Spread Spectrum Access Methods for Wireless Communications

The authors present an overview of the characteristics of CDMA as it is currently being envisioned for use in wireless communications. There are many considerations in the design of such systems, and there are multiple designs being proposed.

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Over the past several years, code division multiple access (CDMA) has been shown to be a viable alternative to both frequency division multiple access (FDMA) and time division multiple access (TDMA), and the use of spread spectrum techniques (upon which CDMA is based) in wireless communications applications has become a very active area of research and development [1, 2]. While there does not appear to be a single multiple accessing technique that is superior to others in all situations, there are characteristics of spread spectrum waveforms that give CDMA certain distinct advantages. The two basic problems which the cellular mobile radio system designer is faced with are multipath fading of the radio link and interference from other users in the cellular reuse environment. Spread spectrum signals are effective in mitigating multipath because their wide bandwidth introduces frequency diversity. They are also useful in mitigating interference, again because of their wide bandwidth. The result of these effects is a higher capacity potential compared to that of non-spread access methods.

Consider the use of direct sequence (DS) spread spectrum. As is well-known, DS waveforms can be used to either reject multipath returns that fall outside of the correlation interval of the spreading waveform, or enhance overall performance by diversity combining multipath returns in a RAKE receiver [3]. The above will hold any time the spread bandwidth exceeds the coherence bandwidth of the channel, that is, when the channel appears frequency-selective to the spread spectrum signal. Alternately, in frequency hopped (FH) spread spectrum, frequency diversity is obtained through coding the data and interleaving it over multiple-hops.

Another consideration in using CDMA in cellular systems is the so-called reuse factor. For non-spread multiple accessing techniques (i.e., FDMA and TDMA), frequencies used in a given cell are typically not used in immediately adjacent cells. This is done so that a sufficient spatial isolation will exist to ensure cells using the same frequency will not cause excessive interference (i.e., co-channel interference) with one another. For example, in the analog AMPS system, a frequency reuse of one-in-seven is employed. However, with spread spectrum signaling, the possibility of a frequency reuse of one-in-one exists. Further, in a CDMA system, performance is typically limited by average (rather than worst-case) interference. For these reasons, in a multicell system, CDMA is anticipated to have a larger capacity than either FDMA or TDMA. Note, however, for an *isolated cell*, because of the nonorthogonality of the CDMA waveforms, the capacity of the cell is less than what would be the case with an orthogonal technique such as TDMA or FDMA.

CDMA also provides a natural way to exploit the bursty nature of a source for added capacity. In the case of a two-way telephone conversation, the voice activity of each participant is about 50 percent of the time. If transmission is discontinued during nonactivity periods, in principle one can double the number of simultaneous conversations in the system.

The above attributes promise the potential of higher system capacity through spread spectrum techniques. Also, the one cell reuse pattern alleviates the problem of frequency planning required with the narrow band systems (although other planning issues may become necessary, like careful power planning and pilot timing for DS systems, or careful choice of hopping patterns for FH systems). As a result, CDMA has become a serious competitor in the cellular arena.

The ability of spread spectrum signals to combat interference has also been applied in a different arena, that of the so-called industrial, scientific, and medical (ISM) bands. The ISM bands are frequency bands which, by Part 18 of the U.S. FCC regulations, were originally designated for operation of equipment which "generate and use locally RF energy for industrial, scientific, and medical" applications, "excluding applications in the field of telecommunications." In view of the local nature of these RF radiations, it was later suggested to use these bands for telecommunications, also of a local nature, such as on-site communications. Spread spectrum techniques, both DS- and FH-based, were established, and a byproduct of the use of spread spectrum is the ability to allow unlicensed operation, per Part 15 of the FCC regulations.

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Direct Sequence Cellular CDMA

DS spread spectrum signals are generated by linear modulation with wideband PN sequences which are assigned to individual users as their signature codes. The wideband character is utilized to achieve enhanced performance in the presence of interference and multipath propagation. For a description of DS spread spectrum at a tutorial level, see [4]; for an in-depth treatment, see references such as [5] and [6].

In DS/CDMA, the time/frequency space is usually shared by the users in the following way. One frequency band is used for the base-to-mobile link (also called the forward or down link). A separate frequency band is used for mobile-to-base link (i.e., the reverse or up link). Except for this frequency division duplex (FDD) operation, no other frequency or time division between the mobiles takes place.

The two links, forward and reverse, differ in certain fundamental ways. On the forward link, a cell's common pilot can be used for channel estimation and time synchronization. Furthermore, the users can be orthogonalized. (However, the orthogonalization is not preserved between different paths of the multipath propagation, nor is it preserved between the forward links of different cells.) The reverse link, on the other hand, does not enjoy these features. For example, it typically cannot be orthogonalized, in view of the different locations as well as independent movements of the mobiles. It is the task of the designer to balance the two links.

Characteristics of DS/CDMA

Universal Frequency Reuse — FDMA and TDMA cellular systems must rely on spatial attenuation to control intercell interference. As a result, neighboring cells need to be assigned different frequencies to protect against excessive (co-channel) interference. In contrast, a DS/CDMA cellular system can apply a universal one-cell frequency reuse pattern. If the traffic requirement at a certain location increases, introduction of a new cell will be less restricted than in the case of either FDMA or TDMA. This ability to employ universal frequency reuse not only beneficially affects the capacity of the system, but also results in ease of frequency management (although other management issues may be required such as power management and pilot timing).

