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SPREAD SPECTRUM COMMUNICATIONS

A historical and technical overview

As we all know, the RF spectrum is a finite and exceedingly valuable resource. The practical limits of the existing spectrum, together with the exponential need for new communications, has created an increasing demand for what little free or underutilized space remains. In general, the policy for traditional commercial services has been to place limits on RF power and bandwidth to minimize interference and maximize the number of channels that can be assigned to a given band. For example, although the FCC continues to license a few "clear channel" AM broadcast stations, most frequencies are assigned to multiple stations. The nature of the service, local and regional geography, as well as signal propagation qualities at the operating frequency define the minimum physical spacing between stations sharing the same frequency. The interstation distance ranges from a few hundreds of meters for low-power cellular radio nodes to hundreds or thousands of kilometers for high-powered commercial broadcast stations.

Although congestion may not be obvious to the casual listener on the AM or FM broadcast bands, the current explosion in cellular telephone systems and wireless computer networks is a driving force behind the quest for more communications channels.[1] These and other new technologies that rely on relatively low-power, high-density environments operating at UHF and above suggest that new ways of managing signal bandwidth are critical to maximizing spectrum utilization.

In general, the type of modulation and information filtering used determine the RF signal bandwidth requirements. For example, where a properly filtered voice modulated AM signal requires a bandwidth of about twice that of the modulating frequency, SSB and other techniques can be used to reduce the RF bandwidth requirements significantly. On the amateur bands, the use of SSB instead of AM has resulted in tremendous spectrum savings, as well as increased efficiency of communications. However, despite the savings of spectrum by SSB, the bands remain crowded. The introduction of the newer spread spectrum techniques can further increase efficiency of spectrum use.

Paradoxically, techniques such as spread spectrum are designed to increase spectrum utilization by generating an extremely wide signal relative to the information to be transmitted. In conventional RF communications, the amplitude, frequency, or phase of an RF carrier is varied in accordance with the information to be transmitted. With the exception of those that use FM with a high modulation index, the bandwidth requirements of these systems are simply a function of the information bandwidth.

In contrast to conventional narrowband communications schemes, spread spectrum systems take voice or other relatively narrow-bandwidth information and distribute it over a band that may be several MHz wide. This distribution or "spreading" is accomplished by modulating the information to be sent with a wideband signal. Unlike conventional signals, spread spectrum signals occupy a bandwidth at least an order of magnitude greater than the information bandwidth.[2] The other distinguishing feature of spread spectrum communications is that a function other than the information to be sent (i.e., a wideband spreading signal) determines the RF bandwidth.[3]

Spread spectrum techniques can be used to create additional information channels that can coexist in a band filled with conventional narrowband communications. In addition, spread spectrum systems have characteristics uniquely suited for applications requiring privacy, signal covertness, interference rejection, ranging measurements, selective addressing, and multiple access.

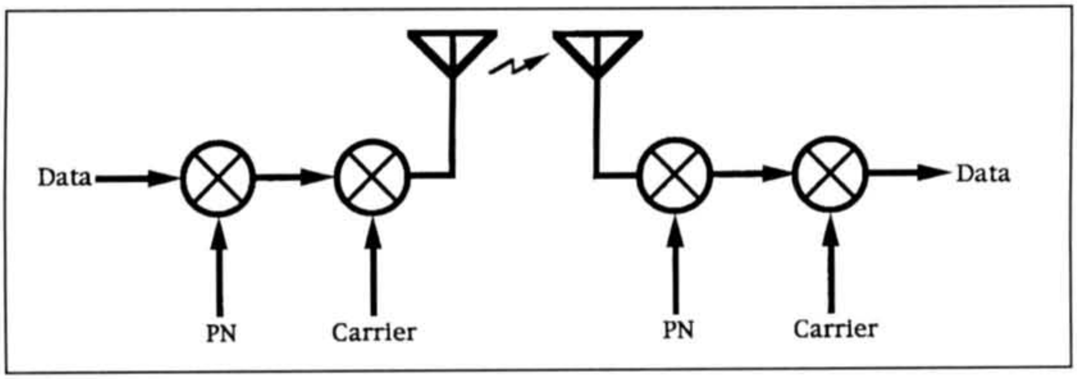

Figure 1. Overview of a direct sequence communications system. Data: digital voice or other information; Carrier: RF source; PN: pseudo-noise source.

In the amateur bands, present law permits the use of spread spectrum only above 420 MHz. Because the assigned bands are fairly narrow, a spreading system could be developed to use the entire band.

The development of spread spectrum

Despite the recent flurry of interest in spread spectrum communications for mobile, computer, and personal communications, the technology is actually well over four decades old. The first commercial spread spectrum communications system in this country, developed around 1949, linked New Jersey and California.[4] Within a few years, the Army Signal Corps commissioned the development of a long-range, jam-proof HF radio teletype link. The Navy, Air Force, and National Security Agency soon followed the Army's lead by developing spread spectrum communications systems of their own. Given the strategic nature of the technology, spread spectrum work was classified, and, until the past few years, research and development efforts in the field were withheld from the public.

The features of spread spectrum communications that stirred original military interest included resistance to jamming, low detectability, and low interference to other systems operating on the same band. Unlike the conventional techniques used to ensure message security, such as cryptography, spread spectrum communications can not only conceal the message, but the sender's identity and location . This ability to create a high level of uncertainty at the "unfriendly" receiver concerning the signal frequency, phase, and transmission time can be attributed in part to the signal spectrum, which can be made to appear as ordinary broad-band noise.

Despite the intense military interest in spread spectrum technology, the early systems were for the most part impractical and expensive prototypes. Like the first computers, the initial

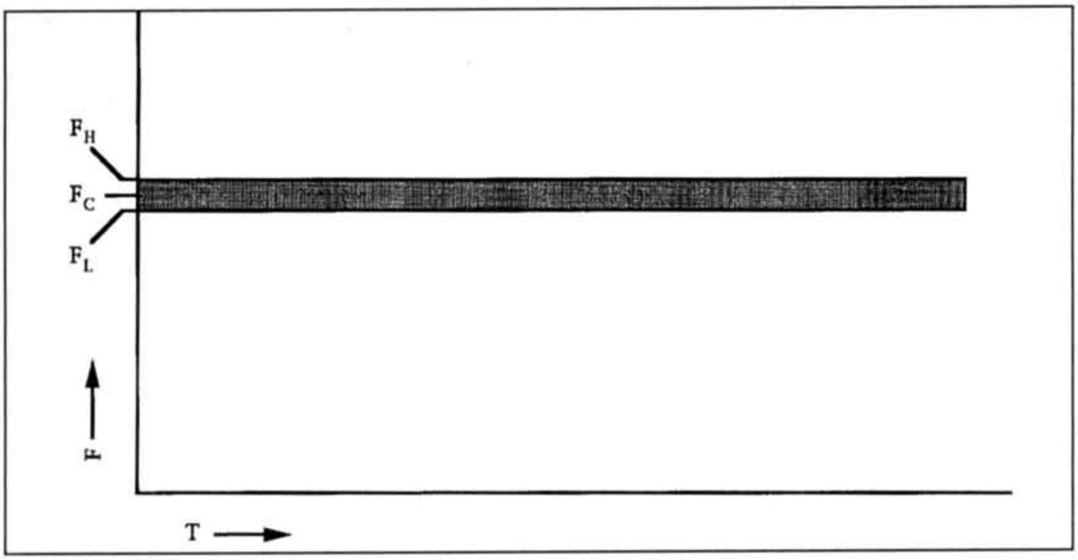

Figure 2. Spectral occupancy versus time characteristics of a conventional amplitude modulated (AM) signal. Bandwidth ($F_H - F_L$) is a function of the modulation frequency, F_C: signal center frequency; F_H: signal high frequency limit; F_L: signal low frequency limit.

