Digital Radio for Mobile Applications

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The technology of time-division multiple-access (TDMA) and code-division multiple-access (CDMA) promises to significantly improve the capacity and operation of existing analog cellular networks. AT&T has been on the leading edge of these breakthroughs, developing trial and commercial systems for both of these advanced digital radio technologies. This paper describes TDMA and CDMA, their advantages, specific features, field test results, and speculations on their futures.

Introduction

The tremendous growth experienced by cellular systems in the past few years has transformed mobile communications from a special service for a select few to a form of communications that is part of our everyday lives. The growth in the number of mobile subscribers has placed a strain on cellular systems in many metropolitan areas, making it increasingly difficult to operate and maintain the quality of such systems. The basic concept of cellular radio, reusing identical frequencies at non-interfering distances, is being tested to its limits, and new technologies are continually being developed to handle this increasing traffic. Call quality has diminished in many systems. As the number of subscribers increases, cells must become smaller. Adjacent cells cannot use the same frequencies, so a limited number of frequencies are being reused at closer distances.

Digital radio promises to solve many of these problems and to enhance services available to mobile subscribers. AT&T's goals for digital radio in cellular systems include:

- Using the limited radio-frequency (RF) spectrum more efficiently to increase the number of subscribers that can be accommodated
- Improving the voice quality beyond what is possible with analog cellular systems, especially to maintain voice quality in areas with heavy traffic
- Providing support for a broader array of services and features, such as fax, data, message services, and vehicle location
- Simplifying the task of operating and maintaining cellular systems, including determining which radio frequencies should be used in which locations, known as *frequency planning*
- Protecting investments in current systems by providing a smooth transition from existing analog cellular systems to digital radio systems.

In 1990, the Telecommunications Industry Association (TIA) completed its initial revision of an interim standard (IS-54) to meet the increased demands on cellular systems and ensure compatibility between cellular networks and telephones.[1] Cellular systems based on this standard, which uses TDMA digital radio technology, are currently being deployed.

While systems were being developed based on the IS-54 TDMA standard, Qualcomm, Inc., which provides communications systems and services, proposed and demonstrated a CDMA cellular system based on spread-spectrum radio technology,[2] which is described later in this paper. This wideband system will increase the number of subscribers that can be accommodated per bandwidth, improve voice quality, and eliminate the need for frequency planning. In 1992, the TIA formed a Wideband Spread-Spectrum Committee to develop a standard based on CDMA technology and techniques. An interim standard (IS-95) was approved in July 1993.

Panel 1. Abbreviations, Acronyms, and Terms

A/D — analog/digital
AM — amplitude modulation
AMPS — advanced mobile phone service
CDMA — code-division multiple access
CELP — code-excited linear prediction
C/I — carrier to interference
D/A — digital/analog
DQPSK — differential quadrature phase-shift keying
DS-SS — direct-sequence spread-spectrum
FM — frequency modulation
I — in-phase
IS — interim standard
kb/s — kilobits per second
kHz — kilohertz
ms — millisecond
PCM — pulse-code modulation
PN — pseudo-noise
Q — quadrature
RF — radio frequency
TDMA — time-division multiple access
TIA — Telecommunications Industry Association
VSELP — verbal-sum-excited linear prediction

The TDMA Cellular System

TDMA employs a time-division multiple-access technique in which multiple subscribers transmit on the same radio frequency, each subscriber transmitting at a different time. Although many communication systems use time-division multiplexing techniques, cellular environments are subject to fading and reflections of radio signals. Simultaneously, there is a need for greater system capacity and better voice quality.

Introducing TDMA digital technology into an existing analog advanced mobile phone service (AMPS) cellular system increases its voice traffic capacity, thereby reducing the number of cell sites needed. It also provides a platform that supports emerging digital services and robust voice signal transmission in the cellular environment.

TDMA systems can carry three digital voice channels on a 30-kilohertz (kHz) analog RF channel bandwidth formerly occupied by one analog frequency-modulated (FM) cellular subscriber. The digital bit streams that correspond to the three distinct voice conversations are encoded, interleaved, and transmitted over the air using a digital modulation scheme called differential quadrature phase-shift-keying (DQPSK). The combination of digital modulation, error-correcting codes, and time-slot interleaving reduces the effects of the most common radio propagation impairments. This, in turn, triples the voice channel capacity without requiring additional RF spectrum, increasing subscriber capacity and making the limited RF spectrum currently allocated to cellular systems more efficient.