Power Control —

Reverse Link: The reverse link is typically designed to be asynchronous, and an asynchronous CDMA system is vulnerable to the "near-far" problem, that is, the problem of very strong undesired users' DS signals at a receiver swamping out the effects of a weaker, desired user's, DS signal. Such interference is due to the nonzero crosscorrelation of the PN sequences assigned to individual users in CDMA. A solution to the near-far problem is the use of power control, which attempts to ensure that all signals from the mobiles within a given cell arrive at the base of that cell with equal power. The primary use of power control is to maximize the total user capacity; an additional benefit is to minimize consumption of the transmitted power of a portable unit. The power control required must be accurate (typically within 1 dB), fast enough to compensate for Rayleigh fading of fast moving vehicles as well as changes in shadowing (closed loop control with an update rate on the order of 1000 b/s) and have a large dynamic range (80 dB).

Forward link: Since all the cell's signals can be received at the mobile with equal power, the forward link does not suffer from the near-far problem. However, power control can be applied by increasing the transmitted power to mobiles that suffer from excessive intercell interference. This usually will happen when a mobile reaches the cell's boundary. It should be noted that the forward link power control is of an entirely different nature relative to that of the reverse link; it requires only a limited dynamic range, and need not be fast.

Soft Handoff and Space Diversity — The universal frequency reuse presents a problem at the cell's boundaries, where the transmission from two or more cell sites are received at nearly equal levels. To resolve the problem on the forward link, the user's information is sent via two or more base stations, which is diversity-combined by the user's receiver. On the reverse link, the user's data is received by the corresponding base station receivers and selection diversity is performed through the fixed infrastructure, which carries the receptions from the spatially separated sites to a common place. Power control of the mobile is coordinated by that base station that receives the strongest signal; this ensures that excessive interference will not be generated. Note that the universal reuse pattern, together with a RAKE receiver, combine to achieve the desired result. The soft handoff mode is particularly helpful in a handoff transition from one cell to another, as it provides a "make before break" handoff transition.

Soft handoff can also be used between sectors of the same base site. The two sectors use the same frequencies and a soft handoff mode is used to cover the boundary region between adjacent sectors. This mode is often termed "softer handoff."

Further, soft handoff can be used for providing space diversity to mitigate multipath having a delay spread that is short compared to the signal's correlation time (e.g., for indoor application). Another case were such soft handoff is proposed is in the satellite-based case (see below) to provide satellite diversity to the mobiles.

Coding — Coding redundancy can be regarded as part of the spreading. In principle, one can envision using very low rate codes [12]. In the limit, a code of rate 1/G, where G is the processing gain, can be considered. In practice, code rates of 1/2 of 1/3 are typically used.

Source Burstiness (Voice Activity) — Multiple access interference (MAI) in CDMA is the most dominant factor in the limitation of capacity. A way to reduce the instantaneous MAI is to stop transmission when voice or data activity is absent. On two-way telephone conversations, numerous measurements have established that voice is active less than 50 percent of the time. Thus, if voice activity detection is employed, the capacity of a cellular CDMA system, in terms of numbers

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of users that are simultaneously served by the system, can be approximately doubled.

Antenna Gain — Fixed sectored antennas and phased arrays also accomplish reduction of MAI, and hence increase the user capacity. That is, the universal one cell reuse pattern can be applied to cells that have been subdivided into sectors. Typically, a three-sectored antenna pattern is employed.

Cellular User Capacity

For the forward link, a base station can employ synchronous transmission to all mobile users, as noted above. This is called synchronous CDMA, and orthogonal codes can be applied for the synchronized transmission to mitigate MAI from within a cell. We concentrate here on a coarse estimate of the capacity of the reverse link, which is typically an asynchronous link [2, 7-9]. We assume perfect power contol, and an identical set of users (e.g., all voice users requiring the same performance).

From Eq. (14) of [2], an effective energy-per-bit-to-noise spectral density ratio can be expressed as

$$\left(\frac{E_b}{\eta_0}\right)_{eff} = \frac{1}{\dfrac{\eta_0}{E_b} + \dfrac{2}{3G}(M-1)(1+K)\alpha}, \tag{1}$$

where we define the following terms:

$\left(\frac{E_b}{\eta_0}\right)_{eff}$ $\triangleq$ energy-per-bit-to-total noise (i.e., thermal noise plus interference) spectral density ratio

$E_b \triangleq$ received energy-per-bit

$\eta_0 \triangleq$ single-sided noise spectral density

$G \triangleq$ processing gain, equal to the number of chips per information symbol (corresponding to a processing gain of rG per coded symbol if rate r forward error correction is employed)

$M \triangleq$ number of users per cell

$\alpha \triangleq$ voice activity factor

$K \triangleq$ adjacent cell spillover factor, given by the ratio of intercell interference to intracell interference.

and

$\frac{2}{3}$ is a coefficient that arises because rectangular pulses were assumed; it will change somewhat if the chip shape changes.

Eq. (1) relates the effective energy-per-bit-to-noise spectral density ratio to the number of users. It can be rearranged to yield the following expression for the number of users per cell:

$$M = 1 + \frac{3}{2}\frac{G}{(1+K)\alpha}\left\{\left[\left(\frac{E_b}{\eta_0}\right)_{eff}\right]^{-1} - \frac{\eta_0}{E_b}\right\} \tag{2}$$

Consider now some interpretations and comments on the above results:

• The concept of an effective energy-per-bit-to-noise spectral density ratio, presented in (1), "makes sense" in view of the fact that a DS/CDMA system operates in an environment where the multiple access noise is caused by a sum of a large number of users, which, by the central limit theorem, tends to be Gaussian. Hence, the DS/CDMA link can be characterized by a specific $\left(\frac{E_b}{\eta_0}\right)_{eff}$ required to achieve a required bit error rate (BER). The actual BER achieved, for a given $\left(\frac{E_b}{\eta_0}\right)_{eff}$, is a function of the characteristics of channels, such as the degree of multipath fading. From Eq. (1), we see that for other parameters held constant, when the value for $\left(\frac{E_b}{\eta_0}\right)_{eff}$ is decreased, the resulting number of users is increased.

