The CDMA Standard

Code Division Multiple Access modulation has been standardized by TIA for the North American cellular telephone system. The author describes the system, its advantages and testing challenges.

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Code Division Multiple Access (CDMA) is a class of modulation that uses specialized codes to provide multiple communication channels in a designated segment of the electromagnetic spectrum. This article describes the implementation of CDMA that has been standardized by the Telecommunications Industry Association (the TIA) for the North American cellular telephone system.

The cellular telephone industry is faced with the problem of a customer base that is expanding while the amount of the electromagnetic spectrum allocated to cellular service is fixed. Capacity can be increased by installing additional cells (subdividing), but the degree of subdivision is limited because of the overhead needed to process handoffs between cells. In addition, property for cell sites is difficult to purchase in the areas where traffic is the highest.

The current analog system divides the available spectrum into 30-kHz-wide channels. This method of channelization (division of the spectrum into multiple channels) is commonly called FDMA, for Frequency Division Multiple Access (Figure 1). Alternate means of channelization are being developed to allow more users in the same region of the spectrum.

TDMA, or Time Division Multiple Access, uses the same 30-kHz channels, but adds a timesharing of three users on each frequency. All other factors being equal, this results in a threefold increase in capacity. CDMA, or Code Division Multiple Access, is a class of modulation that uses specialized codes[1,2] as the basis of channelization. These codes are shared by both the mobile station and the base station.

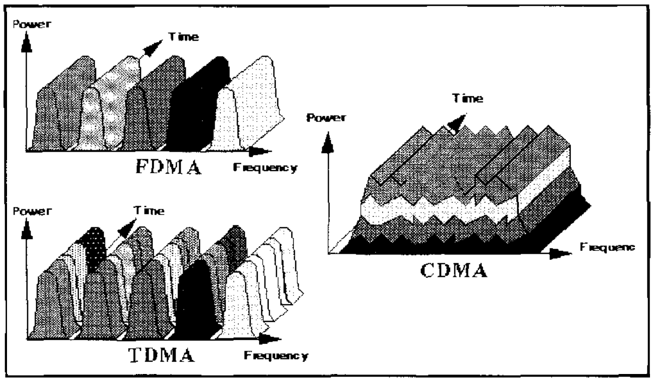


Figure 1. Cellular channelization methods. (a) Frequency Division Multiple Access (FDMA). (b) Time Division Multiple Access (TDMA). (c) Code Division Multiple Access (CDMA).

While CDMA is a class of modulation, this paper focuses on the implementation of CDMA for the North American cellular market, which was initially developed by QUALCOMM, Inc. and has been standardized by the Telecommunications Industry Association (the TIA).

Interference Effects

The analog system requires that the desired signal be at least 18 dB above any noise or interference on the same channel to provide acceptable call quality. The practical ramification of this is that only a portion of the available spectrum can be used in any given cell; not all of the channels can be used in every cell. A frequency reuse pattern of seven is commonly used to provide this attenuation (Figure 2). In other words, only one seventh of all of the cellular frequencies allocated to a carrier can be used in any one cell.

The use of omnidirectional cells does not allow for the required 18 dB attenuation. To overcome this, the cells are divided by sectored antennas (in the aximuthal plane). This reduces the frequencies available in any sector to only one out of 21.

In CDMA, signals can be and are received in the presence of high levels of interference. The practical limit depends on the channel conditions, but CDMA reception can take place in the presence of interference that is *18 dB larger than the signal.* Typically, the system operates with better conditions.

The frequencies are reused in every sector of every cell, and approximately half the interference on a given frequency is from outside cells. The other half is the user traffic from within the same cell on the same frequency.

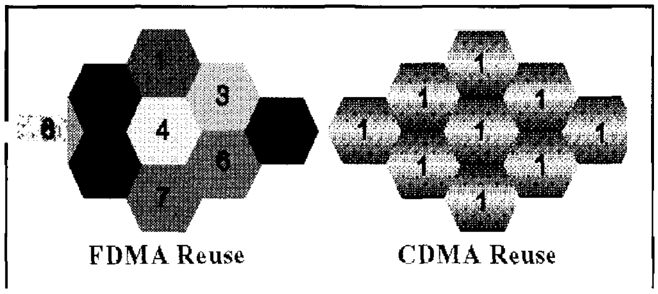


Figure 2. Cellular frequency reuse patterns. (a) FDMA reuse. (b) CDMA reuse.