Using the existing 30-kHz analog RF channels to triple the number of voice circuits that can be carried by a single cellular channel is the key to migrating easily from an analog to a TDMA system.[4] Adding a TDMA radio or replacing an analog AMPS radio with a TDMA radio in the existing cell site hardware can expand cellular capacity without significant modifications to existing channel assignment schemes. In effect, these digital signal processing techniques require only 10 kHz per voice circuit, instead of the 30 kHz required for analog AMPS voice channels.

TDMA Mobile-Assisted Hand-Off. A cellular hand-off occurs as a mobile telephone with an active call moves from an area served by one radio to an area served by another radio, usually at the edge of the cell. The traditional AMPS hand-off process requires the cooperation of the cell site currently serving the active call, the switch, and the neighboring cells that can potentially continue the call. The neighboring cells measure the signal strength of the potential call to be handed off and report the data to the serving cell, which processes the data and determines which neighboring cells can best handle the call. TDMA systems reduce the time needed to complete the hand-off by assigning some of this signal-strength data gathering to the cellular phone handling the active call, thus relieving the neighboring cells of the signal-strength measuring task.

The TDMA system reduces the hand-off interval using a process called ***mobile-assisted hand-off.*** In these systems, a dual-mode cellular telephone, capable of communicating with both the existing AMPS analog system and the new TDMA radios, measures the signal strengths of its potential hand-off candidates and reports the results to the cell site for evaluation. The cell site's main

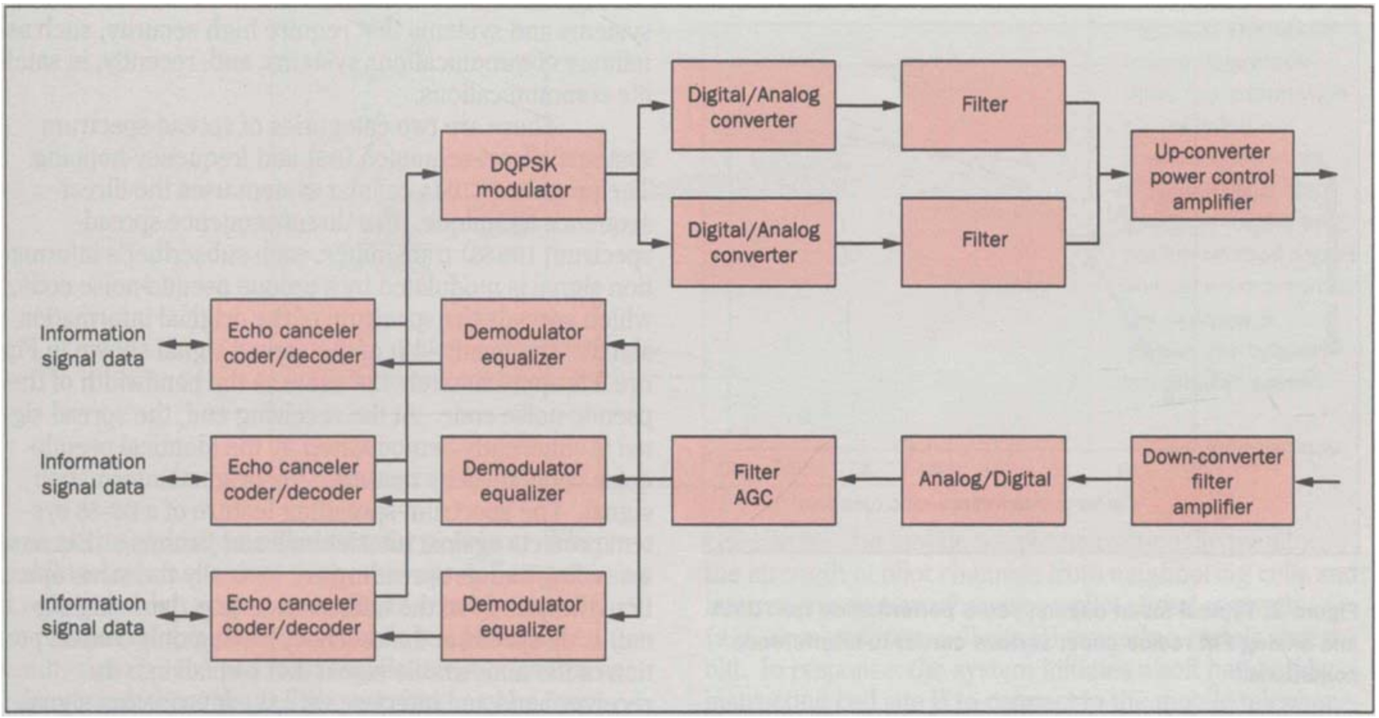

Figure 1. TDMA radio functions.

controller processes this list of potential hand-off candidates from the cellular telephone and issues a hand-off order, moving some of the hand-off processing in TDMA digital systems from the cell site to the mobile telephone.