• Equation (2) represents an average value for M. As the averaging is done with respect to several random variables, one should exercise care in the interpretation. For example, α represents the average voice activity duty cycle. However, the activity of a user is a binomial random variable. The average value for α alone does not indicate the outage probability of the system, and specifying outage probability, which may be a more meaningful way to establish the number of simultaneous users, might result in a lower capacity than does using average BER.

• K represents the reduction of capacity due to intercell interference. It is dependent on several factors, notably, intercell isolation. For terrestrial systems, this is a function of the propagation law exponent (falloff of received power with distance). The lower the propagation exponent, the higher K becomes (see [10]). For a propagation law exponent of 4, $K \simeq 0.5$. Alternately, for a satellite system, cell isolation is primarily obtained through the satellite multibeam antenna pattern. As an example, $K = 1$ is reported in [11]. Further, K is dependent on the users' spatial distribution. The numbers quoted above relate to a uniform distribution; for other distributions, K may change considerably. Finally, there is a difference between the K's of the forward and reverse links; for example, the use of soft handoff causes the forward link to suffer from a worse reuse factor, since mobiles that are in a soft handoff zone require links from two or more base stations.

• Thermal noise reduces capacity, as seen by the second term in Eq. (2). If the mobile power is high enough, we obtain the asymptotic capacity by neglecting the effect of thermal noise. Since $M \gg 1$,

$$M \simeq \frac{3}{2}\frac{G}{\left(\frac{E_b}{\eta_0}\right)_{eff}}\frac{1}{(1+K)\alpha} \tag{3}$$

• The minimum value required for $\left(\frac{E_b}{\eta_0}\right)_{eff}$, denoted $\left(\frac{E_b}{\eta_0}\right)_{min}$, is a key parameter, since it effects the capacity directly, as seen from Eqs. (2) or (3). It depends on the BER required, which, in turn, depends on many factors, e.g., the multipath characteristics of the link in relation to the signal's bandwidth. Multipath returns with time delays greater than the correlation time of the signal can be resolved by a RAKE receiver and constructively combined. While the precise multipath characteristics depend on the operating environment, as will be discussed below in the section on performance, the correlation time of the signal is roughly equal to the chip duration, and thus to ensure that the delay spread of the channel exceeds the correlation time of the signal, a high chip rate is desired, which implies a wide bandwidth. Also, $\left(\frac{E_b}{\eta_0}\right)_{min}$ depends upon the coding employed. Lastly, the minimum $\left(\frac{E_b}{\eta_0}\right)_{eff}$ depends on the modulation. A typical value for $\left(\frac{E_b}{\eta_0}\right)_{min}$ for outdoor cellular terrestial applications, a BER of 10^{-3}, convolutional coding with a rate of 1/3, constraint length $k = 9$, and soft decision decoding, is 7 dB.

•The ratio $M\alpha/G$ can be given the interpretation of efficiency, as it expresses the information bit rate communicated in a cell (one way) per one Hz of bandwidth. In the above example, the efficiency is 0.2 b/s/Hz/cell ($K = 0.5$ is assumed). This efficiency can, of course, be increased through the use of sectorization of the cell.

•The processing gain plays an important role in determining the efficiency of the system. Typically, the larger the processing gain, the better is the ability of the system to mitigate the multipath; for example, smaller delay spreads can be resolved by a RAKE receiver. Also, the "averaging ability" of the system is improved, since more users are sharing the frequency band. This will reduce the outage probability. On the other hand, larger processing gain can cause certain implementation complexities such as a larger power drain; further, there may be a limitation to the allocated spread bandwidth imposed by a regulatory agency. Typical values for G can range from 100 to 1,000.

•Since DS/CDMA systems are invariably interference limited, there exists the option of trading off capacity for coverage. In other words, as a cell's loading (i.e., M) decreases, its coverage can increase. This can be seen from Eq.(1); decreasing M in the denominator of (1) allows for a decrease in E_b without causing the overall denominator to increase. This is helpful in cellular system construction where the spatial distribution of the load is not uniform (which, in practice, is the case). In the core of a typical system, the cells are small, and are heavily loaded. At the fringes of the system, where the load is light, the cells can become large, and the coverage ability is increased. Alternatively, when the system is lightly loaded, less RF power is needed, which is advantageous, for example, in terms of battery life.

•Finally, we make the following observations. The estimate of Eq. (2) is very optimistic, in that it ignores several key effects, such as imperfect power control, and imperfect interleaving. A more realistic capacity estimate, accounting for some of these sources of degradation, is presented below in the section on performance. Further, the use of perfect rectangular chip shapes yields an optimistic result, since it does not account for bandlimiting. All of these latter effects have been treated in the literature (e.g., [12,-16]), and the severity of them depends upon the specific scenario. For example, if the spread bandwidth does not exceed the coherence bandwidth of the channel, multipath fading will cause noticeable degradation because the fading will be flat rather than frequency selective. Similarly, if propagation delay precludes the use of accurate power control, as in a satellite link, this too can cause a significant reduction in capacity.

Also, the simplified analysis presented above assumed a uniform distribution of users (i.e, M users in each cell). For a nonuniform distribution, orthogonal multiple accessing techniques such as TDMA and FDMA have an advantage, because they can take slot assignments from a lightly used cell and transfer them to a more heavily used adjacent cell. For a nonorthogonal CDMA system, this option also exists, but to a much more limited extent. In other words, as the total number of active users become concentrated in a single cell, an orthogonal system will outperform a nonorthogonal system.

The proposal to employ BCDMA is based upon spreading the spectrum of each user over the entire available RF bandwidth.