A North American cellular CDMA system is described in Figure 3. CDMA starts with a basic data rate of 9600 bits/s. This is then spread[2] to a transmitted bit rate, or chip rate (the transmitted bits are called chips), of 1.2288 MHz. Spreading consists of applying digital codes to the data bits that increase the data rate while adding redundancy to the system. The chips are transmitted using a form of QPSK (quadrature phase shift keying) modulation that has been filtered to limit the bandwidth of the signal. This is added to the signal of all the other users in that cell.

When the signal is received, the coding is removed from the desired signal, returning it to a rate of 9600 bps. When the decoding is applied to the other users' codes, there is no despreading; the signals maintain the 1.2288-MHz bandwidth. The ratio of transmitted bits or chips to data bits is the coding gain. The coding gain for the North American CDMA system is 128, or 21 dB. Because of this coding gain of 21 dB, interference of up to 18 db above the signal level (3dB below the signal strength after coding gain) can be tolerated.

An analogy to CDMA is a crowded party. You can maintain a conversation with another person because your brain can track the sound of that person's voice and extract that voice from the interference of all other talkers. If the other talkers were to talk in different languages, discerning the desired speech would be even easier, because the crosscorrelation between the desired voice and the interference would be lower. The CDMA codes are designed to have very low cross correlation.

base link, which is called the reverse direction).

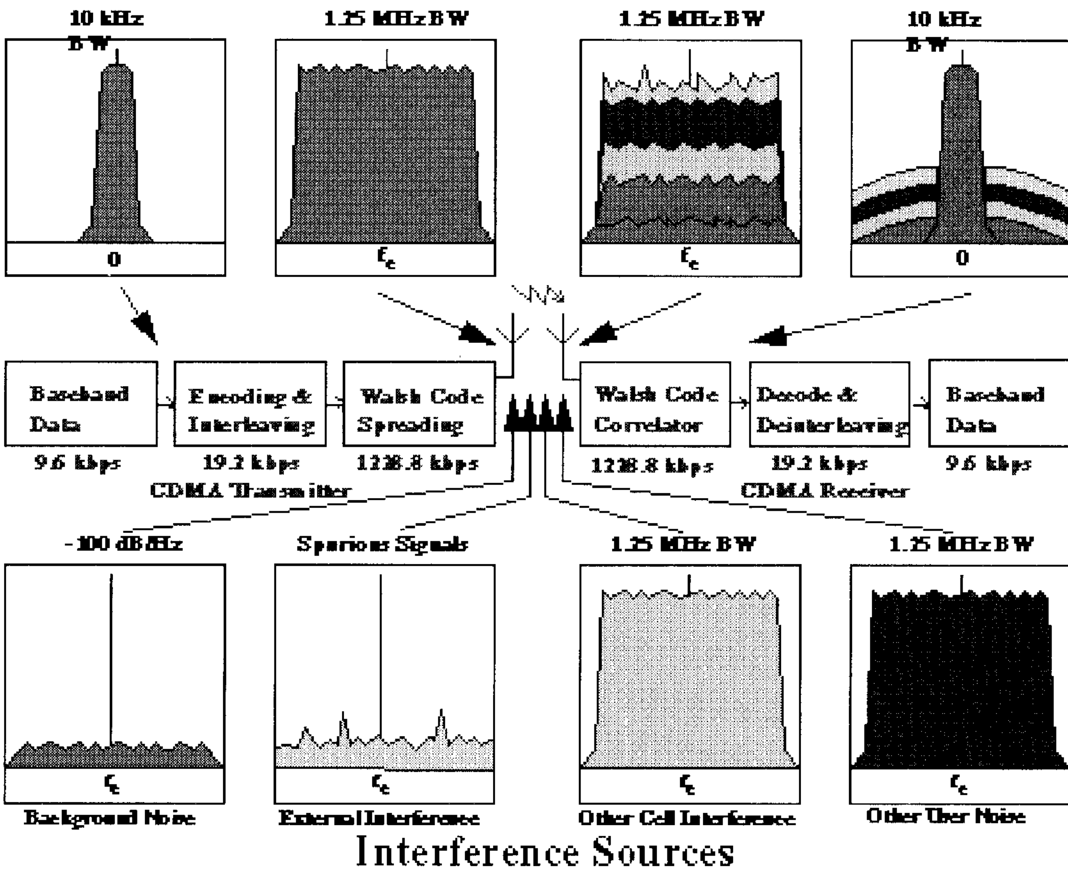


Figure 3. North American cellular CDMA system.

