Tutorial on Spread Spectrum Technology

Spread spectrum technology has blossomed from a military technology into one of the fundamental building blocks in current and next-generation wireless systems. From cellular to cordless to wireless LAN (WLAN) systems, spectrum is a vital component in the system design process.

Since spread-spectrum is such an integral ingredient, it's vital for designers to have an understanding of how this technology functions. In this tutorial, we'll take on that task, addressing the basic operating characteristics of a spread-spectrum system. We'll also examine the key differentiators between frequency-hop spread spectrum (FHSS) and direct-sequence spread spectrum (DSSS) implementations.

How It Works

Spread spectrum uses wideband, noise-like signals that are hard to detect, intercept, or demodulate. Additionally, spread-spectrum signals are harder to jam (interfere with) than narrow band signals. These low probability of intercept (LPI) and anti-jam (AJ) features are why the military has used the spread spectrum scheme for so many years. Spread-spectrum signals are intentionally made to be a much wider band than the information they are carrying to make them more noise-like.

Spread-spectrum transmitters use similar transmit power levels to narrowband transmitters. Because spread-spectrum signals are so wide, they transmit at a much lower spectral power density, measured in watts per hertz, than narrow band transmitters. This lower transmitted power density characteristic gives spread-spectrum signals a big plus. Spread-spectrum and narrowband signals can occupy the same band, with little or no interference. This capability is the main reason for all the interest in spread spectrum today.

The use of special pseudo noise (PN) codes in spread-spectrum communications makes signals appear wide band and noise-like. It is this very characteristic that makes spread-spectrum signals possess a low LPI. Spread-spectrum signals are hard to detect on narrow band equipment because the signal's energy is spread over a bandwidth of maybe 100 times the information bandwidth **(Figure 1)**.

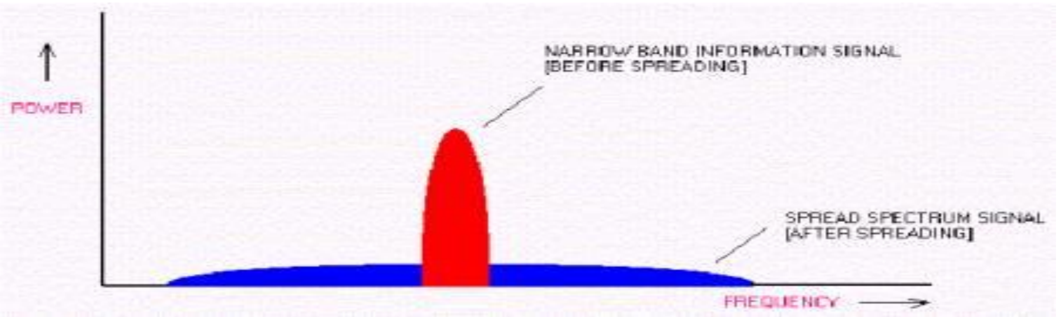

Figure 1: In a spread-spectrum system, signals are spread across a wide bandwidth, making them difficult to intercept, demodulate, and intercept.

The spread of energy over a wide band, or lower spectral power density, also makes spread-spectrum signals less likely to interfere with narrowband communications. Narrowband communications, conversely, cause little or no interference to spread spectrum systems because the correlation receiver effectively integrates over a very wide bandwidth to recover a spread spectrum signal. The correlator then "spreads" out a narrowband interferer over the receiver's total detection bandwidth.

Since the total integrated signal density or signal-to-noise ratio (SNR) at the correlator's input determines whether there will be interference or not. All spread spectrum systems have a threshold or tolerance level of interference beyond which useful communication ceases. This tolerance or threshold is related to the spread-spectrum processing gain, which is essentially the ratio of the RF bandwidth to the information bandwidth.

Direct or Hopping
Direct sequence and frequency hopping are the most commonly used methods for the spread spectrum technology. Although the basic idea is the same, these two methods have many distinctive characteristics that result in complete different radio performances.

The carrier of the direct-sequence radio stays at a fixed frequency. Narrowband information is spread out into a much larger (at least 10 times) bandwidth by using a pseudo-random chip sequence. The generation of the direct sequence spread spectrum signal (spreading) is shown in **Figure 2**.