Current DS Designs

To illustrate the actual designs currently being proposed, we will consider both the IS-95 standard [8], and the proposed broadband CDMA (BCDMA) system [17]. The former system employs BPSK data and QPSK spreading on the forward link, in conjunction with synchronous intracell transmissions, which means that the forward link is made orthogonal so that there is essentially no intracell multiple access interference. (There will, of course, be intracell cell interference because of multipath, since the delayed returns are no longer orthogonal to the dominant path.) The chip rate is about 1.228 Mchips/s, the spread bandwidth is about 1.25MHz, and forward error correction is employed with a rate - $\frac{1}{2}$ convolutional code. The use of a spread pilot tone allows coherent detection to take place.

On the reverse link, 64-ary binary orthogonal signaling is used in conjunction with a rate - $\frac{1}{3}$ convolutional code. The receiver employs non-coherent detection, and an adaptive power control scheme is employed to attempt to have all intracell users arrive at the base with the same received power level.

By contrast, the proposed BCDMA system spreads the data over a 10 MHz bandwidth, and, in one version [17], overlays the current analog AMPS system. Both forward and reverse links employ QPSK data with BPSK spreading, and coherent reception is used on both links. This latter characteristic is achieved by using spread pilot tones on both links. The forward link uses a common spread pilot tone, and the reverse link is designed so that each user transmits a spread pilot tone at a power level 6 dB below that of its information-bearing signal. Also, rate - $\frac{1}{2}$ convolutional coding is employed on both links. The chip rate is 8 Mchips/s, and, as with the IS-95 based design, adaptive power control is required on the reverse link.

While there are numerous detailed differences between the two systems (e.g., type of modulation, algorithm for implementing adaptive power control, etc.), the fundamental difference is the extent to which the spectrum is spread. As pointed out in [18], an advantage of a narrower spread is the flexibility to use a non-contiguous spectrum. That is, if a total spectral band of, say, B Hz is available, but not as a single contiguous band, a system employing a narrow spread bandwidth might be able to constructively use all the bandwidth by operating in an FDMA/CDMA mode. Alternately, advantages of a wider spread include the ability to more effectively use the multipath and operate with interference averaged over more mobiles for enhanced performance [18, 19].

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There is another interesting difference between the two approaches, and that involves the manner in which one transitions from the current analog cellular system to one based upon CDMA. In the case of narrowband CDMA, the transition is basically one of replacement, i.e., to deploy a set of CDMA users in a given frequency band, that band must first be vacated by the narrowband signals. In the case of BCDMA, the spread spectrum waveforms overlay the narrowband signals, meaning that both sets of users simultaneously occupy the same frequency band. This is possible, because with AMPS, only $\frac{1}{7}$ ($\approx$ 14 percent) of the frequencies are used in any given location. Initially, when all AMPS users are present, the capacity of the BCDMA system is constrained; as time evolves, and more users convert to the digital technology, the number of AMPS users decreases, and the capacity of the BCDMA system increases.

The concept of an overlay has been proposed for both the 1.8-GHz PCS band [20] and the cellular band [17]. Clearly, the key consideration in such an overlay is whether the interference that one set of users imposes upon the other is within tolerable limits, and this is ensured by using notch filtering techniques in the CDMA transmitters and receivers. For example, if a narrowband notch is placed in the transmit spectrum of each CDMA waveform such that it coincides with the location of a narrowband signal, the interference from those CDMA waveforms to the overlaid narrowband waveforms will be minimized [17, 18]. Alternately, if narrowband notch filtering is employed at each CDMA receiver, the interference from the narrowband waveforms to the BCDMA signals will be reduced [22-24].

In Europe, DS/CDMA for the future Universal Mobile Telecommunications System (UMTS) has been studied through the Code Division Testbed (CODIT) [25] research project within the framework of the Research in Advanced Communications in Europe (RACE) program. CODIT is intended to be the basis of a third-generation system. The "generation count" considers the analog system as first generation, the current (GSM in Europe, IS-54 in the United States, and PDC in Japan) as well as near future (IS-95 in the United States) digital systems as second generation. Third generation extends beyond that to, say, the year 2000. As such, CODIT deviates in some key respects from second generation DS/CDMA systems. Its main requirement is variety of services with flexible coexistence.

Interference Cancellation

The capacity of DS/CDMA is dependent upon the accuracy in power control, voice activity gain, antenna gain, and other techniques of the physical layer. In order to increase capacity, two main obstacles have to be overcome. First, conventional spread spectrum matched filter receivers are suboptimal in the presence of multiple access interference. Second, they are highly sensitive to the near-far effect. To address these issues, many researchers have recently proposed and investigated adaptive spread spectrum receivers that can potentially combat these impediments.

The conventional receiver demodulates each signal with a single-user detector consisting of a matched filter followed by a threshold detector, and MAI caused by cross-correlation of the desired and interfering spreading sequences severely limits the error performance, in particular, because of the near-far problem. If the ultimate goal is to approach the information theoretic capacity, it is necessary to utilize a maximum likelihood multiuser receiver (MLMR) [26]. The MLMR consists of a bank of matched filters followed by a maximum likelihood sequence detector. Such a receiver displays resistance to the near-far problem, and thus results in error performance considerably superior to that of the conventional single user receiver. However, such schemes are prohibitive because of their extreme implementation complexity.

To achieve a reasonable level of complexity with some compromise in performance, several multiuser receivers based on interference suppression and cancellation techniques have been studied [27-30]. These receivers employ a multiuser detection strategy based on a set of appropriately chosen linear transformations on the outputs of a matched filter bank. The computational complexity increases linearly with the number of users, as opposed to exponentially in the MLMR. The receivers are often "near-far resistant," thus reducing the need for strict power control.

MAI in the literature on CDMA has generally been modeled as Gaussian noise. The proposed adaptive receivers that exploit the cyclostationary character of the interference can achieve considerably improved error rate. For example, consider the system of [31]. The receiver estimates replicas of the transmitted sequence for each user by multiplying the received signal with its despreading sequence. Then each estimated sequence is passed through a digital filter adaptively matched to the channel in order to compute the estimates of the MAI for each user, and the MAI estimates are subtracted from the original received signal. This MAI detection and cancellation is combined with an adaptive array antenna for temporal and spatial filtering.