CDMA Features

The data rate of 9600 bits/s can be thought of as a modem's transmission. Both the signaling overhead of the system as well as the useful data transmission payload must share this fundamental data rate. The system is designed so that multiple service options can use the modem. Currently, service option 1 is speech, service option 2 is a data loopback mode used for test purposes, and service option 3 is being defined as data services (both fax and asynchronous data, or "terminal" usage).

CDMA communication systems have many differences from analog systems:

1) Multiple users share one carrier frequency. In a fully loaded CDMA system, there are about 35 users on each carrier frequency. (There are actually two carrier frequencies per channel, 45 MHz away from each other. One is for the base-to-mobile link, which is called the forward direction, while the other is for the mobile-to-base link, which is called the reverse direction).

2) The channel is defined by a code. There is a carrier frequency assignment, but the frequency band is 1.23 MHz wide.

3) The capacity limit is soft. Additional users add more interference to the system, which can cause a higher data error rate for all users, but this limit is not set by the number of physical channels.

CDMA makes use of multiple forms of diversity: spatial diversity, frequency diversity, and time diversity. The traditional form of spatial diversity, using multiple antennas, is used for the cell site receiver. Another form of spatial diversity is used during the process of handing off a call from one cell to the next. Called *soft handoff*, it is a make-before-break system in which two cell sites maintain a link with one mobile simultaneously (Figure 4).

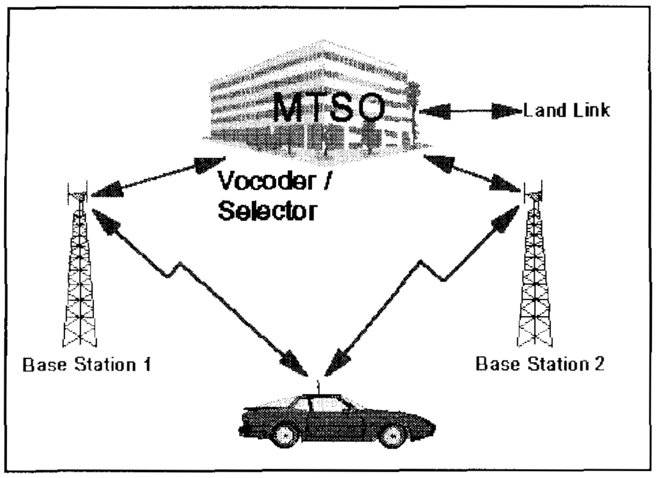


Figure 4. Spatial diversity during soft handoff.

The mobile station has multiple correlative receiver elements that are assigned to each incoming signal and can add these. There are at least four of these correlators—three that can be assigned to the link and one that searches for alternate paths. The cell sites send the received data, along with a quality index, to the MTSO (mobile telephone switch ing office) where a choice is made as to the better of the two signals.

Frequency diversity is provided in the bandwidth of the transmitted signal. A multipath environment will cause fading, which looks like a notch filter in the frequency domain (Figure 5). The width of the notch can vary, but typically will be less than 300 kHz. While this notch is sufficient to impair ten analog channels, it only removes about 25% of the CDMA signal.

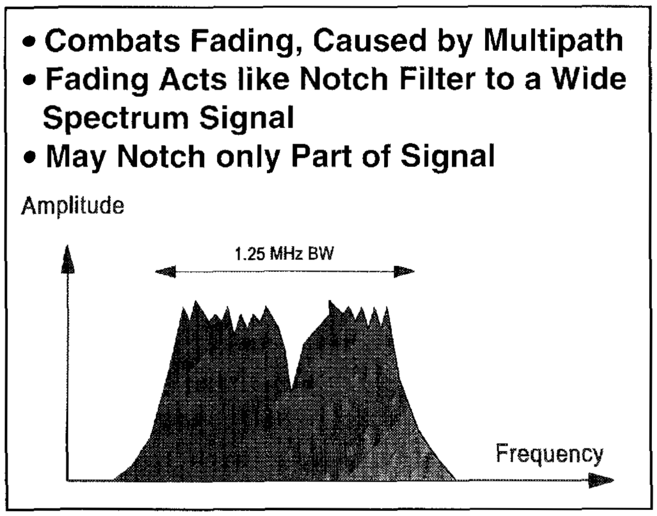


Figure 5. CDMA frequency diversity. The wide spectrum combats fading caused by multipath transmission. Fading has the effect of a notch filter to the wide-spectrum signal. Typically only a small part of the signal is lost.

