SPREAD-SPECTRUM COMMUNICATION

HISTORY

The origin of spread spectrum (SS) dates back to the early days of wireless communications. In the 1920s and 1930s, several proposals for reference-based frequency warbling or noise masking secret telephony concepts were proposed on both sides of the Atlantic. The tempo of activity in SS increased during World War II, motivated by the need for secure and jam-resistant techniques in communications and radar.

The first applications of spread spectrum signals to radar emerged in Germany and the United States toward the end of World War II. It was realized that a wide band coded or frequency modulated (FM) chirp transmit pulse resulted in a compressed receive pulse after matched filtering. This offered better ranging accuracy, improved clutter performance, and higher jam resistance. Also, guided weapons began to be introduced, and it became important to make the command links jam resistant. Spreading the information signal over a larger bandwidth was an attractive way to achieve this. The jamming signal cannot match the spreading code and is therefore suppressed at the receiver. Also, spreading the signal energy over a larger bandwidth makes it less likely to be detected.

Applications to communications followed later. The use of code division multiple access (CDMA), where orthogonal or quasi-orthogonal codes are used to support multiple users in the same band, goes back to the work of J. Pierce in the late 1940s. Even though SS had been used in several military applications since in the late 1950s, a commercial SS communication system was developed only in the 1980s when CDMA began to be deployed in small earth stations for satellite communication. In 1985, the American regulatory body [the Federal Communications Commission (FCC)] allowed unlicensed use of SS radios in the industrial, scientific, and medical (ISM) band. It would take another 10 years before a new CDMA wireless standard (IS-95) emerged. IS-95 went into field trials in 1994 and has witnessed widespread adoption.

WHY SPREAD SPECTRUM?

In a spread-spectrum system, the information signal bandwidth is spread during transmit and, after passing through the channel, it is despread at the receiver (see Fig. 1). During spreading, the information signal is multiplied by a high-rate spreading code and then up-converted to radio frequency (RF) before transmission. After passing through the channel, the received signal is down-converted and then despread by multiplying it with the same spreading code synchronized with

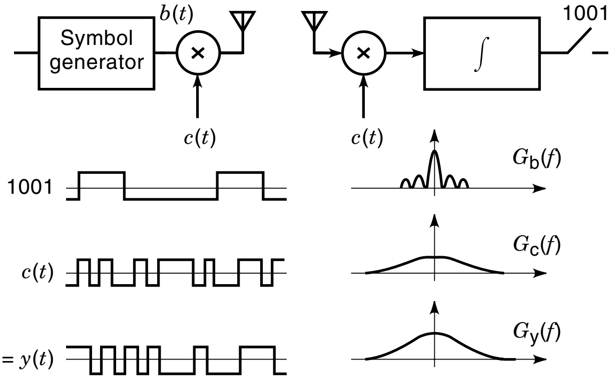

Figure 1. The information bit stream $b(t)$ is spread at the transmitter by the spreading code $c(t)$, thus decreasing the power spectral density of the transmitted signal $y(t) = b(t)c(t)$. At the receiver, the signal is despread back to its original bandwidth, integrated, and thresholded to recover the information bits.

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the received signal and then integrated over the duration of a symbol period. This reduces its bandwidth to that of the original information signal. The resulting signal can then be thresholded to recover the information bits. If the channel does not introduce distortion or interference, the signals before spreading and after despreading are identical. Spreading results in the dispersion of the signal power over a wide bandwidth, thereby reducing its power spectral density. This appears to be contrary to conventional wisdom, where the signal power is focused within a narrow spectrum to minimize the effect of interference. However, spread-spectrum systems have superior interference mitigation properties and other advantages over conventional modulation. These advantages are described later.

Jam Resistance

A jammer is a strong and usually narrow-band interferer, present inside the band of the SS signal. In SS systems, the effect of jammers is greatly reduced because the interference is added to the desired signal after it has been spread. When the signal is despread back to its original bandwidth at the receiver, the interferer is spread out and dispersed, resulting in its having a much smaller power spectral density. Because detection performance depends on the spectral density of the interferer, the effect of interference is greatly mitigated.

Low Probability of Intercept

In military communications it is often desirable to make the transmitted signal difficult to detect. This property is called low probability of intercept (LPI). The key idea is to transmit signals with a low-power spectral density, even below the ambient noise floor, if possible. This will make the signal hard to detect unless the spreading code is known to the interceptor.

Ease of Spectrum Management

Spectrum management means using the radio spectrum as efficiently as possible to maximize the number of users that can be supported. Because of their low sensitivity to interference, SS systems allow close proximity of interfering users. In networked communications, this could mean closer packing of users and therefore higher capacity. Likewise, SS signals could share the frequency band with other narrow-band non-SS users allowing an overlay use of the frequency spectrum. Adding a few spread spectrum signals merely raises the overall noise floor and, therefore, can be tolerated by the narrowband users. Also, in SS systems, the number of users allowed in the network can be traded for the signal-to-interference ratio and therefore link quality. This is referred to as soft capacity and is another example of flexible spectrum management.

Signal Diversity

Signal diversity requires that multiple branches of the signal with independent fading be available at the receiver. Diversity is a powerful approach to minimizing the effect of fading and is critical to the performance of communications systems. SS systems exploit diversity through the use of a wide-frequency bandwidth. In some SS systems, diversity is obtained directly by hopping across a frequency selective channel. If the signal is faded in one hop, it has a good chance not to be in the next. In other SS systems, spreading allows separation of multipaths that are spaced by more than one chip period. Because paths fade independently, the receiver can exploit path diversity combining to reduce the effect of fading. This form of diversity is referred to as micro diversity.

Interference Diversity

In a multiple access network, one can often take advantage of the interference diversity. In such an SS system, the interference is generated by a number of other user signals. This leads to an interference averaging effect and results in reduced interference fluctuation.

Ranging

Communication systems can provide ranging information by estimating the delay between transmission and reception of the signal. The time resolution will depend on the spread signal bandwidth. In SS systems, the high-spreading bandwidth results in good range resolution. For example, SS signals are used in the well-known GPS system for position localization.

Privacy

In most SS systems, every user has a unique code (sometimes obtained by different time offsets from a single long code) that is not reused within the network. This makes the system immune to cross talk. Moreover, an interceptor will need knowledge of the spreading code and ability to synchronize with it before intercepting a call. This is difficult for most listeners other than sophisticated eavesdroppers.

Soft Handoff

Certain SS systems can use soft handover to obtain macro diversity gain. In this form of diversity, two or more base stations transmit the same information signal so as to arrive closely time aligned at the subscriber unit. The SS receiver combines these multiple signals prior to detection. Likewise, on the subscriber to base station link, the signal transmitted by the subscriber unit is received by multiple base stations and then combined at a central location before detection. Since the loss from shadowing tends to be different from base station to base station (for a given mobile), soft handoff provides effective macro diversity. In general, soft handoff is hard to implement in non-SS systems.