Since all received signals from mobile terminals are demodulated at a base station, a multiuser receiver based on MAI cancellation is more feasible for the reverse link than it is for the forward link. An advanced DS/CDMA receiver, using such interference cancellations, might be considered as a possible candidate for a future generation CDMA cellular system. However, at present, more time is required to prove the feasibility of these interference cancellation techniques.

Frequency Hopping Cellular CDMA

We now consider the use of frequency hopping for wireless communications. Since, for practical reasons, virtually all FH systems proposed for this type of application are slow FH (SFH) systems (i.e., multiple bits are transmitted on each hop), we limit our discussion to SFH.

SFH was first proposed for cellular systems in the literature in [32, 33], and the use of such systems has been discussed more recently in [34]. The motivation behind FH is the same as DS, i.e., spread the spectrum, so that frequency diversity is obtained to help mitigate the multipath, and diversify the interferers as seen by any given user, so that the latter user's performance is determined by an average pattern of interference. This is achieved with the help of a sufficient degree of error correction coding, combined with bit interleaving and a proper choice of hopping sequences that cause fading, as well as the interferers, seen by any user, to be uncorrelated from hop to hop. Compared to DS, where it can be said the diversity effect is gained in parallel, with FH the diversity is achieved sequentially.

The main difference in the performance between DS and FH is linked to the different forms the intracell interference take in the two methods. While in DS, intracell interference is typically the dominant source of interference, for FH it can be approximately orthogonalized such that users within a cell do not interfere with one another. This can be accomplished by choosing hopping sequences that are orthogonal within the cells, combined with advancing/retarding the transmit time of the mobiles so that the time of arrival at the base receiver of the uplink bursts are time-synchronized. Clearly, FH/CDMA enjoys the same universal one cell reuse pattern as does DS/CDMA. The potential advantages of this type of FH system are as follows.

Less Total Interference — In [10], the ratio of intracell-to-intercell interference was estimated to be about two to one, under the assumption of a fourth power propagation law. It follows that the major interference is intracell, and cancelling it will mean a higher capacity potential.

Solving the Reverse Link, Near-Far Problem — Because the multipath delay spread is typically much smaller than the duration of a hop, the reverse link can be made approximately orthogonal in a given cell by appropriately aligning the transmission time of each burst, and allowing for some guard time. As the channels are orthogonal, the extensive power control arrangement, which is the basis for the DS system, is not needed. Power control for FH is employed only to reduce intercell interference, but for this purpose, the requirements on the power control system do not extend beyond the level currently carried out with existing systems, such as AMPS and GSM.

External Jamming — Most existing users in any given frequency band are narrowband. A certain level of out-of-band spurious emission is unavoidable and, in fact, is legally permitted. Such jamming from existing services to new mobile services, can, at times, be more benign to an FH system than it is to a DS system. That is to say, on the one hand, jamming to either system by an external interferer does not knock out specific channels; however, jamming reduces capacity. With an instantaneously narrowband system, such as FH, a saturation effect exists, i.e., a narrowband jammer cannot take out more capacity than determined by the ratio of its bandwidth to the system bandwidth. In DS, there is no such saturation, so that, in the limit, when the interferer gets very close to a base site, it can significantly degrade the capacity of the entire cell.

Frequency Agility — While a given DS/CDMA signal requires a wide and contiguous frequency band, FH is agile in the sense that the spectrum does not have to be contiguous. In particular, this allows the implementation of FH/CDMA for private land mobile operation (FCC, Part 90), where operational licenses are given on the basis of single and isolated narrowband channels. Furthermore, the instantaneous narrowband characteristic of FH/CDMA is beneficial in restricting out-of-band emissions. DS/CDMA, being a wideband signal, requires considerable guard bands at the fringes of its spectrum in order to control the level of emissions into adjacent bands.

For FH systems currently under consideration, typical values of the various parameters are summarized below:
- Coding is usually done with a rate one-half code, and a soft decoding metric is employed at the receiver.
- Bit interleaving is performed over 10 to 20 hops.
- If we allow a time delay of 40msec for the interleaving, a hopping rate of 250 hops/s (for an interleaving depth of 10 hops) to 500 hops/s (interleaving depth of 20 hops) is obtained.
- Power control is used to reduce intercell interference. As such, a dynamic range of, say, 30 dB, with a step of 3 dB, similar to what is employed by current analog systems, is sufficient. Also, voice activity detection can be employed to increase capacity.
- Hopping sequences are assigned for both intracell orthogonality and minimum correlation with respect to intercell interference [35]. The latter means that any two users in adjacent cells interfere only at one hop during the period of the hopping sequence.
- As the hop durations are relatively short compared to the coherence time of the Rayleigh fading, if we assume synchronized base stations, the individual hop's carrier-to-interference ratio (C/I) is fixed during the hop's duration. Hence, each hop is characterized by a C/I, and the link's performance is determined by a histogram of C/I values. The individual hop's C/I can be estimated and used as side information in a soft decision decoder. For example, one can use this procedure to erase hops which have been severely hit by adjacent cell users.

In principle, the hopping carrier can be either a single channel or multiple channels through a time division structure. The latter has an implementation advantage, as the mobile is engaged in transmission or reception only part of the time, and so the remaining idle time can be used to allow the synthesizer more acquisition time. For example, with GSM, the carrier is divided into eight timeslots. A mobile transmits on one timeslot, receives on another, and uses a third one for monitoring other carriers for mobile-assisted handoff. However, the ability of the system to average interference is reduced if timeslot hopping is not added. By timeslot hopping, we mean that the users multiplexed on a single time division carrier hop from one timeslot to another (from one TDMA frame to another) to ensure that there is sufficient randomization with respect to the interference seen by any user caused by the other users.

