonal Variable Spreading Factor (OVSF) codes (sometimes called Walsh Codes)</td>
<td>Complex-Valued Gold Code Segments or Complex-Value codes</td>
<td>Complex-Valued Gold Code Segments or Pseudo Noise (PN) codes</td>
</tr>
<tr>
<td>Length</td>
<td>256 chips</td>
<td>4-512 chips</td>
<td>38400 chips / 256 chips</td>
<td>38400 chips</td>
</tr>
<tr>
<td>Duration</td>
<td>66.67 us</td>
<td>1.04 us – 133.32 us</td>
<td>10 ms/66.67 us</td>
<td>10 ms</td>
</tr>
<tr>
<td>Number of Codes</td>
<td>1 primary code / 16 secondary codes</td>
<td>= spreading factor 4-256 UL 4-512 DL</td>
<td>16,777,216</td>
<td>512 Primary / 15 Secondary for each primary code</td>
</tr>
<tr>
<td>Usage</td>
<td>To enable terminals to locate and synchronies to the cell’s main control channels</td>
<td>UL: To separate physical data and control data from same terminal DL: to separate connection to different terminals in a same cell</td>
<td>Separation of terminal</td>
<td>Separation of sectors</td>
</tr>
</tbody>
</table>

Table 1: A summary of spread spectrum codes.

The signal is transmitted in a channel, which is below noise level. The receiver then uses a correlator to de-spread the wanted signal, which is passed through a narrow bandpass filter. Unwanted signals will not be de-spread and will not pass through the filter. Codes take the form of a carefully designed +-1 sequence produced at a much higher rate than that of the baseband data. The rate of a spreading code is referred to as chip rate rather than the bit rate.

CDMA spread spectrum codes are not required to provide call security, but create a uniqueness to enable call identification. Codes should not correlate to other codes or time shifted version of itself. Spread spectrum codes are pseudo-random noise-like (PN) codes, channel codes are designed for maximum separation from each other, and cell identification codes are balanced not to correlate to other codes of it self.

One key advantage of a CDMA system is the capability of using signals that arrive in the receivers with different time delays. This phenomenon is called multipath. TDMA, which is a narrow band system, cannot discriminate between the multipath arrivals, and resort to equalization to mitigate the negative effects of multipath. Due to its wide bandwidth and rake receivers, CDMA uses the multipath signals and combines them to make an even stronger signal at the receivers. These receivers are called Rake Receivers which is essentially a set of several receivers. One of the receivers constantly
searches for different multipaths and feeds the information to the other three fingers. Each finger then demodulates the signal corresponding to a strong multipath. The results are then combined together to make the signal stronger.

**TDMA**

Now, let’s move on from CDMA and have a look at TDMA. Time-division multiple access is based on dividing access time among all stations on a network and allowing each station to use the full system bandwidth and power to transmit framed bursts of data. The system is controlled by a master station, and the mobile transmission is accommodated in precisely synchronized time slots, all operating on the same carrier frequency.

Channel capacity in a TDMA system is fixed and indisputable. Each channel carries a finite number of "slots", and you can never accommodate a new caller once each of those slots is filled. An example of generating TDMA output is shown in Fig. 5. A1-A4, B1-B4, and C1-C4 represent digital data from three different sources. A multiplexer (MUX) is used to combine all source data to one data stream. A key to successful data multiplexing is the multiplexing frequency FM must be fast enough so that the throughputs of the A, B, and C data are output fast enough so that the system does not become congested and none of the data is lost.

![Diagram of TDMA output](image)

**Fig5:** An example of generating a DMA output. (MEC p. 440)

The TDMA output data stream in Fig. 5 shows the placement of the A, B, and C data in the TDMA frame. Each block represents a time slot within the frame. The time slot provides a fixed location (relative in time to the start of a data frame) for each group of data so at the receiver, the data can easily be recovered. The process of recovering the data is shown in Fig. 6. The data is input into a demultiplexer, which recovers the A, B, and C grouped data. If only the information in the A time slots is to be recovered, then the data in the B and C time slots are ignored.
The arrival of the TDMA data can be an issue. This is because of potential multipath RF propagation problems with stationary systems and the added RF propagation path problems introduced by mobile communications. To compensate for the variation in data arrival times, guard times are added to the TDMA frame. If the data arrive too closely together, then potential inter symbol interference (ISI) due to data overlapping can occur resulting in an increase in the bit error rate (BER). The guard times provide an additional margin of error, thereby minimizing inter symbol interference and bit errors.

One key advantage to TDMA is the transceiver’s ability to monitor other channels during slots when it is neither transmitting nor receiving signals. Fig. 7 is operating on slot 2, with a frame of 8 slots, where the transmitting frame is three slot positions displaced from the receiving frame.

Monitoring another signal can be done, say, in time slot 7. The transceiver will re-synthesize its oscillator as it changes from receiver to transmitter to monitor abnormalities in the sequence.
Conclusion

Both CDMA and TDMA both come close to Shannon’s realization of a reliable channel and offer their own distinct ways of allowing multiple user access. By utilizing methods such as direct sequencing and frequency hopping along with channel, synchronous, and scrambling codes allows a system to achieve near maximum channel capacity. CDMA has the advantage of multipath to allow increased signal strength and TDMA the advantage of monitoring other channels to insure the flow of data. The impressive advances in technology gives ever-increasing signal processing capabilities, higher degrees of miniaturization, advanced antenna technologies, etc., helping to pave the way towards the development and implementation of more sophisticated algorithms to achieve reliable and efficient cellular networks.
References