PROCESSING GAIN

Consider a scenario where the desired signal is transmitted with a total power of S watts (W) at a rate of $R_b = 1/T_b$ bits per second (bps), where T_b is the symbol period in seconds. During spreading, the signal bandwidth is increased from R_b to R_s hertz (Hz), where

$$R_s \gg R_b$$

Let a white thermal noise be present at the receiver, having a single-sided power spectral density (PSD) of N_0 W/Hz. Because the noise is assumed to be white, its PSD is constant for all frequencies, and is thus not affected by the spreading or despreading operations. In addition to the noise, let the channel between transmitter and receiver introduce an interference (a jamming signal) of total power J and bandwidth W_J. The received signal is thus the sum of the (spread) desired signal, the noise and the jammer. The bandwidth of the desired signal after despreading at the receiver is again equal to R_b. On the other hand, the jammer is spread so that its PSD is now J/R_s. As explained previously, the noise PSD is unaffected by the despreading operation. The energy-per-bit E_b to total-noise-plus-interference power spectral density N_t ratio is given by

$$\frac{E_b}{N_t} = \frac{S/R_b}{N_0 + J/R_s} \tag{1}$$

Assume that the power of the jammer is much larger than the power of the thermal noise, which is the case in many applications (i.e., $J/R_s \gg N_0$). We can then write Eq. (1) as

$$\frac{E_b}{N_t} \approx \frac{S/R_b}{J/R_s} = \frac{S}{J}\frac{R_s}{R_b} \tag{2}$$

where S/J is referred to as the signal-to-interference ratio (SIR) and where

$$R_s/R_b \triangleq P \tag{3}$$

is called the spreading factor or processing gain of the SS system. It is clear from Eq. (2) that we can make the SIR larger by increasing P. The performance in a practical system will be limited by the thermal noise; as P increases, E_b/N_t approaches E_b/N_0.

PSEUDORANDOM NOISE SEQUENCES

In an SS system, the spreading is achieved by modulating the signal by a code sequence at a rate much higher than that of the original information bit stream. The binary code sequence is designed to appear to be truly random. Zeroes and ones are equally distributed. Likewise, the runs of 2 ones, 2 zeros, a one followed by a zero, and a zero followed by a one are equally distributed. Such random sequences are called pseudorandom noise (PN) sequences and are generated by a digital circuits known as pseudorandom binary sequence generators. The PN sequence can be duplicated and synchronized at the receiver. Each bit of the PN sequence is called a chip. The autocorrelation function of the PN code should exhibit a strong peak at lag zero, in order to facilitate synchronization in the receiver.

Another important feature of the spreading codes is that it is desired that they are orthogonal or at least quasi-orthogonal to each other in order to distinguish between the different users in the system. This means that the cross correlation between the codes of different users should be zero or near zero. Orthogonal codes (e.g., Gold and Walsh sequences) and quasi-orthogonal codes (e.g., m-sequences) are often overlayed to construct the final spreading code.

SPREAD-SPECTRUM TECHNIQUES

All SS systems can be viewed as a two-step modulation process. First, the information to be transmitted is spread using a code sequence to increase the signal bandwidth, and then the data stream is modulated with a pulse-shaping function. The three spreading techniques most commonly used in communications are direct sequence (DS), frequency-hop (FH), and time-hop (TH) modulation.

Direct Sequence Modulation

Direct sequence modulation is a form of spreading in which a very fast random binary bit stream is used to shift the phase of the information signal. The resulting signal is spread in frequency by a factor equal to the processing gain, see Fig. 2. The PN code multiplies the information signal at the chip rate, and the resulting binary sequence is binary phase-shift key (BPSK) modulated. Other types of spreading include balanced quadrature spreading, which uses two independent PN carriers on the same information signal. A block diagram of a DS communications system is shown in Fig. 3.

Mathematically, the code signal is given by

$$c(t) = \sum_{n=-\infty}^{\infty} \gamma(n) g(t - nT_c) \tag{4}$$

where $\gamma(n)$ is the PN code sequence at chip rate $1/T_c$ and $g(t)$ denotes the pulse-shaping function. The real transmitted signal is obtained by multiplying the BPSK modulated bit stream $s(t)$ (at rate $1/T_b$) with the code $c(t)$ and the carrier to get

$$y(t) = \mathrm{Re}\{c(t)s(t)e^{j(2\pi f_c t + \theta_c)}\} \tag{5}$$

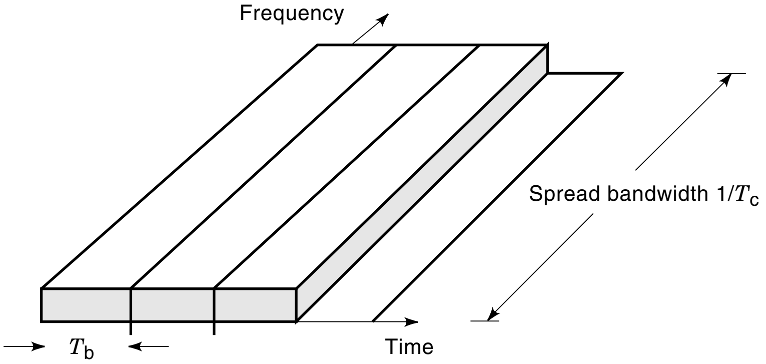

Figure 2. In direct sequence spectrum spreading, each symbol (of duration T_b) is multiplied by the chip sequence to obtain a bandwidth of $1/T_c$ after spreading.

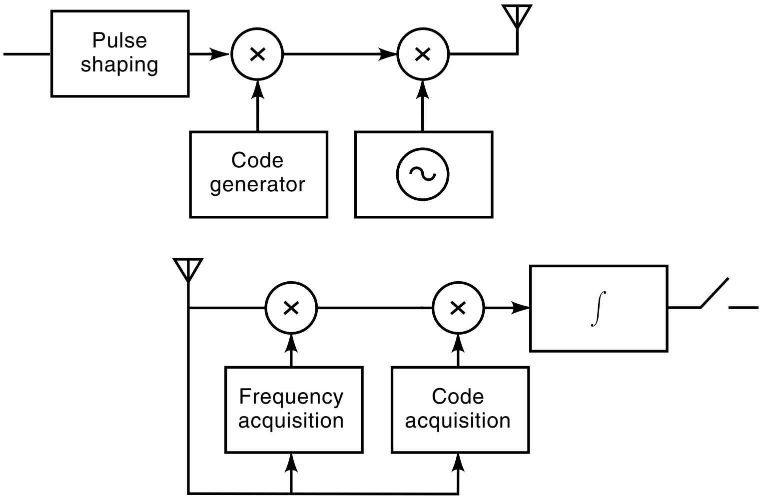

Figure 3. Block diagram of a direct sequence communications system. At the transmitter, the symbols are pulse-shaped and spread in frequency by being multiplied by the code. The resulting sequence is modulated and transmitted over the radio channel. The received signal is demodulated and once again multiplied wih the code. After integration and thresholding, the original symbols are recovered.

where f_c and θ_c denotes the carrier frequency and phase, respectively. The channel between transmitter and receiver introduces thermal noise and interference. At the receiver, the signal is demodulated and again multiplied with the spreading code which, as was explained previously, reduces the effect of the interference. Ideally, the DS/BPSK signal is now returned to its original BPSK form, with the addition of noise and (spread) interference. In practice, however, the DS receiver must perform a number of tasks in order to achieve the despreading.

One important task of the DS receiver is the code acquisition. Because of the delay between transmission and reception of the signal, the PN generator at the receiver must be adjusted to synchronize with the transmitter PN generator. In the code acquisition process, a search algorithm steps the PN generator sequentially and checks for correlation with the transmitted signal. As mentioned before, it is important that the autocorrelation function of the PN code shows a strong peak at zero lag to facilitate the synchronization. After the codes are coarsely aligned, a tracking algorithm keeps the codes aligned to within a small fraction of a chip period. If there is multipath present, a separate tracking circuit is needed for each path. Carrier and chip rate acquisition circuits are also needed. Finally, the demodulated signal is integrated (over one bit period) and passed through a thresholding device that decides upon the value of the information bit.