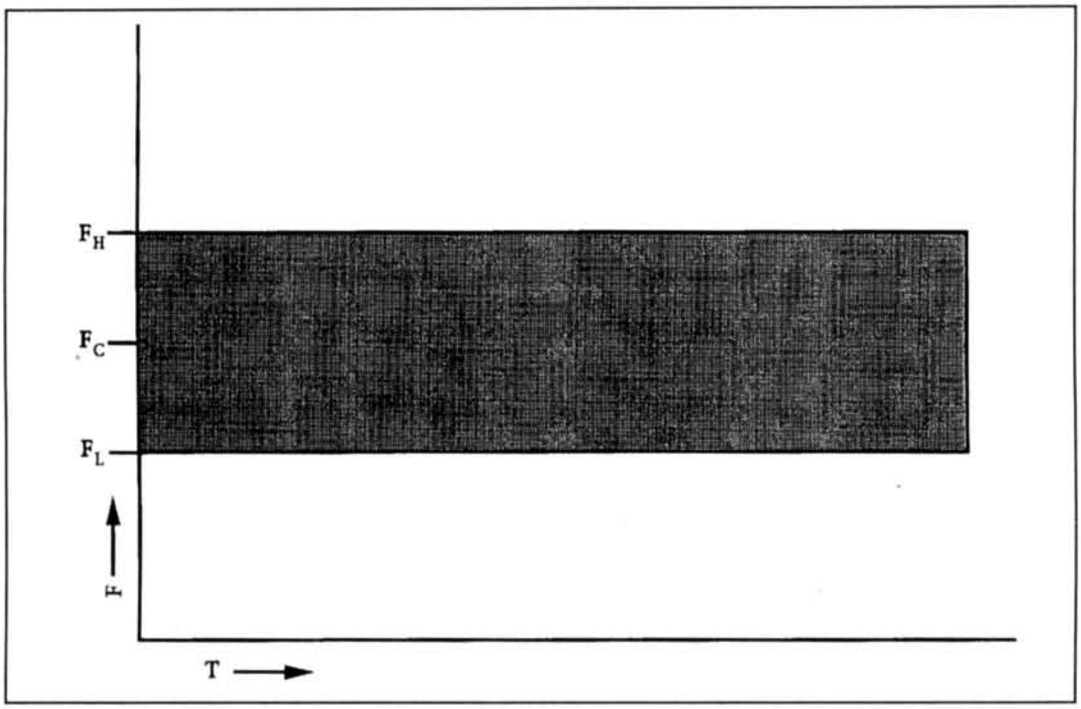

Figure 3. Spectral occupancy versus time characteristics of a direct sequence (DS) signal. Bandwidth (F_H - F_L) is a function of the spreading signal, typically a pseudo-noise source. Because of spreading, the signal bandwidth is much larger than the information bandwidth. Compare with Figure 2.

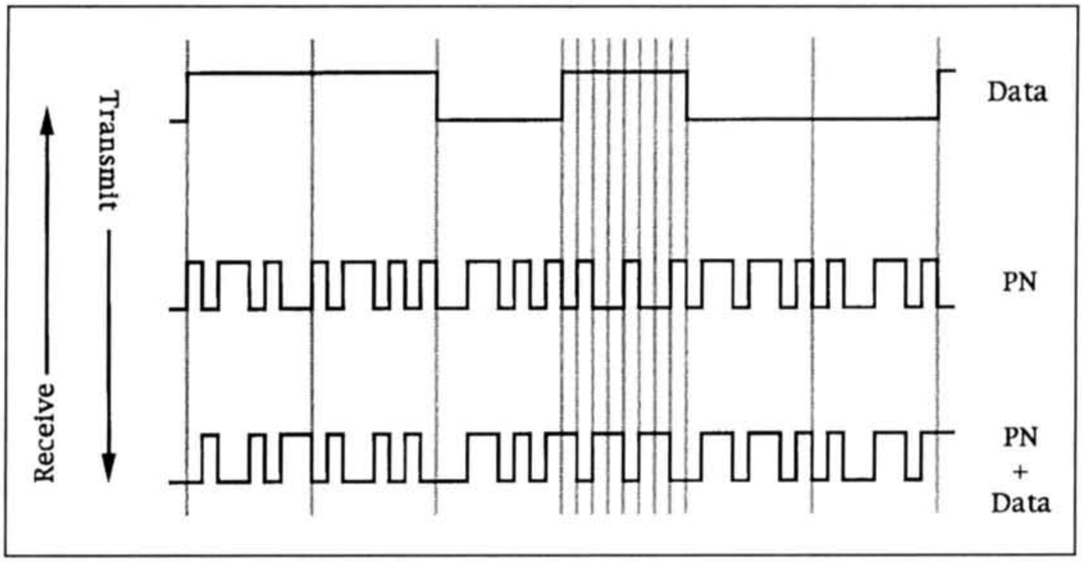

Figure 4. Generating a direct sequence signal involves the combination of a pseudo-noise source (PN) with the data to be transmitted (data). In this example, combination involves the exclusive-OR sum of the data and the PN source. On receive, a PN sequence identical to that used in transmit is XORed with the spreading signal to extract the data. In this example, the PN source is clocked at eight times the data rate; i.e., there are eight chips per data bit.

spread spectrum systems relied on rooms full of power-hungry and heat-producing vacuum tubes. Practical spread spectrum became a reality only with the advent of the transistor and integrated circuits. The lower cost afforded by inexpensive digital circuitry, together with the lifting of security restrictions, has made spread spectrum a viable alternative for many commercial applications.

Spread spectrum applications

Modern military and commercial applications of spread spectrum range from satellite

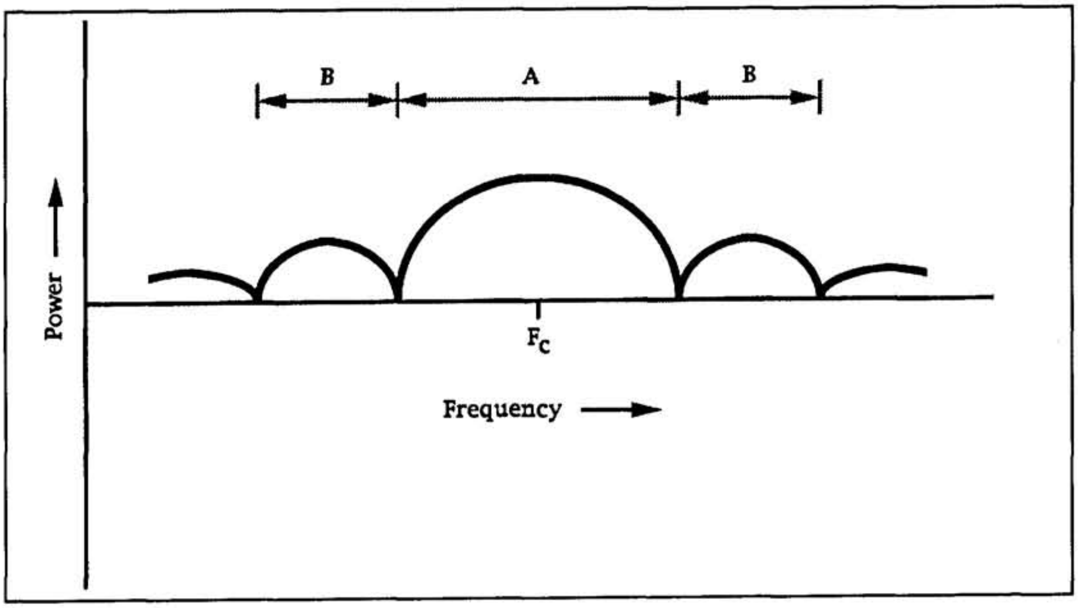

Figure 5. The power spectrum for a binary phase shift keying (BPSK) DS signal in which the carrier has been suppressed. The envelope of the distribution is primarily a function of the chip rate. The main lobe (A) is 1/2 of the chip rate wide, centered around the carrier frequency, F_C. Approximately 90 percent of the signal power lies in the main lobe; the side lobes (B) contain only about 10 percent of the total signal power.