Cellular systems in the field which allow for the use of SFH are GSM and DCS 1800. The latter system is basically GSM shifted in frequency to the 1800 MHz range. In GSM, the carriers are separated by 200 kHz, and each multiplexes eight (voice coder) full-rate channels by time division. A TDMA frame is 4.615-ms long. Frequency hopping is

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A fundamental difference between the satellite channel and the terrestrial channel is related to the overall time delay a signal experiences when transmitted over the channel.

specified as a system option, and is used on the basis of a TDMA frame, resulting in a hopping rate of 217 hops/s.

The air interface of GSM could benefit from some modifications [36] if the full advantages of its FH are to be achieved. Also, current GSM recommendations hop only the traffic carriers, leaving the common control carrier fixed. This makes the system easier to implement, particularly with regard to system acquisition by the subscriber unit. In [37], a technique to hop the GSM common control channel is described.

Performance on Terrestrial-Based and Satellite-Based Wireless Links

CDMA has been proposed for both terrestrial links and satellite links. However, there are key differences in the characteristics of the two types of links relative to the way they affect a CDMA system. We now show how the ideas presented above affect both terrestrial-and satellite-based systems.

Multipath

For either type of link, the two characteristics most relevant to CDMA performance are the coherence bandwidth, which is roughly the inverse of the multipath delay spread, and the fading amplitude statistics. The latter characteristics are typically described as being either Rician or Rayleigh, depending upon whether a dominant line-of-sight path does or does not exist between transmitter and receiver.

Terrestrial-Based Systems — For terrestial systems, we make a distinction between indoor and outdoor links; for outdoor links, we further distinguish between street level antennas (microcells) and high elevation antennas (macrocells), and also note that rural and urban macrocells display different delay spread characteristics [20, 38-40]. For a typical indoor environment, the coherence bandwidth is about 2 to 5 MHz for large offices and rooms (e.g., banks), and can be greater than 10 MHz for smaller rooms. Thus, a CDMA system designed to take advantage of the multipath enhancement characteristics of DS waveforms should be spreading over an RF bandwidth on the order of 10 MHz. Alternately, for outdoor terrestrial links, the multipath delay spread is typically much larger, so the coherence bandwidth is correspondingly smaller. This is especially true in rural areas, where the multipath delay spread is often on the order of several microseconds; thus, the spread bandwidth of the transmitted signal can be on the order of 1 MHz and multipath enhancement can be realized. At the other extreme, namely in the downtown area of most major cities, the multipath delay spread is once again small when antennas are placed on ground level, and thus a wider spread bandwidth (i.e., a higher chip rate) is required.

Satellite-Based Systems — Now consider a typical satellite link [14, 41]. There are many mobile satellite systems currently being proposed/designed, some of which employ CDMA. Of those that are envisioning using CDMA, most are low earth orbiting satellite (LEOS) systems, and for such systems, the multipath delay spread is on the order of 100 nanoseconds because of the inclined path of propagation, implying that the coherence bandwidth is about 10 MHz. Since the proposed spread bandwidth of most of these LEOS systems is less than 10 MHz, and can be as low as 1.25 MHz, they will be unable to take advantage of the multipath enhancement potential of the spread spectrum waveforms. Rather, they can attempt to implement a dual satellite diversity system, whereby each mobile unit will be in view of two satellites; the mobile will transmit to both satellites simultaneously, and the two satellites will then retransmit the waveforms to a fixed earth station, where they will be combined in a manner which yields a diversity gain.

Path Delay/Power Control

A second fundamental difference between the satellite channel and the terrestrial channel is related to the overall time delay a signal experiences when transmitted over the channel; this time delay affects the ability of the system to implement closed-loop power control. Recall that in order for the currently designed DS systems to function, there must be accurate power control so that all waveforms arrive at the receiver with roughly the same power. This power control invariably has both an open loop and a closed loop component; the open loop power control is useful for overcoming variations in power caused by both differences in distance and differences in levels of shadowing, since both such effects are roughly reciprocal (i.e., the loss in signal power from the mobile to the base is about the same as the loss from the base to the mobile). But the loss due to multipath fading is not reciprocal; because the frequency band for base-to-mobile transmission is separated from that for mobile-to-base transmission by an amount that exceeds the coherence bandwidth of the channel, the two bands experience independent fading. Therefore, closed loop power control must be used for this latter purpose. However, if the round trip time delay is greater than the duration of most of the deep fades, this latter technique will not be effective.

The proposed CDMA LEOS systems operate in a "bent pipe" mode, in the sense that all the satellite does is act as a transponder, which frequency translates the radio links. That is, a signal originating, say, at a mobile, goes from the mobile to the satellite, and then down to a gateway on the ground, and so the propagation delay far exceeds that of a terrestrial channel. For example, as pointed out in [42], the round trip time delay for LEOS systems is on the order of tens of milliseconds, yet for mobile velocities as low as 10-to20 miles-per-hour, fade rates in excess of 0.5 dB per millisecond have been measured, and individual fade events can vanish within the duration of a round trip delay. Therefore, while closed loop power control is effective in terrestrial systems, where the time delay is small, it is significantly less useful over LEOS links, and, of course, even less useful on a geostationary link.