An important advantage of DS modulation is its immunity to interference discussed earlier. Another advantage of DS modulation is its immunity to multipath. Multipath arrivals separated in time by more than one chip period are substantially decoupled at the receiver. Therefore, they do not give rise to intersymbol interference (ISI) as in standard narrowband modulation. This results from the complex waveform of the coded pulse shape. Also, resolved paths can be exploited to provide diversity, a powerful approach to mitigate fading. When DS modulation is used in a multiple access system where a number of users access the network, it suffers from the near-far problem, and the transmit power of the users needs to be tightly controlled to arrive with equal power. Power imbalances can reduce network capacity. DS schemes are at a disadvantage in very high speed applications (e.g., > 20 Mbit/s) because the high information rate multiplied by the spreading factor will make such systems use extremely high chip rates, which in turn can make the technology expensive. Also, high chip rates can result in a large number of resolved paths and will require complex receivers.

Frequency-Hopping Modulation

In frequency-hopping modulation, the PN code sequence $c(t)$ is used to change the carrier frequency in a random fashion between a number of predetermined frequencies, see Fig. 4. If there are 2^k frequencies in the set, each k-tuple of the PN sequence corresponds to one frequency. At each time instant, the bandwidth of the frequency-hopped signal is equal to that of the information bit stream, but averaged over time the signal has a spread bandwidth. The time the signal resides at each frequency is called the hop or dwell time. The shorter the dwell time, the better the immunity from narrow-band jammers. The frequency separation between the carriers is usually at least equal to the bandwidth of the information bit stream.

In the FH transmitter (see Fig. 5), the information bit stream is first pulse-shaped and then multiplied with the frequency-hopped carrier. Mathematically, this can be described as follows. The spreading sequence $c(t)$ can be written as

$$c(t) = \sum_{n=-\infty}^{\infty} e^{j(2\pi f_n + \theta_n)} g(t - nT_\mathrm{f}) \tag{6}$$

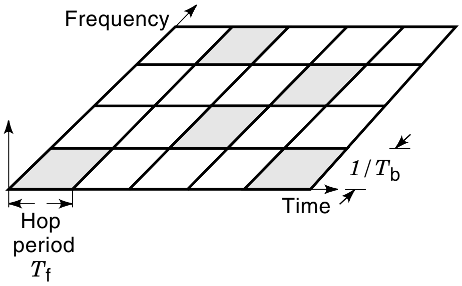

Figure 4. In frequency-hop spectrum spreading, the symbols are transmitted at different frequencies for each time period of length T_f, where the bandwidth is equal to the bandwidth of the original sequence: $1/T_\mathrm{b}$. Averaged over time, however, the signal is spread.

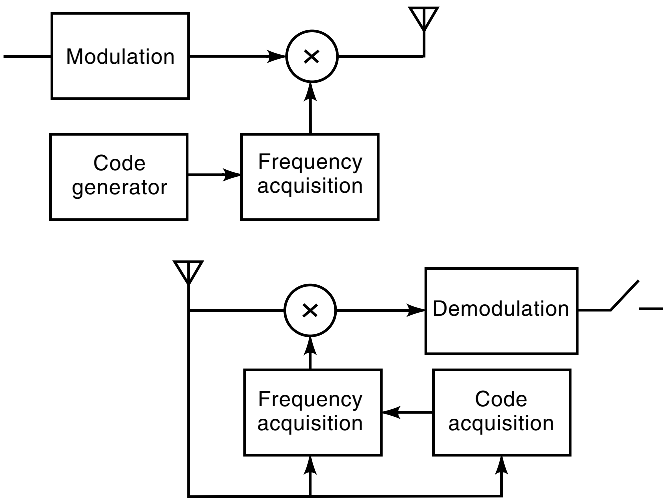

Figure 5. Block diagram of a frequency-hop communications system. At the transmitter, the modulated signal is given a frequency offset determined by the code sequence. At the receiver, this offset is removed before demodulation of the signal.

where f_n is the random hop frequency, $g(t)$ is the pulse-shaping waveform of duration T_f (the hop period), and θ_n is a random phase shift that is introduced by the frequency synthesizer. Often, FH is used together with multiple-frequency-shift-keyed (MFSK) modulation of the information signal. Then, the real transmitted FH modulated signal will be

$$y(t) = \mathrm{Re}\left[c(t)e^{2\pi j[f_c+s(t)]t}\right] \tag{7}$$

In the receiver, the spread signal (plus noise and interference) is demodulated by a frequency synthesizer driven by a synchronized replica of the transmitter PN code, which is aligned to the received signal; the desired signal is dehopped (i.e., returned to its original MFSK format). As in the case of a DS system, accurate code and frequency acquisition is necessary to perform the despreading operations. Early-late gate demodulators, code-loop filters, and voltage-controlled oscillators (VCO) are used to achieve and maintain timing and frequency synchronization.

FH systems are divided into two broad classes, fast frequency hopping (FFH) and slow frequency hopping (SFH). In FFH, there are several hops in one symbol period, so that $T_b = mT_f$, where m is an integer. On the other hand, in SFH there are multiple symbols per hop, which means that instead $T_f = mT_b$. In FH systems, the chip rate R_c is commonly defined as the larger of the hop and symbol rates (i.e., $R_c = 1/T_f$ for FFH and $R_c = 1/T_b$ for SFH). In SFH, the hop frequencies are separated by an integer multiple of $1/T_b$ and span the spread spectrum bandwidth R_s. In FFH, the hop frequencies are separated by $1/T_f$ and again lie within R_s.

FH systems has several advantages. Because the carrier frequency is hopped randomly, jammers (who do not know the hop pattern) can at best jam a small percentage of the hops. Good antijam properties have made FH systems popular for military applications. Equally important, a wide frequency range of hopping means excellent frequency diversity even if the channel is only weakly frequency selective. When an FH system suffers errors in some hops because of interference or fading, forward error correction (FEC) with interleaving can be used to recover the lost information. In multiple access applications, FH with random hop patterns in each cell results in each hop being interfered with by a different cochannel user. This along with FEC and interleaving averages out the multiuser interference yielding interference diversity. Yet another advantage of FFH systems is in multipath environments. The multipath arrivals may be sufficiently delayed by which time the signal has hopped to a new frequency, thus decorrelating the multipath. It is also worth noting that only a small percentage of the hops are likely to suffer from severe fading. Also FH systems do not suffer from high chip rate and near-far problems associated with DS systems.

Time-Hopping Modulation

In time-hopping modulation, the time axis is segmented in intervals of length T_t. Each interval is further subdivided in 2^k parts, each of width $T_t/2^k$. A pulse of duration equal to one of these $T_t/2^k$ second segments is transmitted once in each T_t second interval, with a pseudorandom location within that interval, see Fig. 6. In TH the spreading is thus obtained by compressing the pulse to have a duration that is (much) shorter than one symbol period. The location within the T_t second interval is determined by the PN code. Each k-tuple of the sequence determines a certain delay. Mathematically, this is expressed as

$$c(t) = \sum_{n=-\infty}^{\infty} g\left[t - \left(n + \frac{a_n}{2^k}\right)T_t\right] \tag{8}$$

where a_n denotes the pseudorandom position of the pulse within the T_t second interval.

In TH spread spectrum systems, time delay modulation is commonly used, and the transmitted signal can be written

$$y(t) = \mathrm{Re}\left\{c[t - s(t)]e^{j(2\pi f_c + \theta_c)}\right\} \tag{9}$$

(see Fig. 7). At the receiver, after code and frequency acquisition, the despreading operations mainly consist of removing the delays introduced by the code $c(t)$, which again spreads the interference, and then extracting the information from the pulse delay.