and terrestrial communications to navigation and radar. Spread spectrum technology continues to play a central role in military communications because spread spectrum signals can be made to be resistant to jamming and interference, are difficult to detect and intercept, can provide message privacy, and can support multiple, selectively addressed users.

Spread spectrum ranging and radar systems use the spreading signal to determine signal transmit and receive times precisely. For example, the Global Positioning System (GPS) uses spread spectrum technology to allow personnel with military GPS receivers to determine their location within about 1 meter (commercial receivers are handicapped to a resolution of about 100 meters). The GPS system is based on 21 satellites, each transmitting on the same frequency, but using a different spreading signal.[5]

One of the most appealing characteristics of spread spectrum communications to spectrum-hungry commercial services is that it allows multiple signals to occupy the same RF bandwidth simultaneously with minimal mutual interference. Adding spread spectrum signals to a communications band already full of conventional communications signals has the effect of raising the overall background noise level. Each additional spread spectrum signal adds to the noise floor, causing a gradual decrease in the communications efficiency for all users of the band. In comparison, adding conventional communications users in such a situation would cause severe interference to other conventional stations. Another reason that spread spectrum allows multiple stations to coexist in the same band is that spread spectrum receivers are relatively immune to both intentional and accidental interference. All signals not spread by the expected spreading signal, whether narrowband or spread, are suppressed.

Perhaps the greatest commercial interest in the use of spread spectrum technology is in the areas of wireless computing and mobile cellular communications. Spread spectrum techniques are being used to provide wireless local area network (LAN) installations in offices and factories. In addition to minimizing interference from other electronic devices, spread spectrum provides a number of benefits over competing technologies. For example, most computer network protocols allow only one computer to transmit over the network at one time. In contrast, spread spectrum techniques can be used to support network access without the delay or collisions, even under heavily loaded conditions.

The advantages of using spread spectrum communications for cellular telephone systems include relative insensitivity to fading, freedom from interference, and spectral efficiency. In one spread spectrum cellular radio system design, the spectrum is divided into only two channels—one for the stationary base and one for mobile transmissions. Each station is distinguished from others transmitting on the same channel by a unique spreading signal. In this code division multiple access (CDMA) scheme, each signal is created with a unique spreading signal, and only receivers using the same spreading signal can clearly decode and receive the information.[6] Interference is minimized by assigning encoding signals that differ greatly from one station to the next. In addition, the wideband nature of the spread spectrum signal provides some protection against fading, relative to fading that might occur if a fixed-frequency, narrowband signal were used.

Types of spread spectrum communications

Spread spectrum communications systems vary considerably in design and function, depending on the application and operational constraints. The most common spread spectrum designs include direct sequence (DS), frequency hopping (FH), time hopping (TH), pulsed FM, and a variety of hybrid techniques. These systems are described in more detail in the paragraphs that follow.

Direct sequence. Figure 1 provides a simplified view of the most common spread spectrum system design, direct sequence (DS)—sometimes referred to as pseudo-noise (PN) spread spectrum. On the transmitter side, the data and spreading signal or PN code (e.g., 0100010110101011 1...) are mixed, and the resulting wideband signal is used to modulate an RF carrier for transmission. The modulation may be AM, FM, or more commonly, some form of phase shift keying. Although not shown here, it is also common to modulate the carrier source with the data and then modulate the resulting signal with a spreading signal before transmission. In either case, the mixing is usually performed digitally.

Since the information bandwidth is relatively narrow compared to that of the spreading signal, the bandwidth of the transmitted signal (assuming no RF filtering) is essentially determined by the bandwidth of the code function.

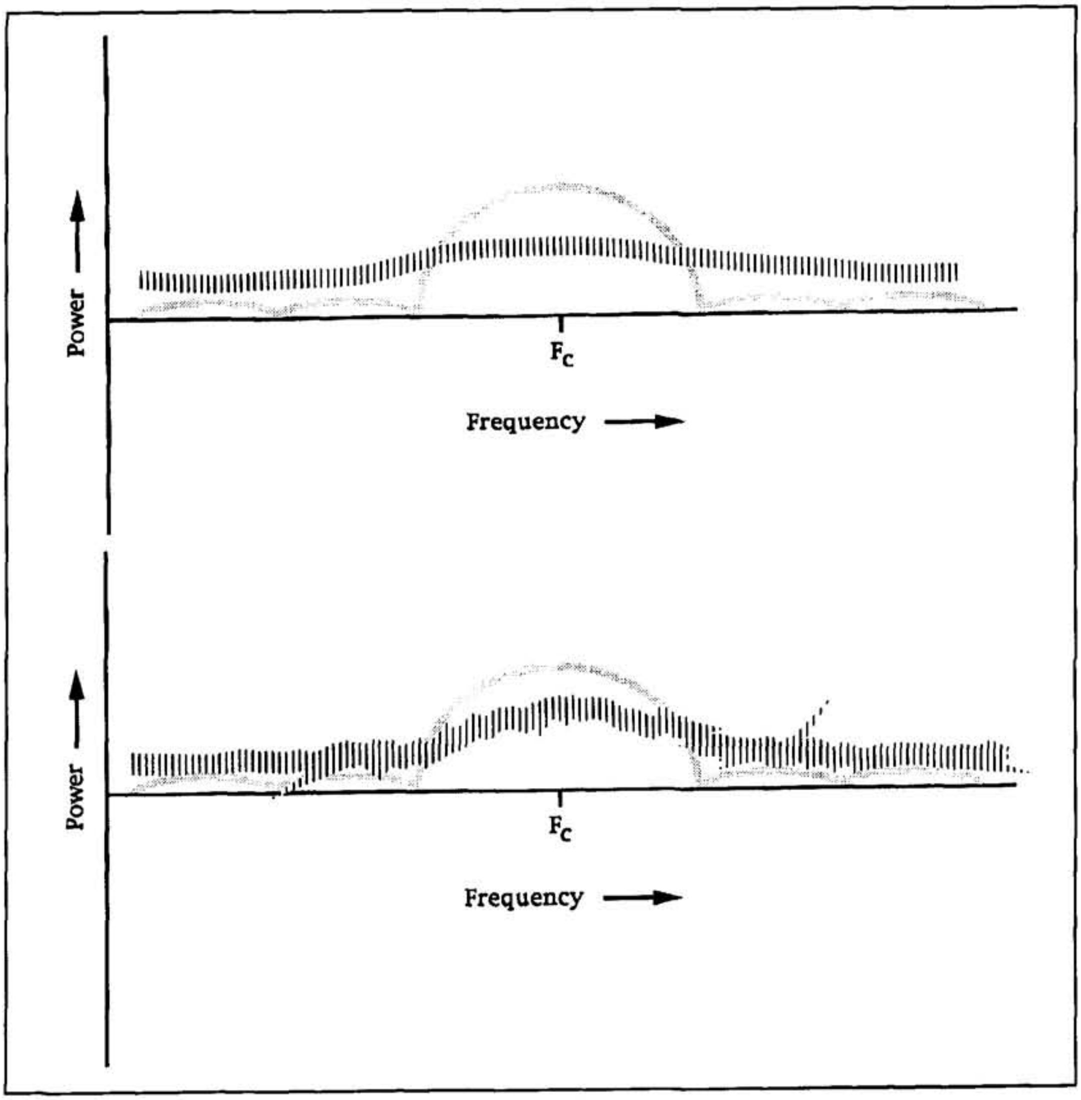

Figure 6. A typical received power spectrum for a DS signal (foreground), superimposed on the power spectrum of a DS transmitter in which the side lobes have been clipped (A). To a conventional receiver, the wideband signal appears as noise (B). F_C: center frequency.