TDMA Air Interface. The TIA IS-54 standard[1] defines the TDMA radio interface between the mobile telephone and the cell site radio in the cellular network. The ***radio downlink*** — from the cell site to the mobile telephone — and the ***radio uplink*** — from the mobile telephone to the cell site — are similar. Thus, the functions to be performed by the mobile telephone are similar to those of the cell site radio. Figure 1 is a block diagram of these network functions. The TDMA cellular radio is responsible for speech coding, channel coding, signaling, modulation, demodulation, equalization, signal strength estimates, and communication with the cell site controller.

The speech coder uses the vector-sum-excited linear predictive (VSELP) coding technique and transfers μ-law pulse-code-modulated (PCM) speech data at 64 kilobits per second (kb/s) to and from the network. A special set of code books, derived from vector sums of basic excitation vectors representative of speech contained in a speech database, is used by the VSELP coder. The encoder processes 20-ms blocks of speech, each block containing 159 bits, at a source rate of 7.95 kb/s. Using a convolutional error-correction code, interleaving to mitigate the damage of Rayleigh fading, and cyclic redundancy checking, the channel coder performs channel encoding and decoding, error correction, and bit interleaving and de-interleaving. It operates on speech and signaling information, builds time slots for the channels, and communicates with the main controller, modulator, and demodulator.

The modulator receives the coded information and signaling bits for each of the three TDMA time slots from the channel coders. It performs the digital $\pi/4$ DQPSK modulation and produces in-phase (I) and quadrature (Q) components of the 48.6-kb/s transmitter waveform.[5] These samples are converted from digital to analog (D/A) signals and then sent to the transceiver, which transmits and receives digitally modulated RF control and information signals to and from cellular telephones. The demodulator/equalizer receives baseband I and Q components from each of the two diversity branches in the transceiver. It performs filtering, automatic gain control, receive signal strength estimation, adaptive equalization

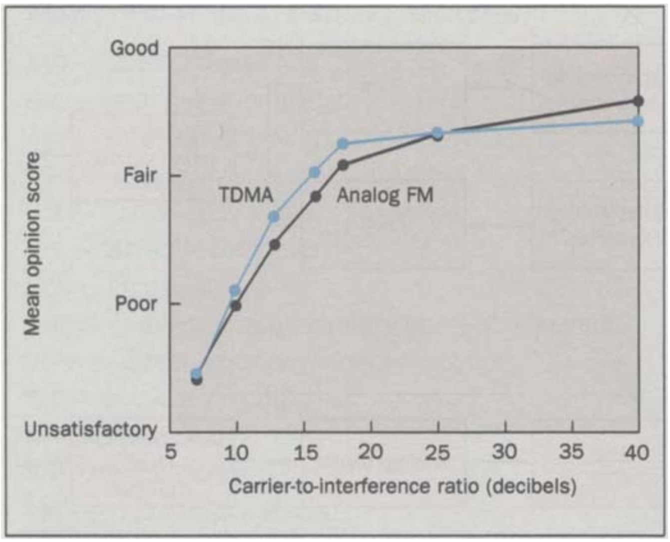

Figure 2. Typical mean opinion score performance for TDMA and analog FM radios under various carrier-to-interference conditions.

(with diversity combining), and symbol demodulation. The demodulated data for each of the three time slots is then sent to the channel coder for decoding.

TDMA System Performance. The performance of TDMA in cellular environments can be assessed by examining the voice quality under a variety of RF conditions.[4] Several test subjects listen to and assign scores to tapes of recorded sentences, the average of which is the mean opinion score.