TH systems have advantages over certain types of jammers. However, TH systems suffer from implementation difficulties and have not been popular in practice.

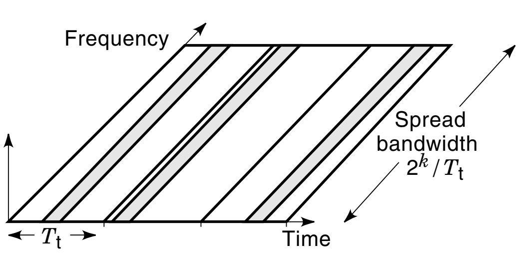

Figure 6. In time-hop spectrum spreading, the spreading is achieved by compressing the pulse to have a duration that is smaller than the symbol period. The resulting pulse is then transmitted at random time instants that are determined by the spreading code.

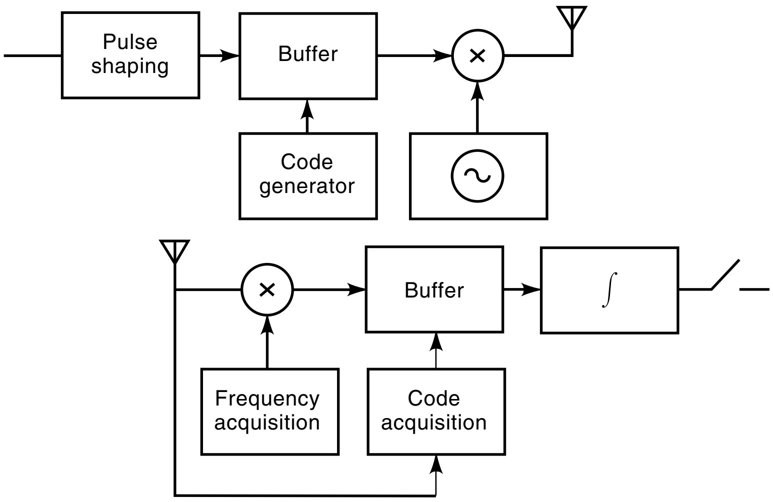

Figure 7. Block diagram of a time-hop spread spectrum communication system. Each compressed pulse is stored in a buffer and is modulated and transmitted at a random time instant that is determined by the spreading code. The spreading is achieved by the compression of the pulse, which makes it have a duration that is (much) shorter than a symbol period.

Hybrid Modulation

A hybrid system is formed by combining an SS scheme with other modulation techniques or with other SS schemes into a single system. In recent years there has been a number of such proposals mostly in the context of multiple access networks. Some of these hybrid schemes follow:

- *Direct Sequence / Frequency Hop (DS / FH).* This scheme combines DS spreading with FH. The advantages of interference and multipath immunity of DS is combined with improved frequency diversity of FH. Introduction of FH also improves near-far performance in multiple access networks.
- *Multicarrier / Direct Sequence (MC / DS).* This scheme combines multicarrier modulation with DS spreading. Typically, MC modulation may use an orthogonal (over the symbol period) frequency set [as in Orthogonal Frequency Division Multiplexing (OFDM)] or a frequency set that is well spaced to avoid any spectral overlap after spreading. MC modulation handles frequency selective channels more efficiently by using optimum allocation of power in each carrier. Also, large symbol periods provide immunity to multipath. The MC/DS hybrid combines the advantages of MC schemes while reducing the chip rate of the carrier as well as offering immunity from different sources of interferences such as multipath and intersymbol, interchip, and multiuser interference.
- *Multicarrier / Frequency Hop (MC / FH).* This scheme is a combination of OFDM and FH. It combines the efficiency of OFDM and its multipath tolerance along with the interference immunity and frequency diversity advantages of FH.

MILITARY APPLICATIONS

In military applications, it is of paramount importance that a communicated message is not destroyed (jammed) or detected (intercepted) by the enemy. In spread spectrum, the jammer is spread over a large range of frequencies at the receiver, thus decreasing its PSD. Furthermore, the spreading of the transmitted signal energy over a large bandwidth makes the desired signal hard to detect by the enemy. These antijam and low probability of intercept properties of spread spectrum communication signals makes them suitable for military applications.

Antijam Communications

Earlier we illustrated the effect of a jammer with a bandwidth W_J on the signal-to-total-noise ratio. In this section we will derive the result for a tone (single-frequency) jammer on a BPSK-modulated DS spread-spectrum system. Let the received signal be given by

$$x(t) = \sqrt{2S}c(t)d(t)\cos(\omega_0 t) + \sqrt{2J}\cos(\omega_0 t + \theta) + n(t) \qquad (10)$$

where S is the power of the desired spread-spectrum signal, J is the power of the tone jammer, θ is the phase of the jammer referenced to the signal phase, and $n(t)$ is the noise. It can be shown that the symbol energy-to-noise plus interference power density ratio at the receiver output is given by

$$\frac{E_\mathrm{b}}{N_\mathrm{t}} = \frac{E_\mathrm{b}}{N_0 + J\cos^2\theta/P} \qquad (11)$$

where $E_\mathrm{b} = ST_\mathrm{b}$ is the symbol energy of a DS spread BPSK symbol, and as before, N_0 is the thermal noise power spectral density, and P is the processing gain. We see that the jammer power is effectively reduced by P.

Assuming that the noise is Gaussian and averaging over all possible jammer phases θ, we find the probability of error to be

$$P_\mathrm{e} = E_\theta\left[\phi\left(\sqrt{\frac{E_b}{N_0 + J\cos^2\theta/P}}\right)\right] \qquad (12)$$

where $\phi(x) \triangleq (2\pi)^{-1/2}\int_{-\infty}^{x}\exp(-y^2/2)dy$. For a fixed jammer power, the P_e performance is poor and will show an error flooring for small values of the processing gain P. However, with higher processing gain, the effect of the jammer is effectively mitigated, and the performance approaches that limited by the noise.

Low Probability of Intercept

The idea of LPI is to hide the transmitted signal from a potential enemy so that the communication can remain unnoticed, and thus it will not be exploited or jammed by the adversary. Spread-spectrum signals achieve this by spreading the signal over a large bandwidth, decreasing the peak value of the PSD by an amount on the order of the processing gain. If the code is made long enough, the processing gain will be large, and the spectral density of the transmitted signal will fall below the noise floor. This means that it is unlikely to be detected by a nonintended listener. Note, however, that the total power of the transmitted signal is not decreased; it is only spread over a larger frequency band. An intercepting device that has knowledge of the signal location can still detect the signal by integrating over a sufficiently long time interval to reliably estimate the power in a band containing the signal and comparing it to the expected thermal noise level. An increased power level would indicate the presence of a signal. But if the signal is buried well below the thermal noise level, its presence will be hard to detect. Also, even if the signal is detected, it cannot be extracted without knowledge of the spreading sequence.

In the case of FH spread spectrum, a full-power narrowband carrier is hopped among many channels. The concentrated power of the carrier can be observed by an intercept receiver. However, it will catch only a glimpse of the FH signal as it briefly visits the channel being observed.

Example Systems

Several military systems employing SS techniques have been developed and deployed. Some examples follow:

- Joint Tactical Information Distributions System (JTIDS) is an SS system that provides secure jam-resistant communications, navigation, and identification for combat aircraft.
- Global Positioning System (GPS) is the well-known satellite-based positioning system that serves both military and civilian needs. It is also issued to obtain time reference in many applications.
- Single Channel Ground and Air Radio System (SINCGARS) is an FH system that provides tactical combat net communications in the VHF band.
- Position Location and Reporting System (PLRS), together with enhanced PLRS (EPLRS), provides direct user-to-user data communications, identification, and position and navigation services to units in the air and on the ground. It uses FH techniques to provide AJ capability.