Because of the spreading signal, the transmitted signal's frequency spectrum appears as a band of noise centered around the carrier frequency (compare **Figures 2** and **3**). Obviously, the transmitter hardware must be capable of wideband operation.

On the receiver side, the incoming DS signal is *despread* by generating a local replica of the PN code in the receiver and then synchronizing this local PN signal to the one that is superimposed on the incoming waveform. Multiplication or remodulation of the incoming signal by the local PN signal collapses the spread signal into a data-modulated carrier by removing the effects of the spreading sequence (see **Figure 4**).

Correlation, a measure of signal similarity, is used to identify a signal that has been spread with a particular pseudo-noise sequence. Correlation is typically performed with a mixer followed by a low-pass filter. The filter output provides an average of the mixer output; a high output (1) indicates that the mixer signals differ little from each other, while a low output (0) indicates no matches. In addition to averaging correlation information, the low-pass filter also has the function of reducing noise while passing the narrowband information. After despreading, the narrowband signal can be filtered and handled by a conventional demodulator. It is the despreading process that is responsible for spread spectrum's immunity from noise and interference.

As shown in **Figure 4**, the smallest duration within the DS signal is the *chip*. Since the chip duration is much shorter than the data bit duration, the spectral components cover a much wider frequency spectrum than the data bits, so the data is spread over a wide spectrum at a very low spectral density. Typical chip frequencies are between 1 and 10 MHz, with carriers in the low GHz region.

Figure 5 shows the power spectrum for a binary phase shift keying (BPSK) DS signal in which the carrier has been suppressed. The envelope of the distribution of a DS spread spectrum signal can be approximated by:[5]

$$E(f) = t_c/2 \text{ x } \{\sin(\pi f t_c/\pi f t_c\}^2$$

where $\mathbf{t_c}$ is the chip duration and **f** is frequency. The chip rate defines the spread of the signal, in addition to the size of the main lobe and the location of the nulls. The main lobe is (chip rate)/2 wide, centered around the carrier frequency, and nulls occur at multiples of 1/(chip rate).

As shown in **Figure 5**, 90 percent of the signal power lies in the main lobe. The side lobes, which contain 10 percent of the total signal power, are commonly clipped to reduce interference. Stripping the side lobes has the effect restricts the rise and fall times of the modulating code, because the sidelobes contain much of the harmonic power of modulation. **Figure 6A** shows a typical received power spectrum for a DS signal, superimposed on the power spectrum of a DS transmitter in which the side lobes have been clipped. **Figure 6B** shows the signal as seen by a conventional receiver.

Frequency hopping. Frequency hopping (FH) spread spectrum is perhaps the easiest to understand conceptually (see **Figure 7**). In FH, the carrier remains at a given frequency for a duration called the dwell time and then hops to a new frequency somewhere in the spreading

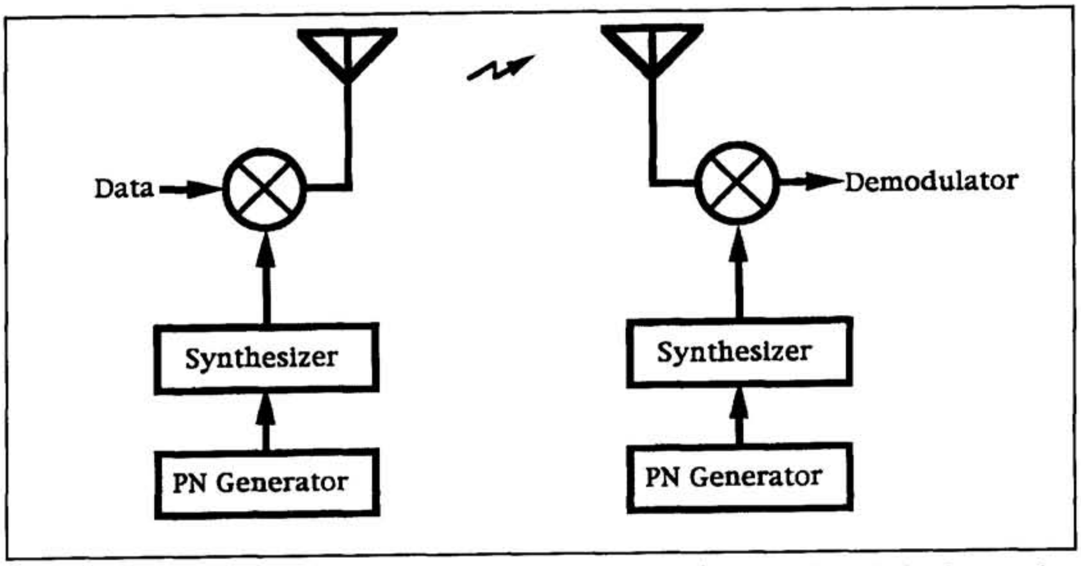

Figure 7. Overview of a frequency hopped (FH) communications system. Transmitter (left) synthesizer frequency is controlled by a pseudo-noise signal. On the receiver end, the FH signal is captured by moving the receiver synthesizer frequency in step with a pseudo-noise signal that matches the spreading signal used at the transmitter. After despreading, the resulting narrowband signal can be processed by a conventional demodulator.