Multipath signals are used to advantage, providing a form of time diversity. The multiple correlative receiver elements can be assigned to different, time delayed copies of the same signal. These can be combined in what is called a RAKE receiver[3] which has multiple elements called *fingers* (Figure 6). The term RAKE refers to the original block diagram of the receiver (Figure 6b), which includes a delay line with multiple taps. By weighting the signal at each tap in proportion to its strength, the time-diverse signals are combined in an optimal manner. The picture resembles a garden rake, hence the name.

Another form of time diversity is the use of forward error correcting codes followed by interleaving. Loss of transmitted bits tends to be grouped in time, while most error correction schemes work best when the bit errors are uniformly spread over time. Interleaving helps spread out errors and is common to most digital systems.

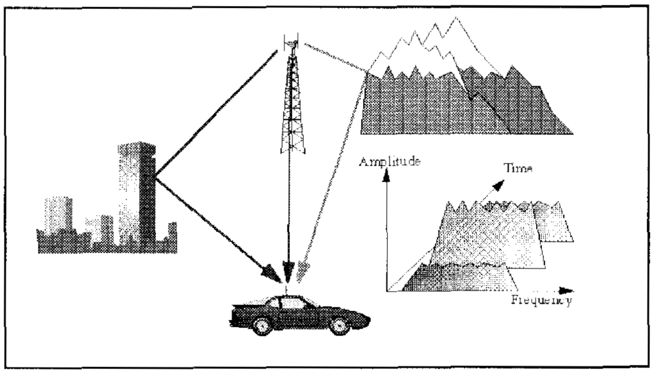
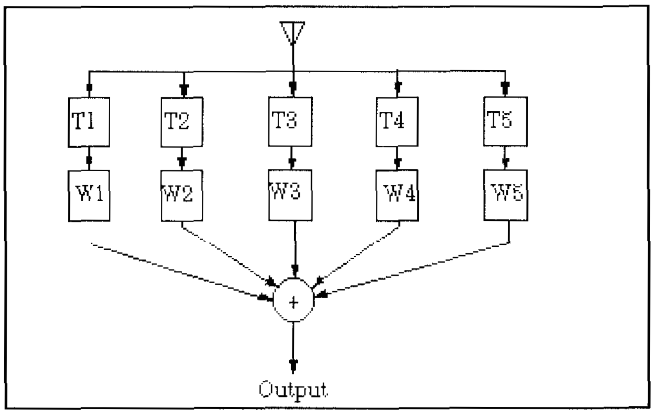


Figure 6. (a) The RAKE receiver takes advantage of multipath transmission to realize a form of time diversity.



(b) RAKE receiver block diagram.

Mobile Station Power Control

Control of the mobile station power is essential for

CDMA to work. If one mobile station were to be received at the base station with too much power, it raises unnecessarily the amount of interference experienced by other users, and could jam them.

The goal is to have the signal of all mobile stations arrive at the base station with exactly the same and adequate power. Two forms of power control are used: *open-loop* and *closed-loop* .

Open-loop power control is based on the similarity of loss in the forward and reverse paths. The received power at the mobile station is used as a reference. If it is low, the mobile station is presumed to be far from the base station, therefore it transmits with high power. If it is high, the mobile station is assumed to be close and transmits with low power. The product of the two powers (or the sum of the two powers measured in dB) is a constant. This constant is -73 when the receive and transmit powers are measured in dBm. For example, when the received power is -85 dBm, the transmitted power is +12 dBm.

Closed-loop power control is used to force the power from the mobile station to deviate from the open-loop setting. This is done by an active feedback system from the base station to the mobile station. Power control bits are sent every 1.25 milliseconds to direct the mobile station either to increase or decrease its transmitted power in a 1 dB increment.

Because the CDMA mobile station transmits only enough power to maintain a link, the average transmitted power is much lower than that required for an analog system. An analog cellular phone always transmits enough power to overcome a fade, even though a fade does not exist most of the time. The CDMA's advantage in transmitting with lower power has the potential of longer battery life and smaller, lower-cost output amplifier design.

Speech Encoding

The speech is encoded before transmission. The purpose of encoding is to reduce the number of bits required to represent the speech. The CDMA voicecoder (*vocoder*, as it is called) has a data rate of 8550 bits per second. After additional bits are added for error detection up to the channel data rate of 9600 bits/s. This full channel capacity is not used, however, when the user is not speaking. The vocoder detects voice activity, and lowers the data rate during quiet periods. The lowest data rate is 1200 bits/s. Two intermediate rates of 2400 and 4800 bits/s are also used for special purposes.