Figure 2 shows a typical mean opinion score performance for TDMA and analog FM radios under various carrier-to-interference (C/I) conditions. In good C/I conditions, analog FM performs slightly better than the TDMA channel, because the FM channel does not contain a voice coder and decoder. However, under lower C/I conditions, which are typical in today's cellular systems, the TDMA channel performs better than the existing analog FM cellular channel.

The CDMA Cellular System

CDMA uses a 1.25-megahertz (MHz) bandwidth that can be simultaneously shared by many subscribers. It is an application of spread-spectrum technology in a multiple-access environment. Traditionally, spread-spectrum techniques have been used in antijamming systems and systems that require high security, such as military communications systems, and, recently, in satellite communications.

There are two categories of spread-spectrum systems: direct-sequence (DS) and frequency-hopping. The proposed CDMA cellular system uses the direct-sequence technique. In a direct-sequence spread-spectrum (DS-SS) transmitter, each subscriber's information signal is modulated by a unique pseudo-noise code, which spreads the spectrum of the original information signal. The bandwidth of the spread signal shown in Figure 3 is approximately the same as the bandwidth of the pseudo-noise code. At the receiving end, the spread signal is coherently demodulated by the identical pseudo-noise code, thereby restoring the original information signal. The spectrum-spreading feature of a DS-SS system protects against interference and jamming. Because spreading and de-spreading are basically the same operation, the energy of the interference (e.g., jamming signal) is de-spread at the receiver, leaving only a small portion of the undesirable signal that can fall into the receiver band and interfere with the information signal. The ratio of the bandwidth of the spreading signal to that of the original information signal is commonly called the processing gain. The higher the processing gain, the better the protection against interference or jamming.

Using Multipath in CDMA. In addition to interference protection, DS-SS systems also possess several other unique system characteristics.[2,6] CDMA system performance is enhanced in a multipath environment, typical for mobile communication systems. In contrast, narrowband system performance is degraded by the presence of multipath fading.

Characteristics of a Spread-Spectrum System. When two or more multipath signals are separated in time by more than one chip duration, these multipath signals become independent of one another. Using multiple *rake receivers* — each of which gathers signal energies arriving from independent multipaths and combines them to give diversity at the receiver — and diversity combining to receive these independent multipath signals improves the performance of the receiver. Thus, when the rake receiver is used at both the cell site and the mobile telephone, the multipath environment becomes an advantage for CDMA.

CDMA Power Control. The unique features of a DS-CDMA system do not preclude some technical challenges,

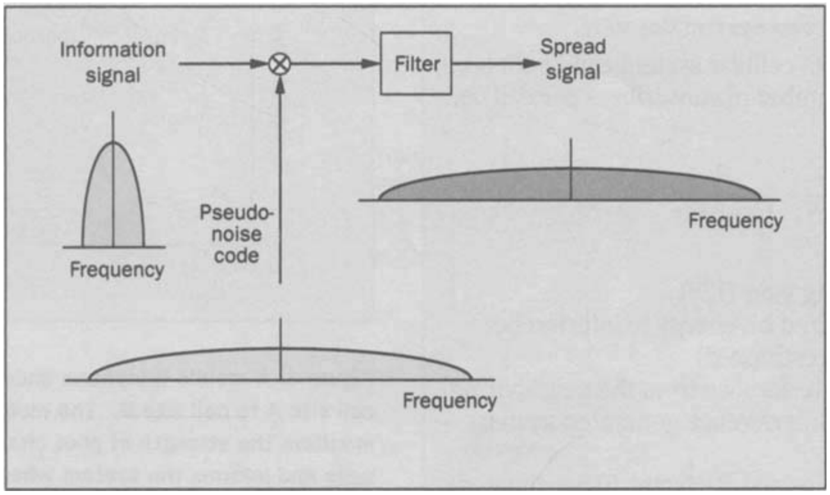

Figure 3. The DS-SS transmitter modulates the information signal using a pseudo-noise code, which spreads the spectrum of the original information signal. The receiver reverses the process to restore the original information signal.

such as the typical, so-called near-far problem. When a mobile telephone is close to the cell site and transmitting at relatively high power, the cell site receiver may be overloaded by this particular mobile telephone. As a result, signals received from mobile telephones that are more remote from the cell site receiver may be overwhelmed. The solution to this problem is to control the power transmitted from mobile telephones. The closer a mobile telephone is to the cell site, the lower the power necessary for transmission. The CDMA cellular system uses sophisticated power control algorithms that maintain the signal quality transmitted to the cell site from all mobile telephones at an acceptable level.