COMMERCIAL APPLICATIONS

There have been several applications of the principles of SS in commercial applications. The major drive for commercialization of SS technology was the allocation of unlicensed industrial, scientific, and medical bands by the FCC. There are several ISM bands, and new bands are being opened gradually. Usage of the ISM band under the current rules (Part 15) for communications and radio location applications usually require some form of SS technique to be employed to tolerate interference from other users. Several products for point-to-point links, cordless phones, telemetry, and factory automation have been applied in the ISM band and show a growing market.

The second major drive for applications of SS techniques has been the increasing demand for cellular wireless communications and the need to develop spectrally efficient multiple access methods. In a mobile telephone network, the area to be covered is divided in different cells. In the center of the cell is the base station that communicates with the mobiles within that cell. A certain frequency band is allocated to each cell, so that nearby cells do not share the same spectrum. In this way co-channel interference can be avoided. However, because the available frequency band is limited, the same spectrum must be reused in cells that are sufficiently separated. The frequency reuse factor depends upon the interference tolerance of the underlying modulation and coding scheme. The reuse factor is 7 in AMPS (uses FM modulation), 4 in GSM (uses Gaussian minimum shift keying digital modulation), and 1 in IS-95 (uses DS/SS modulation).

Multiple Access Techniques

The different multiple access (MA) approaches in commercial use (see Fig. 8) are described next.

Frequency-Division Multiple Access (FDMA). This approach concentrates each signal's power in a very narrow frequency band. The available spectrum is then divided, so that different users occupy different frequencies. Band-pass filtering is

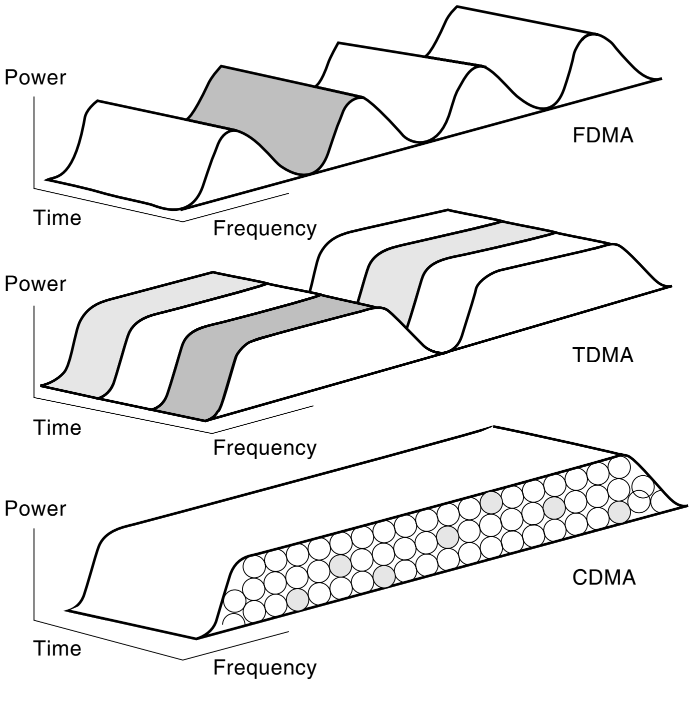

Figure 8. Different multiple access techniques: frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA). In FDMA, each user transmits simultaneously but at different nonoverlapping frequencies. In TDMA, different users can share the same frequency band, but they are active in different time slots. In CDMA, all users transmit simultaneously using the same frequency band. They are separated at the receiver through the use of the spreading codes.

used to separate the received signals. Theoretically, for a given frequency reuse factor, the capacity in an FDMA system can be increased without bound by decreasing the size of the cells. However, too small cells are not feasible in practice because of the higher costs in infrastructure and the increased hand-offs (when a mobile moves from one cell to another, the communication link is "handed over" to the new cell's base station). AMPS and TACS are examples of FDMA cellular networks.

Time-Division Multiple Access (TDMA). This approach divides the time axis into time slots. Each user's signal periodically occupies one time slot. Interference is limited by the use of a time gate that passes only the signal that is received at the proper time. Often a combination of FDMA and TDMA systems is used. IS-136 and GSM are examples of TDMA cellular networks.

Frequency-Hop Multiple Access (FHMA). This approach lets users hop in frequency in an orthogonal manner within a cell to avoid collisions with each other. Therefore, two users will never occupy the same frequency at a given instant. The hopping codes beween cells are usually unsynchronized and appear to be random to each other. This ensures that cochannel interference from outer cells arrives from different users in each hop. As a result, a variety of interferers will be observed, and strong and weak interferers will affect all the users. With interleaving and coding, this interference can be averaged out to provide interference diversity. GSM has incorporated many FHMA principles and incorporates cyclic and random FH. Pure FHMA systems have not been extensively used. An FHMA network is being developed in the United States for future deployment.

Code-Division Multiple Access. This approach functions by having each user signal modulated by a different pseudorandom binary sequence, the PN code. The available spectrum is shared by a large number of user signals, all of which occupy the same frequency band. In the time-frequency plane, the signals appear to be superimposed one on top of the other. The signals can be separated by a correlation receiver. When the received signal is multiplied by one of the spreading codes, the corresponding signal is despread to its original bandwidth. The other user's signals (whose PN codes are chosen to be orthogonal or quasi-orthogonal to the desired user's code) are not despread and therefore contribute only to the overall noise floor. The amount of interference rejection is determined by the processing gain. A good example of a DS/CDMA system is IS-95, which is just entering service. Several other CDMA systems (e.g., Airloop) have also been developed.

Hybrid Systems. Hybrid systems have also been proposed. These could be obtained by using hybrid modulation schemes or hybrid multiple access schemes, both of which were discussed previously, or some combination of both. Some examples follow:

- *DS/FHMA.* In such a scheme, users employ DS/FH SS modulation. Users within a cell use different PN codes and synchronized hopping. Users may either transmit continuously while hopping or access the network in specific time slots as in TDMA.
- *DS/T-CDMA.* This scheme uses DS modulation and TDMA within a cell so that there is no multiuser interference within a cell. However, the reuse factor is one, and every cell reuses the whole frequency band. The use of different PN codes between cells provides interference immunity and makes the low reuse factor possible.

DS/CDMA Systems

DS/CDMA networks are interference limited and require all users to have a set interference-to-signal power ratio J/S that depends on the spreading gain P and the required E_b/N_t. Neglecting thermal noise, if there are Q users within a cell, and each user arrives with equal power S, the total interference power seen by any one user will be $(Q - 1)S$, and the system can support $1 + J/S$ users. Note that if a user arrives with power higher than the set level S, the user will experience an excess E_b/N_t but will hurt other users by increasing the interference level. For example, if one user arrives with a power of $10S$, the number of users the network can accomodate will drop by 9, in order to maintain the required E_b/N_t for the other users. This implies that tight power control of all users is necessary, independently of their distance from the base station. This is the so-called near-far problem. Also, the capacity of a CDMA system can be increased if we can reduce the interference from other users. Interference can arise from within the cell and from outer cells. We discuss some of these issues next.

Power Control. As explained previously, a CDMA system operate by allowing a controlled amount of interference. The amount of interference induced by each user is determined by its power. A strong user will enjoy good signal quality but increase the amount of interference to other users. On the other hand, a weak user will not have adequate signal quality.