The 2400 bits/s rate is used to transmit transients in the background noise, and the 4800 bits/s rate is used to mix vocoded speech and signaling data (signaling consists of link-management messages between the base station and the mobile station). In this last case, the channel data rate is 9600 bits/s, but half of the bits are assigned to voice and the other half to the message. This is called *dim and burst signaling*.

The mobile station pulses its output power during periods of lower-rate data. The power is turned on for 1/2, 1/4, or 1/8 of the time. The data rate is 9600 bits/s when the power is on, so the average data rate is 4800, 2400, or 1200 bits/s. This lowers the average power and the interference seen by other users.

The base station uses a different method to reduce power during quiet periods. It transmits with 100% duty cycle at 9600 bits/s, but uses only 1/2, 1/4, or 1/8 of full power and repeats the transmitted data 2, 4, or 8 times. The mobile station achieves the required signal-to-noise ratio by combining the multiple transmissions.

One important aspect of CDMA is the use of Walsh codes, or Hadamard codes[4]. These are based on the Walsh matrix, a square matrix with binary elements that always has a dimension that is a power of two. It is generated by seeding Walsh (1) = W1 = 0 and expanding as shown below and in Figure 7:

$$(1) \quad W_{2n} = \begin{matrix} W_n & W_n \\ W_n & \overline{W_n} \end{matrix}$$

$$W_{2n} = \begin{matrix} W_n & W_n \\ W_n & \overline{W_n} \end{matrix} \qquad W_2 = \begin{matrix} 0 & 0 \\ 0 & 1 \end{matrix}$$

$$W_4 = \begin{matrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{matrix}$$

Figure 7. Walsh matrices.

where n is the dimension of the matrix and the overscore denotes the logical NOT of the bits in the matrix.

The Walsh matrix has the property that every row is orthogonal to every other row and the logical NOT of every other row. Orthogonal means that the dot product of any two rows is zero. In simpler terms, it means that between any two rows exactly half the bits match and half the bits do not match. The CDMA system uses a 64-by-64-bit Walsh matrix.

Forward Link Encoding

Walsh encoding is used in the forward link (base to mobile) as shown in Figure 8. The fundamental data rate of the channel is 9600 bits/s. The data is packetized into 20-ms blocks and has forward error correction applied by use of a convolutional encoder. This is done at half rate, which yields two bits out for every bit in. The data is then interleaved (a shuffling of the bits during the 20-ms period). This is done to better distribute bits lost during transmission. It has been shown that bit errors tend to come in groups rather than being spread out in time, while forward error correction works best when the errors are distributed uniformly over time. When the data is deinterleaved, the time-linked errors are more uniformly distributed.

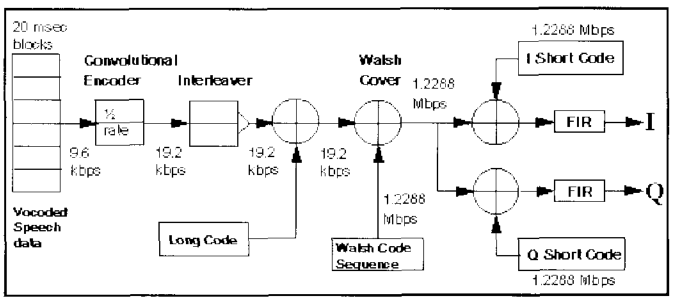


Figure 8. CDMA forward link physical layer.

Following the interleaver, the data is modified by the use of a long code, which serves only as a privacy mask. The long code is generated by a pseudorandom binary sequence (PRBS) that is generated by a 42-bit-long shift register (Figure 9). This register is also used as the master clock of the system, and is synchronized to the limit of propagation delays among all base stations and mobile stations. A mask is applied to the PRBS generator that selects a combination of the available bits. These are added modulo two by way of exclusive-OR gates to generate a single bit stream at 1.2288 MHz. For the forward link, a data rate of only 19.2 kbits/s is needed, so only 1 of 64 bits gets used. The long code generated in this way is XORed with the data from the interleaver.

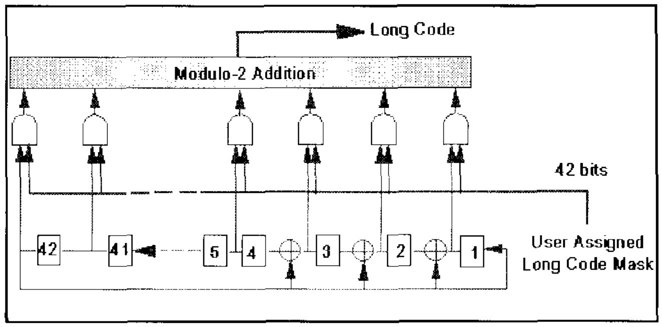


Figure 9. Long code privacy mask generation.