CDMA Call Hand-Off. In an analog FM cellular system, when a mobile telephone is handed off from one cell site to another, the communication link between the telephone and the old cell site is disconnected before the link to the new site is established. For a short time during the hand-off process, the mobile telephone is not connected to either cell site, and the subscriber may hear silence or noise. Mobile telephones sometimes ping-pong between two cell sites as the mobile telephone is handed back and forth between the approaching and the retreating cell sites.

Because a mobile telephone in the CDMA system has more than one demodulator, it can communicate with two or more cell sites, simultaneously, to implement a *soft hand-off.* This eliminates communication gaps, ping-ponging, and noise during hand-off.

To illustrate a soft hand-off, Figure 4 shows a mobile telephone whose existing call is being carried by cell site A. The mobile telephone continually monitors the strength of pilot channels from neighboring cells and informs the system whenever a pilot signal strength (e.g., received from cell site B) exceeds a certain threshold. In response, the system initiates a soft hand-off by instructing cell site B to connect to the mobile telephone. As this soft hand-off occurs, the mobile telephone uses two of its rake receiver demodulators to communicate simultaneously with cell sites A and B.

When a call is undergoing a soft hand-off, separate voice packet streams will appear at the cellular switch, each intended for the same speech coder. Each cell site sends a packet every 20 milliseconds (ms), and a frame selector chooses the best voice packet during each 20-ms interval.

Eliminating Frequency Planning. In traditional cellular systems, frequency planning takes tremendous effort. In CDMA cellular systems, the same frequency can be reused at every cell site, making frequency planning unnecessary.

Increased System Capacity. In addition to the system features and benefits discussed earlier, a CDMA cellular system can accommodate more subscribers at one time than a traditional AMPS/FM cellular system. The capacity of a CDMA cellular system is expected to be approximately 10 to 15 times the capacity of an AMPS/FM system. See Panel 2 for the derivation of CDMA system capacity.

CDMA Air Interface. The concept of DS-SS is being applied in a cellular system by assigning each mobile telephone a unique pseudo-noise code. For a given channel within a cell, the aggregate signal of all other

Panel 2. Derivation of CDMA System Capacity.

The capacity of a CDMA cellular system can be theoretically expressed in number of subscribers per cell per 1.25 MHz as:

$$C = \frac{G_p}{E_b/N_o} \frac{F}{(1+\beta)\upsilon}$$

where
- G_p is the processing gain (128),
- E_b/N_o is the required bit energy-to-interference density ratio (7 dB estimated)
- β is the effective interference from the neighboring cell relative to the interference generated from its own cell ($\cong 0.5$)
- υ is the average voice activity factor (0.5 estimated)
- F is the sectorization gain of a 3-sector cell ($\cong 2.5$).

With all the assumed values, the CDMA system capacity is estimated to be 85 subscribers per cell per 1.25 MHz.

The capacity of the existing AMPS/FM system is six subscribers per cell per 1.25 MHz. Therefore, a CDMA system has approximately 14 times the capacity of an AMPS/FM system.

channels will be perceived as interference, and could be eliminated or reduced by de-spreading the signal.

Figure 5 outlines the radio interface of the CDMA system. Information signal data is created by passing speech through a CELP speech coder similar to that used for TDMA. Unlike TDMA, the CDMA uplink and downlink are not identical.

The speech coder used in CDMA is a variable-rate CELP coder. The instantaneous rate of the coding depends on the voice activity of the speech. When the subscriber is talking, the speech coder will be running at its full rate. When the subscriber is not talking, the speech coder represents speech at one-eighth the full rate. Two intermediate rates are also defined to capture the transitions and eliminate the effect of abrupt rate changes. The variable rate speech coder reduces the average bit rate of the speech coder and, subsequently, increases the system capacity.