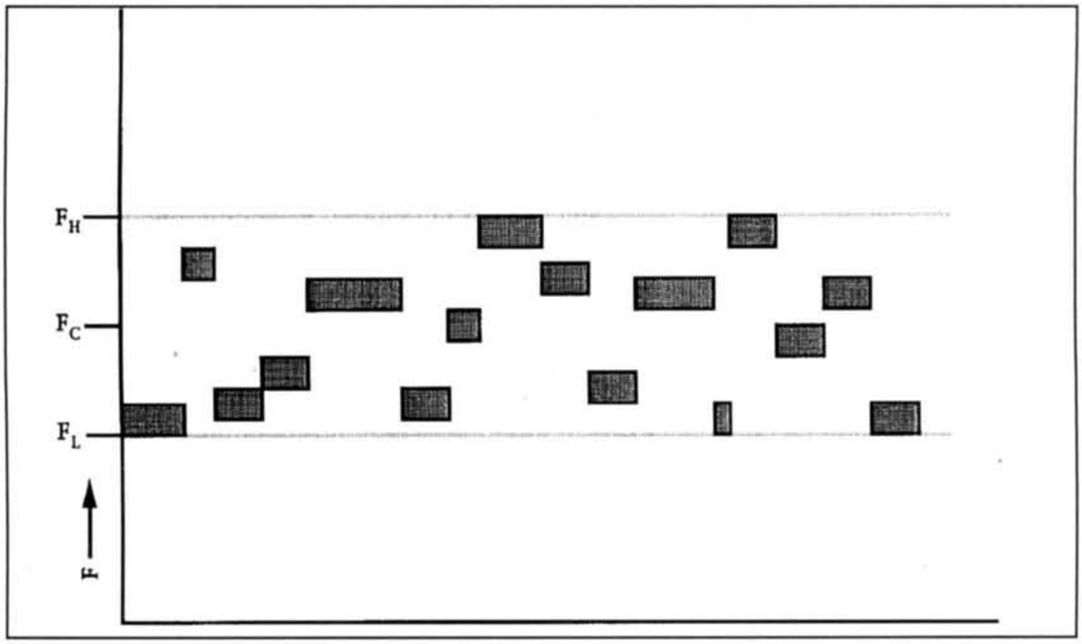

Figure 8. Spectral occupancy versus time characteristics of a frequency hopped (FH) signal. In some FH schemes, each data bit is pseudo-randomly assigned a subchannel whose instantaneous bandwidth is relatively narrow compared to the long-term, average bandwidth (F_H - F_L) of the system. Total bandwidth is determined by the range of subchannels available and the data rate.

bandwidth (see **Figure 8**). Frequency selection is based on a pseudo-random selection from a list of available channels. In other words, the spreading sequence represents the channels to which the frequency hopper will travel. Ideally, each channel should be occupied with equal probability, and the probability of hopping from any channel to any other channel should be equal. Dwell times are generally on the order of a few milliseconds or less in order to avoid interference with conventional communications systems. In addition, the list of potential hopping channels can be modified to reflect frequencies known to be in use.

In order to receive an FH signal, the FH spread spectrum receiver must move from channel to channel according to the PN sequence used at the transmitter. In both the transmitter and receiver, the maximum rate at which frequency hopping can occur is dependent on the technology used to determine frequency. For example, one common approach is to use frequency synthesizers based on phase locked loops (PLLs). However, PLL settling time, the time required for the PLL to settle on a given frequency, limits the hopping rate. To overcome this limitation, some designs make use of two or more PLLs that are cycled into use so the PLL used has had ample time to settle while others are in use. When hopping rates greater than a few hundred hertz are required, direct digital synthesis (DDS) is a viable alternative. DDS, which makes use of values from sinewave lookup tables used to drive D-to-A converters, is capable of providing hopping rates in excess of several kHz.

The bandwidth requirements for an FH system depend on the relative durations of the data and hopping rates. Slow FH designs use several data bits per hop, and hop rates are generally less than 100 hops per second. Fast FH, in contrast, uses several hops per data bit, and the hop rate is generally greater than 100 hops per second. The bandwidth of slow FH spread spectrum signals is essentially equal to that of the data signal, while the bandwidth of fast FH is equal to the reciprocal of the hopping duration.

The optimum hopping rate for a FH system is determined by the type of information to be sent, the information transfer rate, the amount of redundancy used, and the distance to the nearest potential source of interference.[3] For example, assume that 1000 frequencies are available. Unless some form of redundancy were used, an interfering signal on one of the frequencies chosen would cause one error in 1000 or an unacceptable error rate of 1×10^{-3}. Similarly, two interfering signals within the band of hopped frequencies would result in an error rate of 2×10^{-3}. The expected error rate can therefore be expressed as:

$$\text{error rate} = I/N$$

where I is the number of interferers with power sufficient to jam a channel used by the FH system and N is the total number of channels available.

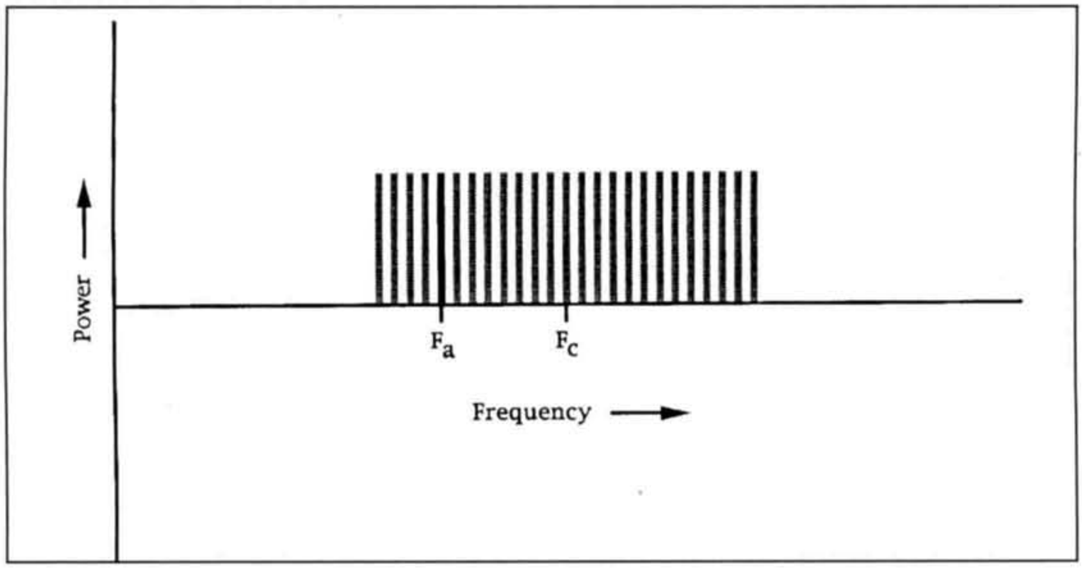

Figure 9. The long-term power spectrum for a FH spread spectrum signal. The instantaneous spectrum is much narrower, because it consists of a carrier that moves pseudo-randomly among the available channels. F_A: currently active channel; F_C: average signal center frequency.

Error rates can be reduced by using some form of redundant transmission. For example, three or more frequencies can be used for each bit of information; i.e., multiple chips per data bit. If the receiver's bit decision is made on the basis of two out of three chips being correct (e.g., at three frequencies per bit, and a received pattern of "101," the bit would be termed a "1"), a single channel interferer would cause no more than $p^2(3 + p)$ errors,[3] where p = the error probability for a single trial. For a 1000 channel FH system (p = 1000), the expected error rate would be:

$$\begin{aligned} \text{error rate} &= p^2(3 + p) \\ &= (1/1000)^2 \times (3 + 1/1000) \\ &= 3 \times 10^{-6} \end{aligned}$$

The error rate has been reduced by a factor of 3000 by increasing the hop rate by a factor of three. The limitations of lowering the bit error rate by sending more chips per bit lie in the capabilities of the frequency synthesizer and the RF bandwidth available. Because the bandwidth required increases in direct proportion to the hopping rate, a tradeoff must generally be made between sending more chips per bit and reducing the number of frequencies available. Alternatively, the bandwidth requirement may be reduced by adjusting the transmit frequency spacing so significant overlap occurs between channels. The overlap reduces the bandwidth requirement for the transmitted spread spectrum signal.