To overcome this potential problem, the power of the mobiles needs to be controlled, so that all signals reach the base station with approximately the same power. Typically, the mobiles estimate the received signal level from the base station and adjust their output power accordingly (open-loop power control). Furthermore, a closed-loop system is used in which the SNR for a given user is periodically estimated at the cell site and compared to a predetermined set point. If the SNR falls below the set point, the mobile is commanded to increase its power, and if the SNR is above the set point, the mobile decreases its power. In the same manner, the power sent to each user in the forward link is varied depending upon the signal quality reported by that user. This power control feature also helps mitigate severe fading sometimes experienced by users as a result of shadowing.

Reuse Between Cells. In a CDMA system, the entire available frequency band is reused in every cell. The total interference in a given cell is given by the sum of the interference from users within that cell and interference from users in other cells. The ratio of interference from mobiles in the cell to the total interference from all cells (denoted by F) is empirically found to be about 0.65 in a typical CDMA system. Thus, the neighboring cells contribute to a modest amount of interference, despite a reuse factor of one.

Reuse Within Cell. In mobile communication systems, the cells are further divided into sectors. This is usually done by deploying three antennas at the cell site, each having a 120°

beamwidth. However, the sectors are not always perfectly isolated. Indeed, the large beamwidth of the antennas, along with multipath propagation, can occasionally make the area covered by the antennas to overlap. Because frequency planning must take into account the worst signal scenario, sectoring cannot be used to increase capacity in narrow-band systems. In a CDMA system, interference due to overlap between sectors affects the system by its average value, as explained previously. Therefore, dividing a cell in m sectors provides nearly m times increase in capacity.

Capacity. Taking all these considerations into account, the total interference (neglecting thermal noise) in a sector with Q users can be expressed as

$$J = \frac{(Q-1)S\nu}{F} \Longrightarrow Q \approx \frac{JF}{S\nu} \tag{13}$$

where S is the power of each user and ν is the voice-duty factor ($\approx$0.5). From Eq. (2) we have that

$$\frac{J}{S} = \frac{R_\mathrm{s}/R_\mathrm{b}}{E_\mathrm{b}/N_\mathrm{t}} \tag{14}$$

Thus, combining Eqs. (13) and (14), the capacity limit per sector is given by

$$Q \approx \frac{R_\mathrm{s}/R_\mathrm{b}}{E_\mathrm{b}/N_\mathrm{t}}\frac{F}{\nu} \tag{15}$$

IS-95 uses a chip rate of 1.25 MHz and a reuse factor of 1. The information data rate is 9.6 kbps. This yields a processing gain of $P = 128$. The system needs a $E_\mathrm{b}/N_\mathrm{t}$ of 6 dB for adequate voice quality. Substituting these parameters into Eq. (15), we get a capacity of approximately 128/3 calls per sector or 128 calls per three-sector cell per 1.25 MHz. In practical systems, we cannot neglect the effect of thermal noise. The ratio of the total interference plus thermal noise over thermal noise power is called rise and is usually limited to about 2. This means that the interference power is approximately equal to the thermal noise power. This in turn will cut the number of calls per cell to 64. Also, the desired set point of 6 dB may sometimes be too low, depending on the amount of multipath and user speed. If higher $E_\mathrm{b}/N_\mathrm{t}$ become necessary, further losses of performance can be expected. The performance is usually different on the forward and reverse links. Achievable capacity varies between 35 and 55 users per cell.

RECEIVER STRUCTURES FOR SS/MA SYSTEMS

So far, we have assumed that the receiver models all multiuser interference as noise. In fact, more sophisticated receivers may give a higher performance. In the following discussion, we will describe such improved receiver structures for SS systems, briefly reviewing FH systems, and then focus most of our attention on DS systems.

Receiver Processing for FHMA

In FHMA networks, the desired signal will not experience any interference from within the cell but rather from users in the outer cochannel cells. The lower the reuse factor, the closer the location of the cochannel cells and the higher the degree of interference. If digital modulation schemes such as FSK, GMSK, or $\pi/4$ DQPSK are used, a simple FH receiver will normally treat the interference as noise and use a standard demodulation procedure. The interference is likely to have an impact on the decision error ony in a small number of hops. This impact will depend on the processing gain and the cell loading.

An improved approach to reducing the effect of interfering cells is using multiple antennas and space-time (ST) processing to null the interference spatially. In the following, we will summarize the theory of optimum receivers with cochannel interference using an array of antennas.

A discrete-time signal model for multiple signals (desired and cochannel) received at an antenna array can be written as

$$\mathbf{x}(k) = \mathbf{H}\mathbf{s}(k) + \mathbf{n}(k) \tag{16}$$

where the $m \times L$ matrix $\mathbf{H}$ is the symbol response channel (m is the number of antennas and L is the channel length in symbol periods). The channel $\mathbf{H}$ is assumed to be time invariant over the period of observation. The vector $\mathbf{s}(k)$ consists of L consecutive elements of the data sequence and is defined as

$$\mathbf{s}(k) = [s(k) \cdots s(k-L+1)]^T \tag{17}$$

The sampled vector of additive noise $\mathbf{n}(k)$ is defined similarly to $\mathbf{s}(k)$. Clearly, the overall signal plus interference-and-noise model at the base station antenna array can now be rewritten as

$$\mathbf{x}(k) = \mathbf{H}_\mathrm{s}\mathbf{s}_\mathrm{s}(k) + \sum_{q=1}^{Q-1}\mathbf{H}_\mathrm{q}\mathbf{s}_\mathrm{q}(k) + \mathbf{n}(k) \tag{18}$$

where Q is the number of users, and the indices s and q refer to the desired and the interfering mobiles, respectively.

Gathering several data vectors in a matrix $\mathbf{X} = [\mathbf{x}(1) \cdots \mathbf{x}(\mathbf{N})]$, Eq. (16) can be written as

$$\mathbf{X} = \mathbf{HS} + \mathbf{N} \tag{19}$$

where $\mathbf{S}$ and $\mathbf{N}$ are obtained (similarly to $\mathbf{X}$) by stacking the vectors $\mathbf{s}(\mathbf{k})$, $\mathbf{n}(\mathbf{k})$ for $\mathbf{k} = 1, \ldots, \mathbf{N}$. We first study the single-user case where we are interested only in demodulating the signal of interest. We therefore treat interference from other cells as unknown additive noise. This is an interference-suppression approach.

The first criterion for optimality in space-time processing is maximum likelihood (ML) or usually referred to as maximum likelihood sequence estimation (MLSE). ST-MLSE seeks to estimate the data sequence that is most likely to have been sent given the received vector signal. Another frequently used criterion is minimum mean square error (MMSE). In (a linear) ST-MMSE, we obtain an estimate of the transmitted signal as a space-time weighted sum of the received signal and seek to minimize the mean square error between the estimate and the true signal at every time instant.

We present ST-MLSE and ST-MMSE in a form which is a space-time extension of the well-known ML and MMSE algorithms.

ST-MLSE. We assume that the noise $\mathbf{n}(\mathbf{t})$ is spatially and temporally white and Gaussian and that there is no interference. The MLSE problem can be shown to reduce to finding **S** that belongs to a finite alphabet (denoted by $\mathscr{A}$) and that satisfies the following criterion:

$$\mathbf{S} = \arg\min_{\mathbf{S}\in\mathscr{A}} \|\mathbf{X} - \mathbf{HS}\|_{\mathrm{F}}^{2} \tag{20}$$

where the channel **H** is assumed to be known and $\|.\|_F$ denotes Frobenius norm. This is a generalization of the standard MLSE problem: the channel is now defined both in space and in time. We can therefore use a space-time generalization of the well-known Viterbi algorithm to carry out the search in Eq. (20) efficiently.