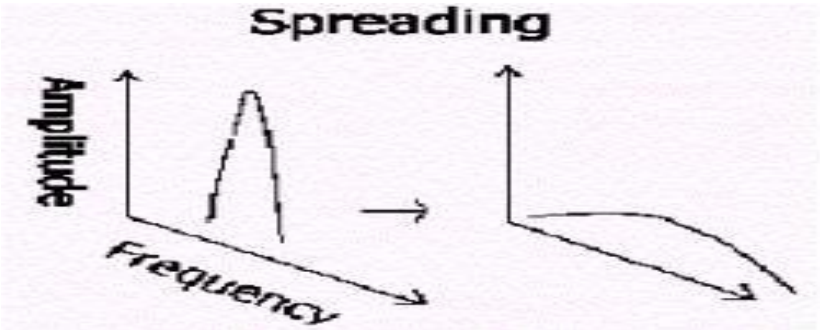

Figure 2: Comparison of the generation of a narrowband and direct-sequence spread spectrum signals.

In Figure 2, the narrowband signal and the spread-spectrum signal both use the same amount of transmit power and carry the same information. However, the power density of the spread-spectrum signal is much lower than the narrowband signal. As a result, it is more difficult to detect the presence of the spread spectrum signal. The power density is the amount of power over a certain frequency. In the case of Figure 2, the narrowband signal's power density is 10 times higher than the spread spectrum signal, assuming the spread ratio is 10.

At the receiving end of a direct-sequence system, the spread spectrum signal is de-spread to generate the original narrowband signal. **Figure 3** shows the de-spreading process.

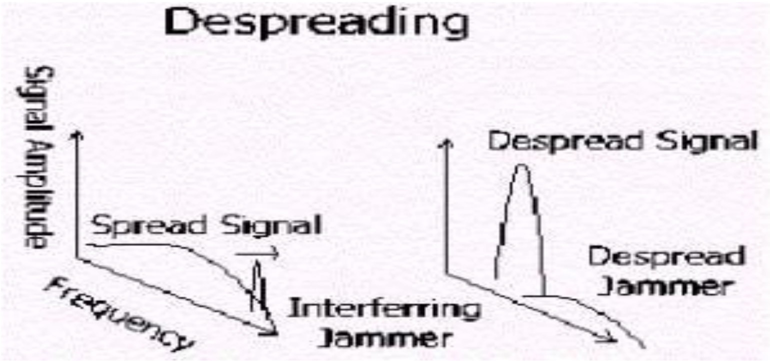

Figure 3: Diagram illustrating the despreading process in a direct-sequence system.

If there is an interference jammer in the same band, it will be spread out during the de-spreading. As a result, the jammer's impact is greatly reduced. This is the way that the direct-sequence spread-spectrum (DSSS) radio fights the interference. It spreads out the offending jammer by the spreading factor **(Figure 4)**. Since the spreading factor is at least a factor of 10, the offending jammer's amplitude is greatly reduced by at least 90%.

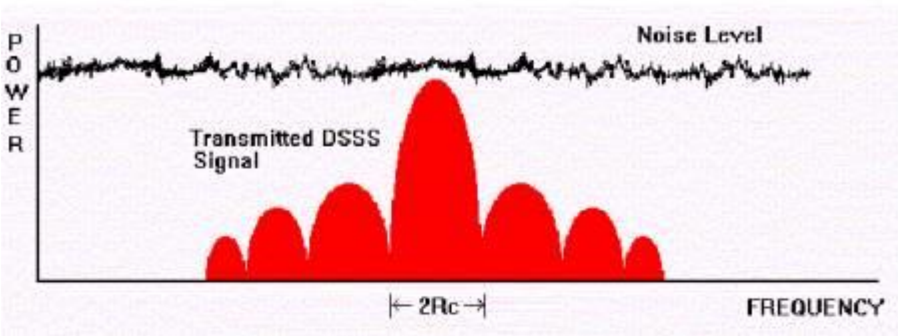

Figure 4: Direct-sequence systems combat noise problems by spreading jammers across a wideband as shown in this figure.

The Hopping Approach

Frequency-hopping systems achieve the same results provided by direct-sequence systems by using different carrier frequency at different time. The frequency-hop system's carrier will hop around within the band so that hopefully it will avoid the jammer at some frequencies. A frequency-hopping signal is shown in **Figure 5a and 5b**.