The resulting data is then encoded using the Walsh matrix. One row of the Walsh matrix is assigned to a mobile station during call setup. If a 0 is presented to the Walsh cover, then the 64 bits of the assigned row of the Walsh matrix are sent. If a 1 is presented, then the NOT of the Walsh matrix row is sent. This has the effect of raising the data rate by a factor of 64, from 19.2 kbits/s to 1.2288 Mbits/s.

The last stage in coding is to convert from a binary signal to two binary channels in preparation for transmission using QPSK (quadrature phase shift keying) modulation. The data is split into I and Q (in-phase and quadrature) channels and the data in each channel is XORed with a unique PRBS short code. The short codes are spreading sequences that are generated much like the long code, with linear feedback shift registers. In the case of the short codes, there are two shift registers, each 15 bits long, with feedback taps that define specific sequences. These run at 1.2288 MHz. The short code sequences, each 32,768 bits long, are common to all CDMA radios, both mobile and base. They are used as a final level of spreading.

After the data is XORed with the two short code sequences, the result is two channels of data at 1.2288 Mbits/s. Each channel is low-pass filtered digitally using an FIR (finite impulse response) filter. The filter cutoff frequency is approximately 615 kHz. A typical FIR filter implementation might output 9-bit-wide words at 4.9152 MHz. The resultant I and Q signals are converted to analog signals and are sent to a linear I/Q modulator. The final modulation is filtered QPSK.

Multiple channels in the base station are transmitted by combining the I and Q signals for each (Figure 10). Because all users share the composite signal from the cell, a reference signal called the pilot is transmitted. The pilot has all zero data and is assigned Walsh row number 0, which consists of all 0s. In other words, the pilot is made up of only the short spreading sequences. Typically 20% of the total energy of a cell is transmitted in the pilot signal.

The pilot signal forms a coherent phase reference for the mobile stations to use in demodulating the traffic data. It is also the timing reference for the code correlation. The short sequences allow the CDMA system to reuse all 64 Walsh codes in each adjacent cell. Each cell uses a different time offset on the short codes and is thereby uniquely identified while being able to reuse the 64 Walsh codes.

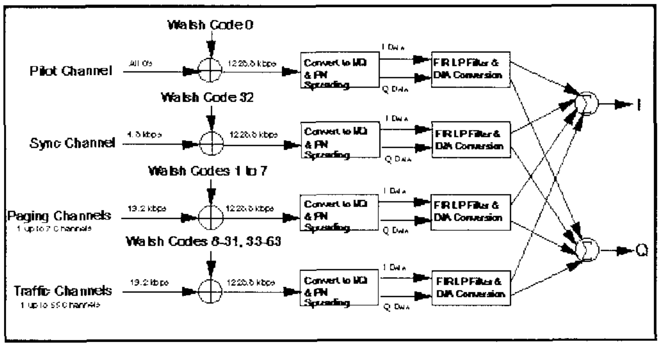


Figure 10. CDMA forward link channel format.

Reverse Link Encoding

The mobile station cannot afford the power of a pilot because it would then need to transmit two signals. This makes the demodulation job more difficult in the base stations. A different coding scheme is also used, as shown in Figure 11.

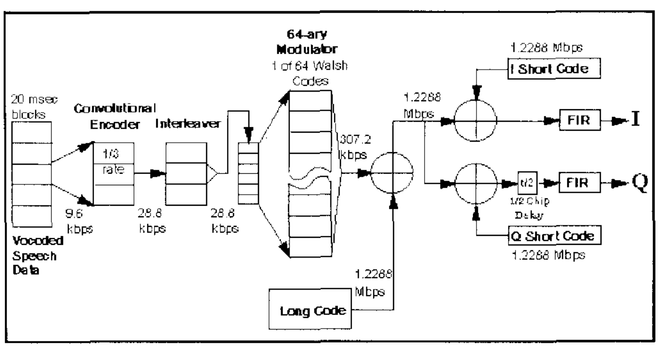


Figure 11. CDMA reverse link physical layer.