In the presence of cochannel interference (CCI), which is likely to be both spatially and temporally correlated (because of delay spread), the MLSE criterion can be reformulated with a different metric to address this problem. However, the temporal correlation complicates the implementation of the Viterbi equalizer, making MLSE less attractive in the presence of CCI with delay spread.

ST-MMSE. In the presence of CCI with significant delay spread, an ST-MMSE receiver is more attractive. This receiver combines the input signals in space and time to generate an output that minimizes the error between itself and the desired signal. This results in a two-dimensional filter that minimizes cochannel and intersymbol interference.

Multiuser MLSE. An improved approach to handling cochannel signals is to demodulate all the arriving signals jointly. We can then search for multiple user data sequences that minimize the ML cost function in Eq. (20). The multiuser MLSE will have a large number of states in the Viterbi trellis, and efficient techniques for implementing the equalizer are needed.

Receiver Processing for DS/CDMA

In DS systems, the pulse shapes (spreading codes) of the signals are different for each user. Therefore, the signals can be distinguished from each other in the time domain itself. The spatial dimension can be further exploited to improve system performance. We first develop the theory of optimum receivers for temporal processing and later address space-time processing for DS systems.

Signal Model. A simplified model for a received continuous-time signal in a DS-CDMA system has the following form:

$$x(t) = \sum_{q=1}^{Q} x_q(t) + n(t) \tag{21}$$

where $x_q(t)$ is the contribution from the qth user, Q is the number of users sharing the same channel, and $n(t)$ is the additive noise. The signal $x_q(t)$ (assuming a repeated spreading code) can be expressed as

$$x_q(t) = \sum_{k=-\infty}^{\infty} s_q(k) p_q(t - kT_{\mathrm{b}}) \tag{22}$$

where $\{s_q\}$ is the information bit stream [typically $s_q(k) = \pm 1$], T_{b} is the symbol period, and $p_q(t)$ the overall channel given by the convolution of the impulse response of the channel and the spreading waveform, that is,

$$p_q(t) = h_q(t) * c_q(t) \tag{23}$$

where $*$ denotes convolution, $h_q(t)$ is the channel impulse response, and $c_q(t)$ is the qth user's spreading waveform given by

$$c_q(t) = \sum_{n=0}^{P-1} \gamma_q(n) g(t - nT_{\mathrm{c}}) \tag{24}$$

where P is the spreading factor or processing gain, T_{c} ($= T_{\mathrm{b}}/P$) is the chip period, $\{\gamma_q(n)|_0^{P-1}\}$ is the qth user's spreading code, and $g(t)$ is the chip waveform. For a specular channel with L paths, $h_q(t)$ can be written as

$$h_q(t) = \sum_{l=0}^{L-1} \alpha_{lq} \delta(t - \tau_{lq}) \tag{25}$$

where α_{lq} and τ_{lq} are the complex path gains and the path delays, respectively.

A number of receiver structures have been proposed in CDMA and are briefly summarized next. We begin with time-only receivers.

Time Processing. A set of sufficient statistics for the detection of the user data is given by the outputs of a bank of matched filters, each matched to an individual user's channel $p_q(t)$:

$$r_q(k) = \int_{kT_{\mathrm{b}}}^{(k+1)T_{\mathrm{b}}} x(t) p_q(t)\, dt \tag{26}$$

We can classify the detection problem into a single-user and a multiuser case. In single-user detection we assume that the signal detection for each user is performed independently. In the multiuser case, all users are detected jointly. Each of these cases can be further classified into a number of subclasses with tradeoffs in complexity and receiver performance. We begin with the single-user receiver.

Single-User DS Receivers. Single-user receivers work on the assumption that the multiple access interference (MAI) is unknown random white noise, whereas MAI, in fact, arises from other user signals and is not really unknown. The penalty for this assumption in DS-CDMA networks is the need for accurate power control wherein the received power from all users must be kept equal. If this is not ensured, the system capacity degrades rapidly. The advantage of a single-user receiver is its simplicity and robustness. We describe two versions of the single-user receiver.

Simple Correlator. In this receiver, the channel is assumed to have a single path. Therefore, the channel $p_q(t)$ reduces to $c_q(t)$, and the correlator output is given by

$$r_q(k) = \int_{kT_{\mathrm{b}}}^{(k+1)T_{\mathrm{b}}} x(t) c_q(t)\, dt \tag{27}$$

The bit decisions are given by

$$\hat{s}_q(k) = \mathrm{dec}[r_q(k)] \tag{28}$$

where dec $(\cdot)$ is a decision (threshold) operation. The simple correlator will indeed be optimal if the following conditions are met: (1) The codes are orthogonal, that is

$$\int_0^{T_\mathrm{b}} c_i(t)c_j(t)\,dt = \delta_{ij} \tag{29}$$

(2) perfect symbol synchronization is achieved, (3) no multipath is present, and (4) the additive noise is white and Gaussian. However, if any of these conditions is not met, the receiver in Eq. (28) will be suboptimal. If quasi-orthogonal spreading codes are used, this receiver will never be optimal due to the presence of MAI. Simple correlators are popular when the multipath is negligible.

The RAKE Receiver. When the channel exhibits a significant multipath with delay spread larger than one chip period, an improved receiver can be designed to match this channel. Note that in DS-CDMA, multipath has both a positive and a negative effect. On one hand, the independently fading paths can be a valuable source of diversity. On the other hand, the multipath introduces interchip interference, and in the case when orthogonal codes are used, it also introduces MAI.

A popular single-user receiver in the presence of multipath is the RAKE combiner first proposed in 1958. The RAKE receiver uses multiple correlators, one for each path, and the outputs of the correlators (called fingers) are then combined into a single output to maximize the signal-to-noise ratio. If the combining (complex) weights are matched to the channel response at these fingers, we get a coherent RAKE receiver, which is identical to a matched receiver,

$$\begin{aligned} r_q(k) &= \int_{kT_\mathrm{b}}^{(k+1)T_\mathrm{b}} x(t)p_q(t)\,dt \\ &= \sum_{l=0}^{L-1} \alpha_{lq} \int_{kT_\mathrm{b}}^{(k+1)T_\mathrm{b}} x(t)c_q(t-\tau_{lq})\,dt \end{aligned} \tag{30}$$

Another version is the incoherent RAKE, in which the fingers are combined after detection (i.e., after removing the channel phase information). The RAKE combining is called maximal ratio when the weights are proportional to the path amplitude and equal gain if the weights are all set to be equal.

The use of a RAKE receiver assumes that the channel impulse response (including path delay, amplitude, and phase) is known. In practice, this is estimated by a tracker that estimates the path delay and computes its complex amplitude. The channel can be estimated using spreading codes and pilot or training signals. We can also estimate the channel with knowledge of spreading codes alone. Many variations of the RAKE have been proposed, and the RAKE is still an area of active research.