The CDMA uplink applies rate one-third convolutional coding and 20-ms block interleaving to the information signal data received from the speech coder. Then the orthogonal modulation is applied using one of 64 orthogonal Walsh functions.[7] Binary phase-shift-key spreading

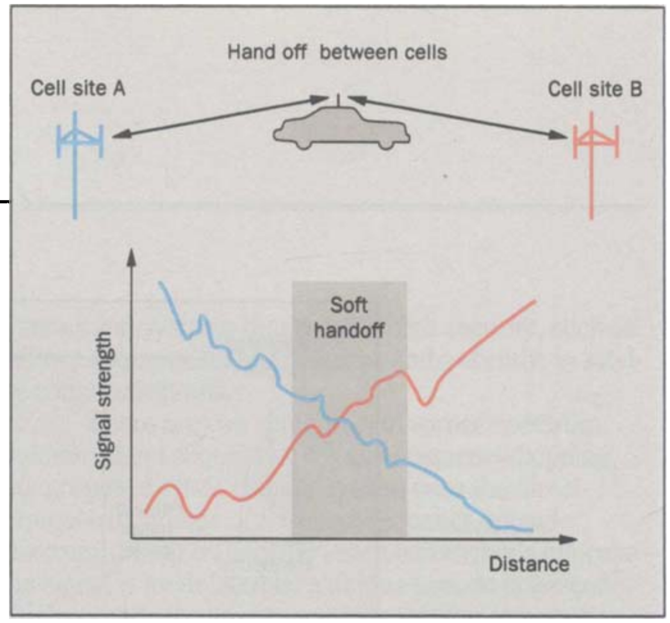

Figure 4. A mobile telephone undergoing a soft hand-off from cell site A to cell site B. The mobile telephone continuously monitors the strength of pilot channels from neighboring cells and informs the system when the signal received from cell site B exceeds a certain threshold. The system instructs cell site B to connect to the mobile telephone. As this soft hand-off occurs, the mobile telephone is communicating simultaneously with both cell sites.

is then performed using a pseudo-noise code. Each CDMA telephone is assigned a unique code when manufactured. Finally, the mobile telephone transmitter produces I and Q channels with a zero-shift pseudo-noise sequence of a shorter period. The transmitted CDMA signal is spread across approximately 1.25 MHz of RF bandwidth.

The CDMA downlink uses rate one-half convolutional coding, followed by a 20-ms block interleaver. The signal is then covered with one of the 64 orthogonal Walsh functions to distinguish each subscriber channel from all others. Quadrature phase-shift-key spreading, with I and Q channels, is then applied with a pseudo-noise sequence.

CDMA System Performance. The application of CDMA technology to cellular systems has already undergone substantial testing in both the laboratory and the field. AT&T, along with other manufacturers and service providers, has supported Qualcomm, Inc. in defining and performing a series of extensive laboratory and field tests to determine how well the technology performs in cellular applications. This testing culminated in a system capacity test in Pacific Telephone's San Diego market in November 1991.

The purpose of the tests was to determine the maximum achievable capacity under benign conditions, and then to quantify the effects of environment, sectorization, reuse, and soft hand-offs. CDMA technology provided greater than ten times the capacity of analog