For speech, the same vocoder is used in both directions. Again, the data rate is 9600 bps. A 1/3-rate convolutional encoder is used, yielding an output rate of 28.8 kbits/s. The output of this is interleaved and then taken six bits at a time. A six-bit number can range from 0 to 63, and each group of six bits is used as a pointer to one row of the Walsh matrix. Every mobile station can transmit any row of the Walsh matrix as needed.

At this point, the data rate is 307.2 kbits/s, but there is no unique coding for channelization. The full-rate, long code is then applied, raising the rate to 1.2288 Mbits/s. This final data stream is split into I and Q channels and spread with the same short sequences as in the base station. There is one more difference. A time delay of 1/2 chip is applied to the Q channel before the FIR filter. This results in offset-QPSK modulation (Figure 12), and is used to avoid the amplitude transients inherent in QPSK. This makes the design of the output amplifier easier in the mobile station.

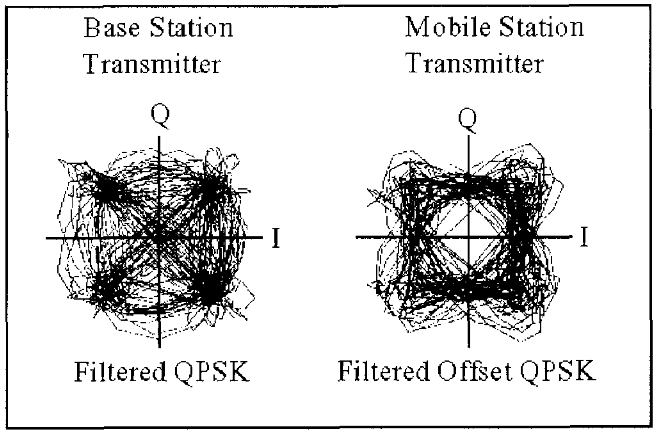


Figure 12. Constellation diagrams for CDMA modulation formats. (a) The base station transmitter uses filtered QPSK. (b) The mobile station transmitter uses filtered offset-QPSK.

The capacity is different in the forward and reverse links because of the differences in modulation. The forward link has the phase reference—the pilot signal—as well as orthogonal codes. The reverse link signal is not orthogonal because the long codes are applied after the use of the Walsh matrix. In this case the signals are uncorrelated but not orthogonal. The base station has the advantage of multiple receive antennas (diversity). All factors taken together, the reverse link sets system capacity.

The CDMA channelization functions are summarized in Table I.

Call Scenario

To better illustrate how the CDMA system operates, the system function will be described in terms of mobile station operation.

When the mobile station first turns on, it knows the assigned frequency for CDMA service in the local area. It will tune to that frequency and search for pilot signals. It is likely that multiple pilot signals will be found, each with a different time offset. This time offset is the

Parameter	Function	Notes
Frequency	Divides the spectrum into several 1.23-MHz frequency allocations.	Forward and reverse links are separated by 45 MHz.
Walsh Codes	Separates forward link users of the same cell.	Assigned by cell site. Walsh code 0 is always the pilot channel. Walsh code 32 is always the sync channel.
Long Code	Sparates reverse link users of the same cell.	Depends on time and user ID. The long code is composed of a 43-bit-long PRBS generator and a user specific mask.
Short Codes, also called the I and Q spreading sequences.	Separates cell sites or sectors of cells.	The I and Q codes are different but are based on 15-bit-long PRBS generators. Both codes repeat at 26.667 ms intervals. Base stations are differentiated by time offsets of the short sequences.

Table I. CDMA Channelization Functions.

means of distinguishing one base station from another. The mobile station will pick the strongest pilot, and establish a frequency reference and a time reference from that signal. It will then start demodulation of Walsh number 32, which is always assigned to the sync channel. The sync channel message contains the future contents of the 42-bit long code shift register. These are 320 ms early, so the mobile station has time to decode the message, load its register, and become synchronized with the base station's system time.

The mobile station may be required to register. This would be a power-on registration in which the mobile station tells the system that it is available for calls and also tells the system where it is. It is anticipated that a service area will be divided into zones, and if the mobile station crosses from one zone to another while no call is in progress, it will move its registration location by use of an idle state handoff. The design of the zones is left to the service provider and is chosen to minimize the support messages. Small zones result in efficient paging but a large number of idle state handoffs. Large zones minimize idle state handoffs, but require paging messages to be sent from a large number of cells in the zone.