Interleaving

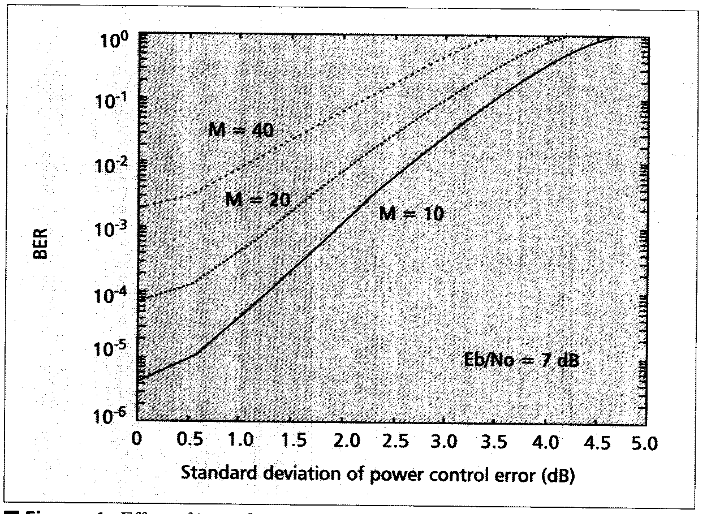
From the previous paragraph, it is evident that for either type of system, the performance is velocity-related; slowly moving subscriber units are more accurately power-controlled than are rapidly moving subscriber units. However, accuracy of power control is not the only velocity-related issue. Because the error correction codes employed in these systems are designed to correct random errors, and because the effect of a fading channel is to cause correlated errors, interleaving must be employed at the transmitter, so that a deinterleaver at the receiver can be used to disperse the correlated symbols. How effective the interleaver/deinterleaver is in accomplishing this task is a function of its span; that is, if it is large relative to the number of consecutive fading symbols (determined by the duration of a fade), then it will be very effective, but if the number of correlated symbols exceeds the capacity of the interleaver, the deinterleaver will be relatively ineffective in enhancing performance.

Consider now the situation of a mobile unit. If the velocity of the unit is large, the multipath channel will be changing rapidly, and the interleaver/deinterleaver will function properly; however, at the other extreme, if the mobile unit is stationary, the interleaver will be relatively useless, because it cannot, as a practical matter, be made large enough to result in the dispersion of errors of an essentially constant channel. Thus, we see that there are counterbalancing effects on the performance of a CDMA system as a result of motion of the mobile unit. At slow speeds, the power control system functions well, but the interleaver is not effective; at high speeds, the interleaver is very effective, but the power control system does not perform well.

As an illustration, we will attempt to quantify the degradation due to imperfect power control by using the model and results of [14]. We assume a flat Rayleigh fading channel for shadowed users, and a flat Rician channel with a ratio of specular power-to-scatter power of 10 dB for non-shadowed users. Note that the fading on either the shadowed or the non-shadowed users can be interpreted as residual fading after the closed loop power control system has tracked out as much of the instantaneous fade as possible.

Assuming M instantaneous users per cell (i.e., ignoring voice activity detection) such that 30 percent of them are shadowed at any instant of time; a system employing a rate 1/3 convolutional code with soft decision decoding; perfect side information regarding the state of the channel; and DS spreading with a processing gain of $G = 150$, we show the effect of imperfect power control in Fig. 1. These curves are based upon the analysis presented in [14], and correspond to an interbeam interference factor (analogous to intercell interference in a terrestrial system) of $K = 1$ in Eq. (1). Because the power control can compensate for shadow loss (as opposed to being able to track out the more rapidly varying multipath fading), the average received signal power of the shadowed user is the same as that of the unshadowed user. However, the performance of a shadowed user is still much worse than that of an unshadowed one, because the former one experiences Rayleigh fading while the latter one experiences Rician fading. To equalize the performance of the two sets of users, one can overcompensate the shadowed user (i.e., boost its power by an amount greater than the power lost due to the shadowing). However, note that such overcompensation for a shadowed user results in a decrease of system capacity, since it results in additional interference to each non-shadowed user.

There are three curves shown in the figure, corresponding to values of M of 10, 20, and 40. The ordinate axis is the probability of error of a *shadowed* user, and the abscissa is the standard deviation of the power control error in decibels; all the results shown correspond to a ratio of energy-per-bit-to-thermal-noise power spectral density of 7 dB. Note that the effect of thermal noise is usually much more pronounced on a satellite link than it is on a terrestrial one, and thus we have chosen a nominal value of $\frac{E_b}{N_0} = 7dB$, as opposed to a much larger value. In particular, asymptotic capacities corresponding to no thermal noise are much less meaningful for satellite communications. To interpret the results, assume a decoded bit error rate (BER) of .001 is desired, corresponding to acceptable quality of voice transmission. From the figure, a standard deviation of 2 dB will limit the number of instantaneously active users per cell to about 10; if the standard deviation can be reduced to 1.5 dB, the capacity would double to about 20. Note that even with perfect power control (i.e., a standard deviation of zero), the system could not support 40 simultaneously active users. In particular, the value of capacity as predicted by Eq. (2) is now seen to be quite optimistic, as was indicated previously.

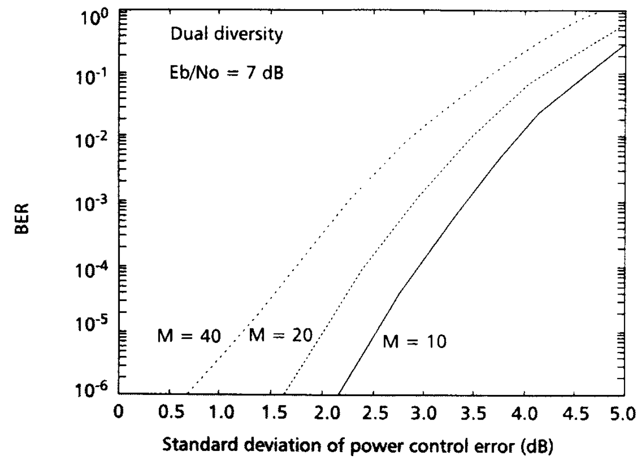


■ **Figure 1.** *Effect of imperfect power control on CDMA performance (from [14]).*

In order to achieve a larger capacity, one can employ diversity. If the overall system constraints allow for an increased spread bandwidth, this diversity can be achieved by spreading beyond the coherence bandwidth and then employing a RAKE receiver. If such additional spreading is not feasible, explicit (e.g., space) diversity can be used. An example of the use of such diversity is shown in Fig. 2, also taken from [14]. The conditions are the same as those which resulted in the curves of Fig. 1, except that dual satellite diversity with maximal-ratio combining is incorporated in the receiver. Note that now, if the standard deviation of the power control error is 2 dB, the system can support 40 simultaneously active users, and 10 users can be supported with a standard deviation as large as 3 dB.