Multiuser DS Receivers. The conventional approach treated previously focused on retrieving the desired user data alone and treated all other user's signals as noise. However, we should be able to achieve better results if we use the knowledge of the signal structure of the other users as well and demodulate all signals simultaneously. Such a receiver was first proposed by Verdú and satisfies the following criterion:

$$\hat{\mathbf{s}}(k) = \arg\min_{\mathbf{s}\in\{-1,1\}^Q} \int_{kT_\mathrm{b}}^{(k+1)T_\mathrm{b}} \left(x(t) - \sum_{q=1}^{Q} s_q(t)p_q(t-kT_\mathrm{b}) \right)^2 dt \tag{31}$$

where $\mathbf{s}(k) = [(s_1(k) \cdots s_Q(k)]^T$ (and again we assume the additive noise to be white and Gaussian). The multiuser receiver that implements Eq. (31) can provide significant performance gains over the single-user receiver, especially in cases of unequal user power (the near-far problem). However, the computational burden of optimization of the criterion is exponential in the number of users and may be prohibitive in most cases. Moreover, this receiver requires exact knowledge of the channel for all users. The need for a simpler and more robust receiver led to the search for linear receivers.

Such linear receivers for multiuser detection in CDMA were investigated by Lupas and Verdú. The general form of a linear CDMA detector is based on bit decisions given by

$$\hat{\mathbf{s}}(k) = \mathrm{dec}[\mathbf{T}\mathbf{r}(k)] \tag{32}$$

where $\mathbf{r}(k)$ is the vector-matched filter output: $\mathbf{r}(k) = [r_1(k) \cdots r_Q(k)]^T$ and $\mathbf{T}$ is a $Q \times Q$ matrix. Depending on the choice of $\mathbf{T}$, different receivers can be obtained, among which the optimal linear receiver $\mathbf{T}$ maximizes the asymptotic efficiency of the receiver. Note also that the conventional matched filter receiver is obtained for $\mathbf{T} = \mathbf{I}$. The following two linear receivers have received some attention in the literature.

Decorrelating Receiver. Assuming no delay spread and perfect symbol synchronization, the output of the matched receivers can be written as

$$\mathbf{r}(k) = \mathbf{P}\mathbf{s}(k) + \mathbf{n}(k) \tag{33}$$

where $\mathbf{P}_{ij}$ is the cross correlation of the ith channel with the jth user signal. It is then natural to choose $\mathbf{T}$ to be

$$\mathbf{T} = \mathbf{P}^{-1} \tag{34}$$

making it analogous to the zero-forcing equalizer. Because $\mathbf{P}$ may be singular, it is more appropriate to use a pseudo-inverse $\mathbf{P}^\dagger$ of $\mathbf{P}$. The bit decisions are given by

$$\hat{\mathbf{s}}(k) = \mathrm{dec}[\mathbf{P}^\dagger\mathbf{r}(k)] \tag{35}$$

Clearly the receiver described in Eq. (35) is not optimal because the premultiplication of the matched filter output colors the noise. However, this receiver is optimal in terms of near-far resistance. Among its advantages are a significant reduction of computational complexity and avoiding the need to estimate channel powers.

MMSE Receiver. An MMSE-type linear receiver can be proposed for multiuser detection in lieu of the decorrelating receiver shown in Eq. (35). In this case the bit decisions are given by

$$\hat{\mathbf{s}}(k) = \mathrm{dec}[\mathbf{T}\mathbf{r}(k)] \tag{36}$$

where each row $\mathbf{t}_q$ of $\mathbf{T}$ is so chosen to minimize the mean square error between the received signal and a known training sequence $\bar{s}_q(k)$

$$\mathbf{t}_q^H = [E\mathbf{r}(k)\mathbf{r}^H(k)]^{-1}E[\mathbf{r}(k)\bar{s}_q^*(k)] \tag{37}$$

The MMSE multiuser detector is near-far resistant and also offers a significant performance improvement over a matched filter receiver. In the asymptotic case of the background noise power going to zero, the MMSE receiver reduces to the decorrelating detector.

Space-Time Receivers. The use of multiple antennas adds a new dimension to the CDMA receiver problem and, as in TDMA, allows improved separation of user signals. Therefore, space-time processing can significantly increase the capacity of CDMA networks.

The received continuous-time $m \times 1$ signal vector in a multiple antenna CDMA system has the following form

$$\mathbf{x}(t) = \sum_{q=1}^{Q} \mathbf{x}_q(t) + \mathbf{n}(t) \tag{38}$$

where the vector signal contribution from a single user is given by

$$\mathbf{x}_q(t) = \sum_{k=-\infty}^{\infty} s_q(k)\mathbf{p}_q(t - kT_\mathrm{b}) \tag{39}$$

where $\mathbf{p}_q(t)$ is the vector channel given by the convolution of the vector channel impulse response, spreading code and chip waveform, that is,

$$\mathbf{p}_q(t) = \mathbf{h}_q(t) * c_q(t) \tag{40}$$

where $\mathbf{h}_q(t)$ is the vector channel impulse response. Once again, for a specular channel, we can write

$$\mathbf{h}_q(t) = \sum_{l=0}^{L-1} \alpha_{lq}\mathbf{a}_{lq}\delta(t - \tau_{lq}) \tag{41}$$

where $\mathbf{a}_{lq}$ corresponds to the array response vector for the lth path from the qth user.

The use of multiple antennas at the receiver, therefore, has merely converted a scalar channel $h_q(t)$ to a vector channel $\mathbf{h}_q(t)$. The output of a filter matched to the ith antenna for user q is given by

$$r_{iq}(k) = \int_{kT_\mathrm{b}}^{(k+1)T_\mathrm{b}} x_i(t)p_{iq}(t)\,dt \tag{42}$$

The collection of $m \times Q$ such outputs constitutes the sufficient statistics for space-time processing. The techniques mentioned in the earlier sections for time-only processing can be adapted with care to space-time processing. ST processing will result in greater immunity to cochannel interference and therefore can be used to increase capacity.

SUMMARY

The last decade has witnessed a large increase in the usage of spread spectrum systems. Even though SS techniques were initially used for military applications, commercial applications are now growing far more rapidly. New SS schemes that exploit more complex modulation and multiple access techniques offer improved capacity and performance. Use of antenna arrays is yet another multiplier for SS network capacity. We can expect to see a growing importance of improved SS systems in the future. In fact, third generation wireless networks are likely to adopt wideband CDMA in preference to TDMA, which was popular in second generation systems.

BIBLIOGRAPHY

C. E. Cook et al., *Spread Spectrum Communications,* New York: IEEE Press, 1983.

R. C. Dixon, *Spread Spectrum Systems,* 3rd ed, New York: Wiley, 1994.

R. C. Dixon, *Spread Spectrum Techniques,* New York: Wiley, 1976.

A. H. M. Ross and K. S. Gilhousen, CDMA technology and the IS-95 North American Standard, in Jerry D. Gibson (ed.), *The Mobile Communications Handbook,* Boca Raton, FL: CRC Press, 1996.

L. B. Milstein and M. K. Simon, Spread spectrum communications, in J. D. Gibson (ed.), *The Communications Handbook,* Boca Raton, FL: CRC Press, 1997.

M. K. Simon, J. K. Omura, R. A. Scholtz, and B. K. Levitt, *Spread Spectrum Communications,* Rockville, MD: Computer Science Press, 1985.

A. J. Paulraj and C. B. Papadias, Space-time processing for wireless communications. *IEEE Signal Processing Magazine,* **14** (6): 49–83, Nov. 1997.

S. Verdú, Demodulation in the presence of multiuser interference: Progress and misconceptions, in F. Perez-Gonzales (ed.), *Intelligent Signal Processing,* Birkhauser, 1997.

A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communication,* Reading, MA: Addison-Wesley, 1995.

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See also Information theory of spread-spectrum communication; Power line communication.

SPREAD SPECTRUM, MODULATION. See Chirp modulation.