The average or long-term power spectrum for

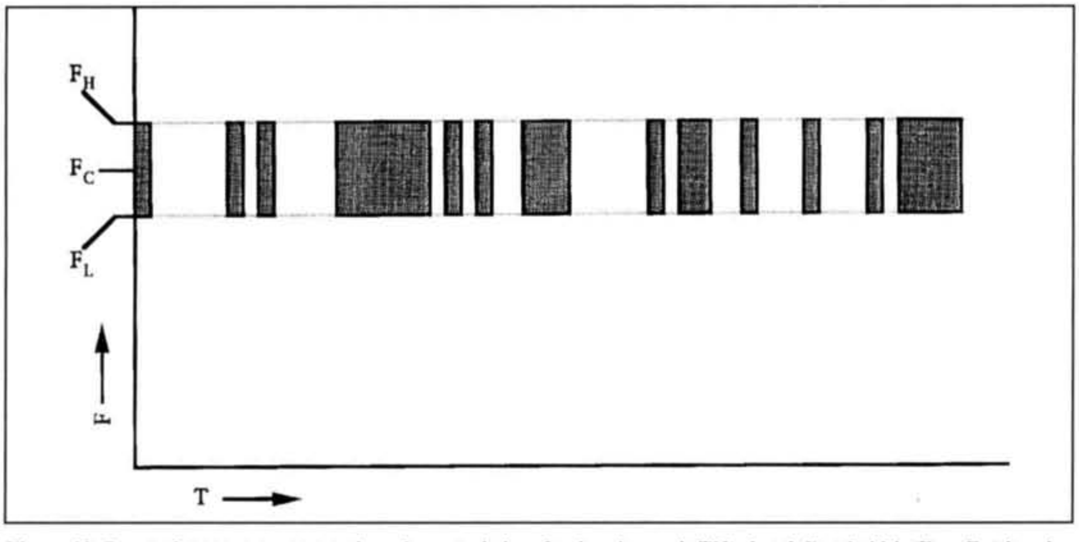

Figure 10. Spectral occupancy versus time characteristics of a time-hopped (TH) signal. Bandwidth (F_H - F_L) is primarily a function of the pulse repetition rate, which is varied in a pseudo-random manner.

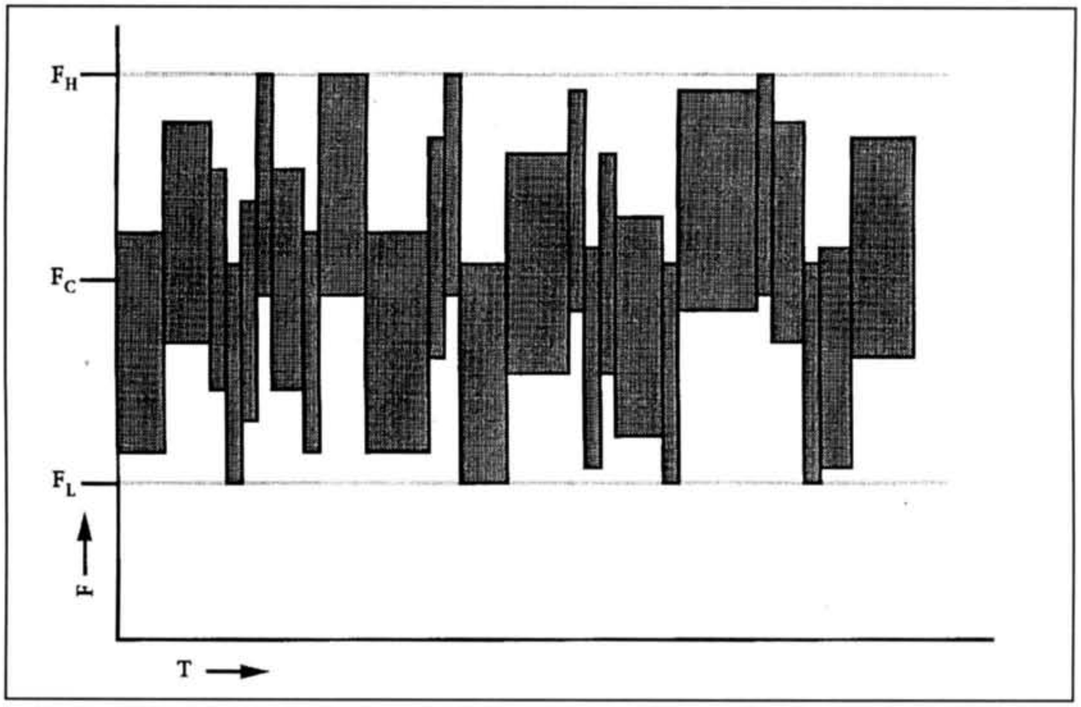

Figure 11. Spectral occupancy versus time characteristics of a Frequency Hopped/Direct Sequence (FH/DS) signal. This hybrid spread spectrum technique is basically a DS system in which the center frequency is periodically hopped. Note that although in this example the DS channels overlap somewhat, in many cases there is no overlap. Compare with Figures 8 and 10.

an FH spread spectrum signal is shown in **Figure 9**. The instantaneous spectrum is much narrower because it consists of a carrier that moves pseudo-randomly among the available channels. One of the features of FH is that channels within the spread spectrum bandwidth known to be allocated for other purposes can be avoided by removing the channel from the lookup table of possible FH channels. The input and output frequencies of conventional repeaters can be easily avoided in this manner, reducing false repeater keying and potential repeater interference.

Time hopping. In time hopping (TH) spread spectrum systems, the carrier is keyed on and off by a PN generator (see **Figure 10**). As in

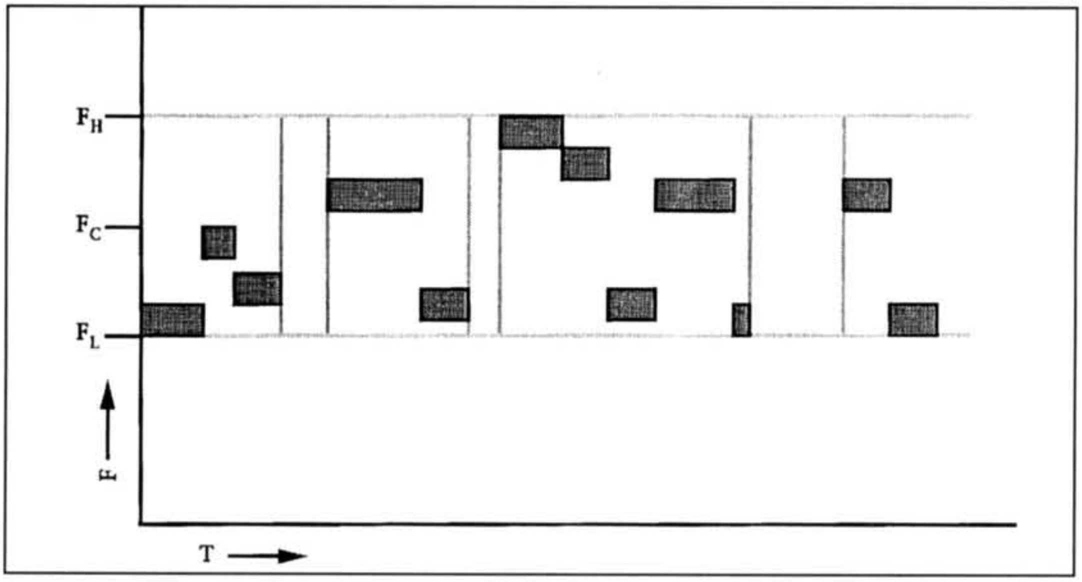

Figure 12. Spectral occupancy versus time characteristics of a Frequency Hopped/Time Hopped (FH/TH) signal. As in simple FH, each data bit is pseudo-randomly assigned a subchannel. However, as in TH, there are randomly assigned periods when no signal is transmitted. The long-term, average bandwidth (F_H - F_L) of the signal is a function of the range of subchannels available, the repetition rate, and the data rate. Compare with Figures 8 and 10.