Spread Spectrum and the ISM Bands

In Part 18 of the FCC regulations, three frequency bands are designated for equipment that generate, and use locally, RF energy for industrial, scientific



■ **Figure 2.** *Effect of imperfect power control when dual satellite diversity is employed (from [14]).*

and medical (ISM) applications, excluding telecommunications. The bands are 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz. Typical applications are industrial heating equipment, microwave ovens, medical diathermy equipment, and ultrasonic equipment (RF energy used for excitation). Since the RF radiation of these devices is localized to the immediate vicinity of the devices, it was determined that these same frequency bands were compatible with telecommunication applications for residences, offices, local area networks, etc. Further, an unlicensed operation per Part 15 of the FCC regulations was sought. Unlicensed operation has the advantage of rapid deployment, but also has the disadvantage of not ensuring interference-free operation. Spread spectrum modulation alleviates this latter vulnerability to interference. Regulation No. 15.247 set forth the parameters of the spread spectrum signals, both DS and FH, which opened these bands for telecommunication applications.

The first band to receive commercial attention was 902-928MHz. Products such as local area data networks, automatic vehicle location devices, and cordless telephones for residential use can be found on the market. A recent thrust of emerging systems is local area data networks in the band 2400-2483.5MHz. The main ISM equipment in the latter band is microwave ovens. This band is wider than the 900 MHz band and enjoys an international flavor in view of the worldwide distribution of microwave ovens. Also, currently, the band is virtually free of communication systems.

An IEEE 802.11 committee has been established to determine a standard for both the physical and the multiaccess communication layers for data LAN applications in the 2.4 GHz band. The basic data rate is 1 Mb/s, with an effort to double the rate to 2 Mb/s. Both DS and FH based physical layers are being pursued.

Discussion

It has become customary to express the capacity of the forthcoming digital systems in terms of the factor by which they increase the capacity over that of the current AMPS analog technology with a seven-cell reuse pattern. This probably was motivated by the CTIA specifying the target capacity of the future technologies in such terms. However, it appears that such a single number cannot be used to make a full comparison between the systems. For example, for CDMA systems, the capacity is a "soft" number, i.e., the capacity, which is set to a target performance of the users, can, in principle, be extended when necessary at the expense of some degradation in performance. This is not the case for the narrowband technologies, where a "hard" capacity holds. On the other hand, CDMA systems operate under the principle of equal performance to all users, and, in the case of full loading, all users are served at the minimal acceptable performance level. For the narrowband technologies, the performance of the users is not equalized; hence, when the capacity limit is reached, only a small fraction of the users will be subjected to the minimal performance level.

As previously mentioned, the users' spatial distribution is another factor that can change the comparison between DS/CDMA and a narrowband technology. Indeed, when the users' distribution is concentrated in "hot" spots, narrowband technologies have an advantage, since, being orthogonal, they enjoy higher capacity in isolated cell situations. On the other hand, for a uniform distribution, DS/CDMA is advantageous.

Other factors that can affect the comparison results are the multipath characteristics of the link and the radio link time delay. The nature of the user information also makes a difference. Bursty activity, like voice and certain data sources, lead to an advantage for a CDMA implementation. On the other hand, largely differing user requirements in terms of service (e.g., information rate, BER) tend to be better served by an orthogonal system. Further, the percentage of shadowed users in any given environment affects the capacity. In the example presented above, we assumed that 30 percent of the users were shadowed; had we assumed a different value, our capacity estimates would have also changed. Since introducing spread spectrum can add complexity, and thus cost, to a system, its use should be predicated on an anticipated net benefit to the system.

With the above ideas in mind, in this article we present an overview of the characteristics of CDMA as it is currently being envisioned for use in wireless communications. As should be evident from the previous sections, there are many considerations in the design of such systems, and, indeed, there are multiple designs being proposed.

For some DS systems, the designs are similar in the sense that they employ an orthogonal forward link within a given cell, but an asynchronous (and, thus, nonorthogonal) reverse link. On the other hand, the designs can also vary greatly. For example, in the cellular band used in the United States, the IS-95 standard uses a hybrid FDMA/CDMA approach of dividing the frequency band into multiple disjoint segments and then employing CDMA with a chip rate of about 1.228 Mchips/sec in each frequency band. However, the proposal to employ BCDMA is based upon spreading the spectrum of each user over the entire available RF bandwidth. With respect to FH, the European-based GSM system has the option of slow hopping, but that option has not been universally exploited as of yet.

Since CDMA has been proposed for use in satellite-based systems as well as terrestrial systems, we have attempted to point out the key differences in using CDMA over those two channels. In particular, it was pointed out that the increased propagation delay, coupled with the smaller multipath delay spread, make the use of CDMA over a LEOS channel inherently less attractive than it is over a terrestrial channel.

However, for a terrestrial link, CDMA appears to be especially well-suited. The combination of RAKE-enhanced performance over multipath fading channels, the simplicity with which voice activity detection can be employed, and the flexibility of complete frequency reuse within adjacent cells, suggests that CDMA will continue to be a strong competitor for wireless applications.

Increased propagation delay, coupled with the smaller multipath delay spread, make the use of CDMA over a LEOS channel inherently less attractive than over a terrestrial channel.

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