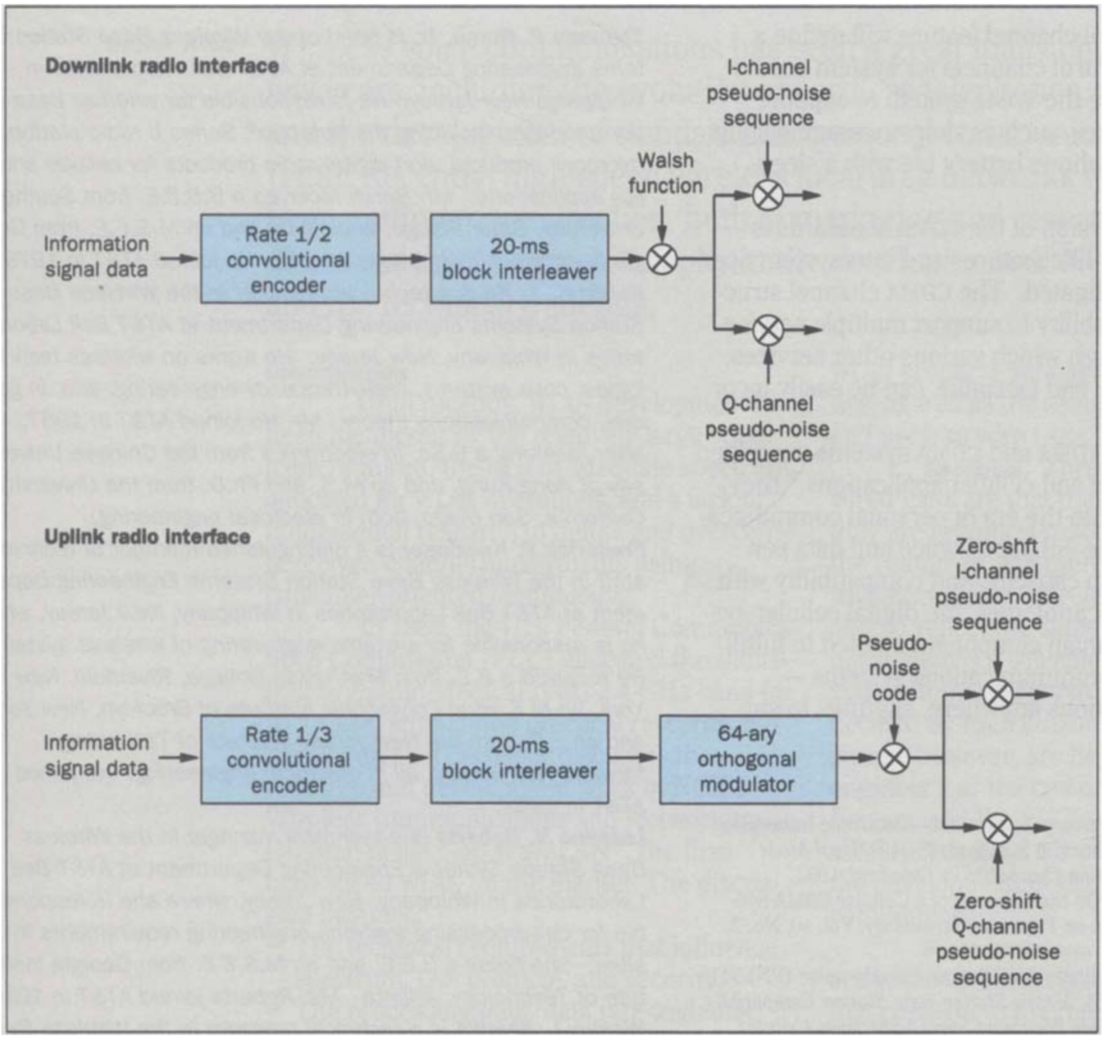

Figure 5. The radio interface of the CDMA system. The downlink uses rate one-half convolutional coding, followed by a 20-ms block interleaver. The signal is covered by orthogonal functions and spread in QPSK. The uplink uses a rate one-third convolutional coding and 20-ms block interleaving. The signal is modulated by an orthogonal function and spread by a unique pseudo-noise code of the mobile telephone.

cellular systems at acceptable error rates.

After various improvements and upgrades to the system stability and performance were completed, a second round of capacity tests was conducted in San Diego in the fourth quarter of 1992. The tests were not only successful at verifying the capacity of the system, but also demonstrated the ability to maintain good voice quality when the system was being used to full capacity. By using its power control and soft hand-off capabilities, and taking advantage of the multipath effects to which analog transmission is susceptible, CDMA provided better overall coverage than an analog system.

Mean opinion scores for CDMA channels under various levels of use are not available yet. However, the code-excited linear predictive (CELP) coder is expected to degrade performance slightly more than analog FM in systems carrying light traffic, but to improve performance as system traffic increases.

Future Directions for Digital Cellular Systems

Initial uses of both TDMA and CDMA provide only basic voice services. Future directions for both technologies include various enhanced data services, such as fax and asynchronous circuit-switched data.

Those involved in developing TDMA standards have discussed additional features that would be most desirable for its future. The standards committees are currently discussing the introduction of a digital control channel and half-rate speech coding. Half-rate speech coding will increase the system capacity by about twofold. The digital control channel feature will define a structure of digital control channels for system access and paging, and enable the TDMA system to support other enhanced services, such as short-message paging. It can also extend telephone battery life with a sleep-mode capability.

As the first version of the CDMA standards is being developed, ISDN-like features and intersystem operations are being investigated. The CDMA channel structure has a built-in capability to support multiple service option requests, through which various other services, such as wideband data and facsimile, can be easily incorporated and supported.

Although the TDMA and CDMA systems described are targeted for mobile and cellular applications,[8] they will evolve smoothly into the era of personal communications systems. With the enhanced voice and data services, very high system capacity, and compatibility with emerging microcell technologies, the digital cellular systems may well be the main component needed to fulfill the vision of personal communications systems — "enabling communications anywhere, anytime, to anyone, in any form."

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