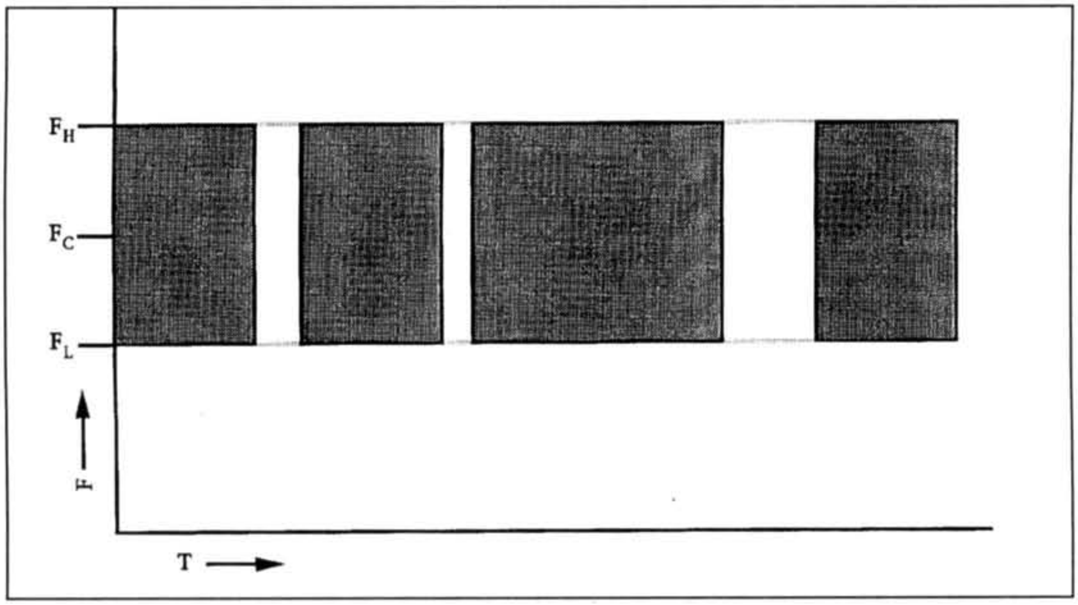

Figure 13. Spectral occupancy versus time characteristics of a Time Hopped/Direct Sequence (TH/DS) signal. This hybrid form of spread spectrum is basically a DS system that is switch on and off at pseudo-random intervals.

conventional CW transmissions, the bandwidth of a TH signal is a function of the keying rate. TH systems can vary considerably in duty cycle. For example, one extreme might be a burst transmission lasting a fraction of a second that is transmitted only once a day. Such a signal would be very difficult to detect, intercept, and exploit.

Hybrid techniques. Hybrid spread spectrum techniques, created by combining two or more forms of spread spectrum into a single system, can often outperform systems based on single techniques or provide the same capabilities with less expense or complexity.

Frequency Hopping/Direct Sequence. FH/DS spread spectrum is in essence a DS system whose center frequency hops periodically (see **Figure 11**). This hybrid technique is used for multiplexing, for multiple and discrete address, and to extend spectrum spreading. FH/DS is often the most attractive means of achieving extended spectrum spreading, because PN code generator limitations place practical limits on DS spreading signal bandwidths and FH frequency hopping rates. For example, to achieve a 1 GHz wide spectrum, a DS system would require a 500 Mbps PN generator, and an FH system would require a 1 GHz bandwidth frequency synthesizer. A cheaper and more realistic alternative to realizing the same 1 GHz bandwidth would be to use a 100 Mbps PN generator and a frequency synthesizer capable of generating 20 frequencies spaced 50 MHz apart.

Time Hopping/Frequency Hopping. FH characteristics are often added to TH systems in antijamming situations (see **Figure 12**). While TH spread spectrum signals can be blocked easily by a carrier at a single frequency, a combined TH/FH system is impervious to blocking transmissions from a single frequency source.

Time Hopping/Direct Sequence. TH/DS spread spectrum is basically a DS system that is switched on and off (see **Figure 13**). Switching occurs at pseudo-random intervals, as determined by the PN generator used for spreading or despreading. The time division afforded by the time hopping permits more channel users, and therefore more access.

Spread spectrum technology

As described above, spread spectrum communications systems can vary greatly in design and function. Even so, there are several key concepts relevant to all spread spectrum communications systems, including the role of the pseudo-noise code sequence, synchronization, despreading, and the concept of process gain.

The pseudo-noise (PN) code sequence

Key to the operation of all spread spectrum systems is the generation of a wideband pseudo-noise (PN) code sequence for spreading and despreading. The pseudo-random "noise" sequence is designed to appear to be random (noise), but in practice only approaches a random distribution.[7,8,9,10]

The code sequence is referred to as pseudorandom because it is deterministic; given any part of the sequence, it is possible to generate the remaining sequence. With a truly random generator, it would be impossible to determine future sequences. For example, consider the repeating sequence {...7 2 4 1 5 7 2 4 1 5 7 2 4 1 5...}. With only five elements in the sequence, the deterministic nature of the sequence is obvious; i.e., given the value 4, we know that 1, 5, 7, and 2 follow before the sequence repeats. A practical PN code generator may create sequences with hundreds or thousands of elements, thereby obscuring the deterministic nature of the sequence. For example, the civilian spreading code used in the GPS system, which allows position to be determined to within about 100 meters, is 1023 bits in length, repeated every 1 ms. By comparison, the secure military code, which supports an accuracy of 1 meter, is a 267 day long code sequence running at 10.23 Mbps.[5]

PN sequences are often generated with linear-feedback shift registers, each of which consist of several one-bit memory registers that shift their contents with each clock pulse. The output of each shift register is deterministic; initializing the shift register with a given sequence will start the entire cycle from that point. The maximum length of the repeating sequence is a function of the number of shift register stages (N), as defined by 2^N-1.[11] For example, a shift register with 12 stages can provide a sequence with up to $2^{12}-1$ or 4095 elements before the sequence repeats.

The type of spread spectrum communications used determines the nature and use of the PN generator. For example, the PN sequence used in DS systems is most commonly a binary pseudo-random sequence (e.g., 0100110101011...) with a variable repetition rate that is usually some submultiple of the clock frequency. In other types of spread spectrum systems, the sequence may take the form of a numerical sequence such as {...2, 45, 1, 255, 87, 109, 14...}, where each value is keyed to a particular channel, time delay, or other signal parameter.

Despreading

In the initial work on spread spectrum communications, the purpose of the PN modulation was to create a signal that, to an "unfriendly" receiver, appeared to have great uncertainty and complexity, while simultaneously appearing perfectly deterministic and predictable to a "friendly" receiver. The goal was to dilute the signal energy to the point where it fell below the noise floor of a conventional receiver, and was undetectable by this type of receiver. As illustrated in **Figure 4**, this duality is possible because of the PN modulation; only a receiver with a copy of the spreading PN sequence can *despread* a spread signal into a data-modulated carrier.

Despreading is the process of correlating the received spread spectrum signal with a local reference PN signal. When the received signal and local PN generator are properly synchronized (a nontrivial task), the information signal collapses to its original bandwidth before spreading. The resulting narrowband information signal can be handled by conventional filtering and demodulation.