At this point the user makes a call by entering the digits on the mobile station keypad and hitting the send button. The mobile station will attempt to contact the base station with an access probe. A long code mask is used that is based on cell site parameters. It is possible that multiple mobile stations may attempt a link on the access channel simultaneously, so collisions can occur. If the base station does not acknowledge (on the paging channel) the access attempt, the mobile station will wait a random time and try again. After making contact, the base station will assign a traffic channel with its Walsh number. At this point, the mobile station changes its long code mask to one based on its serial number, receives on the assigned Walsh number, and starts the conversation mode.

It is common for a mobile station communicating with one cell to detect another cell's pilot that is strong enough to be used. The mobile station will then request soft handoff. When this is set up, the mobile station will be assigned different Walsh numbers and pilot timing and use these in different correlative receiving elements. It is capable of combining the signals from both cells.

Eventually, the signal from the first cell will diminish and the mobile station will request from the second cell that soft handoff be terminated.

At the end of the call, the channels will be freed. When the mobile station is turned off, it will generate a power-down registration signal that tells the system that it is no longer available for incoming calls.

Testing

The complexity of the CDMA system raises substantial test issues. What needs to be tested, and what environment is needed for testing? To test the mobile station, the test equipment must emulate a base station. The tester needs to provide the pilot, sync, paging, and traffic channels. It must provide another signal that uses orthogonal Walsh symbols that represent the interference generated by other users of the same cell, and it must provide additive noise that simulates the combination of CDMA signals from other cells and background noise.

Bit error rate is not a meaningful measure, since substantial errors are expected at the chip rate and these are not available for test. The bits at the 9600-bit s/s rate are the only bits available for test, and these will either be all correct as a result of error correction or will have substantial errors. What is used instead is the frame error rate, a check of the received bits and the associated CRC (cyclic redundancy code) in each 20-ms block.

To test the transmitter, a new test has been defined: *waveform quality*. This is based on the crosscorrelation of the actual transmitted signal to the ideal signal transmitting the same data. This is important to the system because the CDMA receivers are correlators. In fact, they correlate the received signal with the ideal signal. If a signal deviates substantially from the ideal, the correlated portion of that signal will be used to make the link and the uncorrelated portion will act as additive interference. Closed-loop power control will maintain the correlated power at the needed level, and excess power will be transmitted. The specification is that the radios shall transmit with a waveform quality that limits the excess power to less than 0.25 dB. Other transmitter measurements include frequency and power control operation.

CDMA provides an advanced technology for cellular applications, providing high-quality service to a large number of users. It has been extensively tested and has been deployed in precommercial applications. Commercial service is scheduled to begin this year.

AMPS*: Advanced Mobile Phone System.*
This is the current analog FM system in North America. It uses 30-kHz channels and signaling is done superaudio, that is, at frequencies above the audio bandwidth for speech, which is 300 to 3000 Hz.

TACS*: Total Access Communication System. This is the analog FM system used in the United Kingdom and Japan. It uses 25-kHz channels and signaling is super audio.*

NMT*: Nordic Mobile Telephone. Scandinavia led the world in cellular systems. The latest system uses 30-kHz channels, and signaling is done using 1200-Hz and 1800-Hz tones in much the same way as a modem.*

J-TACS*: This is a narrowband analog FM system in use in Japan. Channels are 12.5-kHz wide and signaling is subaudio, that is, at frequencies below the audio bandwidth for speech, which is 300 to 3000 Hz.*

NAMPS*: Narrow Analog Mobile Phone System. This is an analog FM system using 10-kHz-wide channels. Signaling is subaudio .*

GSM*: Global System for Mobile Communications. This is the first digital cellula r system to be used commercially. It has been adopted across Europe and in many countries of the Pacific rim. It uses 200-kHz channels with eight users per channel using TDMA, and has a vocoder rate of 13 kbits/s.*

TDMA*: Time Division Multiple Access. This is the first digital system standardi zed in North America. It uses 30-kHz channels, three users per channel using TDMA, and has a vocoder rate of 8 kbits/s.*

E-TDMA*: Extended TDMA. This system uses the same30-kHz channels as TDMA, but has six users per channel. The vocoder rate is cut to 4 kbits/s, and the channels are dynamically assigned based on voice activity detection. This is being propo sed as a follow-on to TDMA.*

CDMA*: Code Division Multiple Access. This system uses 1.23-MHz-wide channel sets, with a variable number of users on each carrier frequency. The full vocoder rate is 8.55 kbits/s, but voice activity detection and variable-rate coding can cut the data rate to 1200 bits/s. The effective data rate, determined empirically for simulated conversations, is 3700 bits/s. Access is by code.*

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He is the co-inventor of three patents, all dealing with FM in phase-locked loops.

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