To receivers without access to the original spreading code, whether conventional or spread spectrum, spread spectrum signals appear as noise. Received signals that bear little resemblance to the receiver PN code sequence are spread by the PN spreading signal to noise. Similarly, the greater the degree of similarity between the spreading PN code and the sequence used to spread a potentially interfering signal, the less able the spread spectrum receiver is to reject the interference. Ideally, the PN spreading sequence should have a low correlation with shifted versions of itself to avoid interference. Reception of shifted sequences can be a problem in cases of multipath reception or when multiple spread spectrum units operate with the same PN sequence, but with different starting points within the sequence. There is a considerable amount of literature on optimum PN sequences for spread spectrum.[11]

Synchronization

A prerequisite to despreading, and the major operational and design problem in spread spectrum work, is the synchronization of the received signal and the local pseudo-noise sequences. The simplest approach to synchronization is to examine all possible phase relationships between the received PN sequence and the locally generated PN sequence until a match is found. This can be achieved by allowing the two signals to slip past each other by offsetting their clock frequencies, while despreading the two signals. Once a correlation is found, a tracking loop can be used to maintain synchronization.

Synchronization, which usually occurs after the despreading operation,[12] is often viewed as a two-part process, rough and fine synchronization.[13] Rough synchronization or *PN acquisition*, the process of bringing the received and local PN signals into rough alignment, is generally based on a method that provides some measure of correlation—for example, the received and local PN signals are multiplied. Fine synchronization or *PN tracking* attempts to maintain bit or channel dwell timing through some type of tacking loop.

Two methods used to achieve rough synchronization are *epoch* and *phase* synchronization.

In the process of epoch synchronization, the transmitter periodically sends a special synchronization sequence that can be easily detected by the receiver—typically by a digital matched filter. This filter consists of a shift register that clocks the received signal one bit at a time and compares it against the unique sequence. Phase synchronization attempts to identify which of the 2^N-1 (the maximum length of the repeating sequence) possible phases the PN sequence could be in. At least N bits must be received without error for phase to be determined;[13] more than N bits must be received with noisy signals or in conditions with a poor signal-to-noise ratio. Obviously, in cases of both large N and poor signal conditions, PN acquisition time can be significant. Synchronization acquisition time can often be reduced by using timing references available at both the transmitter and receiver site, such as local AM broadcast carriers, to start the PN generators.[2,14]

Fine synchronization, which focuses on the bit or channel level, generally uses a feedback loop to minimize the timing error between the transmitter and receiver PN sequence by adjusting the receiver spreading code clock. Dithering is one commonly used fine synchronization technique. With this technique, the spreading code clock is continually rocked back and forth, and the point at which best synchronization is achieved is used to synchronize the receiver clock. A feature of dithering is that it can track a spreading code whose timing is changing due to changes in propagation or relative motion between the transmitter and receiver.

Depending on the nature of the application, it may be possible to minimize the problem of synchronization by transmitting a preamble before a spread spectrum signal. A preamble signal, which can alert spread spectrum receivers to initialize their synchronization procedure, can take the form of a tone appearing on a prearranged frequency or frequencies. For example, the falling edge of a tone can signal the beginning of PN code generation. Alternatively, a digital sequence preamble can be used to identify the transmitter carrier center frequency, synchronize the receiver local clock, and enable rough synchronization. For instance, a sequence of all zeros can be used to identify the carrier center frequency, and a series of alternating ones and zeros can be used to establish timing information. Similarly, the spreading code can be identified through the use of a synch trigger within the preamble (that is, epoch synchronization).

Process gain

An important concept in spread spectrum communications is that of process gain. Process gain is the difference between output and input signal-to-noise ratios; the greater the process gain, the better. For example, a system with an input S/N ratio of 20 dB and an output S/N ratio of 26 dB has a process gain of 6 dB. The process gain afforded by FH and DS spread spectrum systems operating in conditions of negligible interchannel interference can be approximated by the following relationship:[3]

$$\text{process gain} = \text{BW/DR}$$

where BW is the RF bandwidth of the transmitted spread spectrum signal and DR is the data rate in the information channel. The bandwidth (BW) value for a DS system is approximately equal to twice the system code clock rate. The bandwidth (BW) value for an FH system is approximately equal to the number of frequency channels available multiplied by the channel bandwidth. The process gain for an FH system can be computed from the equation above or by simply summing the number of frequency choices; e.g., the process gain associated with an FH system with 1000 available channels would be 1000 or 30 dB (10 log 1000/1 = 30 dB). Although the above relationship holds for FH and DS spread spectrum, the process gain provided by TH spread spectrum is the reciprocal of the transmit duty cycle.[3]

Although the optimum bandwidth for spread spectrum depends on the desired system capabilities, maximum process gain and signal hiding calls for wide bandwidths. In addition, from the equation above, we can see that, for a given process gain, the RF bandwidth requirements increase with increasing data rates. However, it is often impractical to increase the RF bandwidth to support higher data rates. For example, a system with a 10 Mbps code clock rate and 1 Kbps information rate would provide a process gain of:

$$\begin{aligned}\text{process gain} &= \text{BW/DR}\\ &= (2 \times \text{system code clock rate})/(\text{data rate})\\ &= (2 \times 10^7)/(1 \times 10^3)\\ &= 2 \times 10^4\\ &= 43\ \text{dB}\end{aligned}$$

One way to increase the process gain of this system would be to increase the system code clock rate. For example, doubling the clock rate to 20 Mbps provides an increase in process gain of only 3 dB. This strategy is expensive and fraught with problems, given the cost and bandwidth limitations of ICs operating above a few hundred MHz. Also, because the PN code generators must operate without error for hours or days, as code rates increase, operating errors must decrease in inverse proportion. This means that a 100-MHz clock must operate error free for 3.6×10^{11} bits to allow a system to operate for one hour. However, high speed digital circuitry is more sensitive to noise, consumes more power, and is more susceptible to error than low speed circuitry. A 100 Mbps code generator with an error rate of only 1×10^{-8} would, on average, make one mistake every second—an unacceptable condition for spread spectrum communications.

Given the practical limitations of increasing process gain by increasing RF signal bandwidth, the next best way to increase process gain is to decrease the information bandwidth. Process gain varies inversely with the data rate;[2] reducing the data rate by a factor of two provides an additional process gain of only 3 dB. Despite this modest gain, there are no real technical limitations as to how much the data rate can be decreased. For instance, following the previous example with a clock rate of 10 Mbps, but with a data rate of 10 bps instead of 1 Kbps, the process gain is:

$$\begin{aligned}\text{process gain} &= \text{BW/DR}\\ &= (2 \times 10^{7})/(10)\\ &= 2 \times 10^{6}\\ &= 63\ \text{dB}\end{aligned}$$

which represents an additional 20 dB of process gain. A data rate of only 10 bps might seem agonizingly slow; however, it may be the only possible solution for some harsh communications environments.

Going further

Ready for more? Construction enthusiasts should see the articles by Kesteloot[15,16] for a good introduction to practical spread spectrum hardware projects. Dixon[3] provides an excellent and very readable introduction to spread spectrum techniques. For a good overview of the techniques used in synchronization, see the text by Simon.[12] Dillard's text[17] offers insight into how spread spectrum is used in secure communications.

As was mentioned earlier, radio amateurs can experiment with DS and FH spread spectrum communications above 420 MHz. However, since the FCC rules regarding spread spectrum communications logging, station identification, and other operating procedures are very different from those applied to standard communications, it would be advisable to consult part 97 of the FCC rules and regulations before you set out to explore this technology. ■

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