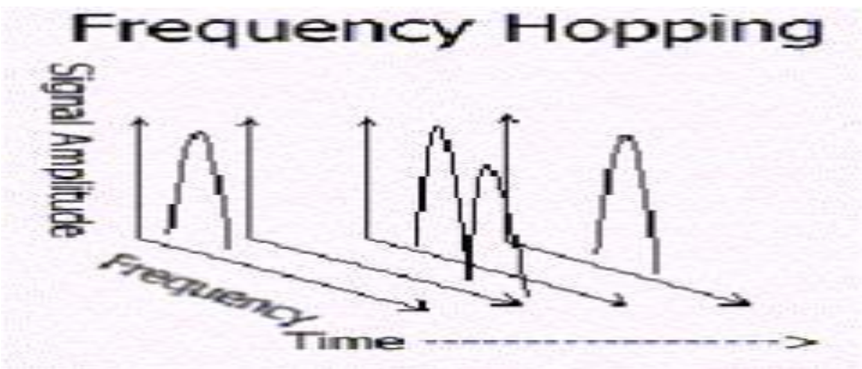

Figure 5: Diagram showing how a frequency-hop system works.

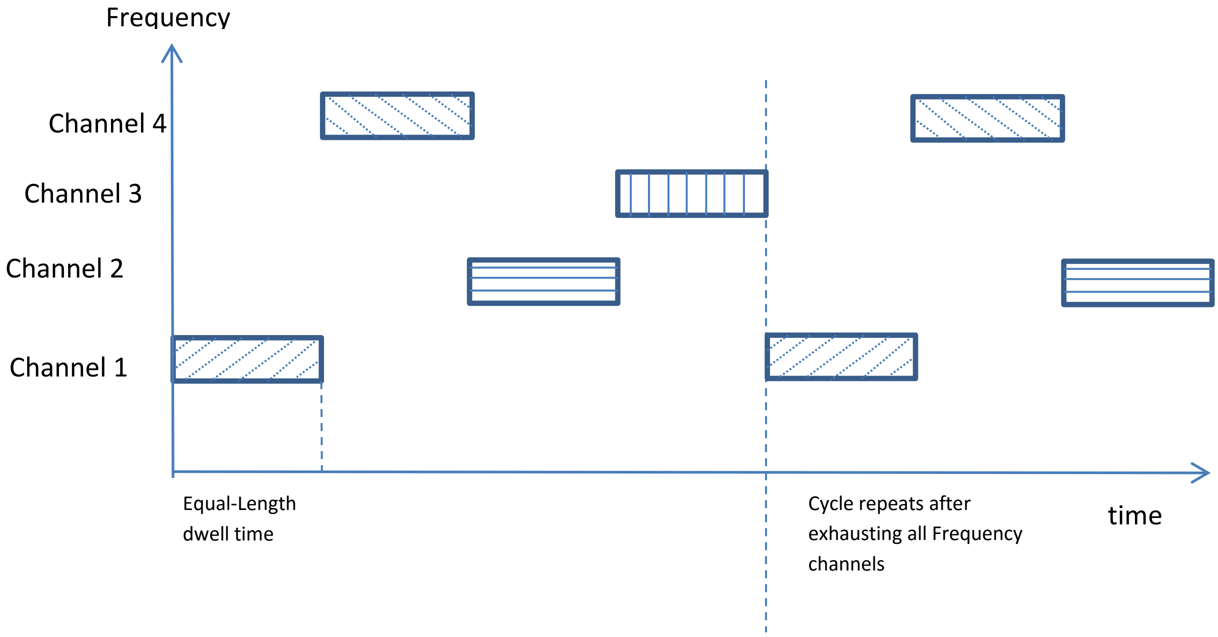

Figure 5b: A four channel FHSS system (Obaidat, et al, 2011).

The frequency-hopping technique does not spread the signal, as a result, there is no processing gain. The processing gain is the increase in power density when the signal is de-spread and it will improve the received signal's Signal-to-noise ratio (SNR). In other words, the frequency hopper needs to put out more power in order to have the same SNR as a direct-sequence radio.

The frequency hopper is also more difficult to synchronize. In these architectures, the receiver and the transmitter must be synchronized in time and frequency in order to ensure proper transmission and reception of signals. In a direct-sequence radio, on the other hand, only the timing of the chips needs to be synchronized.

The frequency hopper also needs more time to search the signal and lock to it. As a result, the latency time is usually longer. While a direct-sequence radio can lock in the chip sequence in just a few bits.

To make the initial synchronization possible, the frequency hopper will typically park at a fixed frequency before hopping or communication begins. If the jammer happens to locate at the same frequency as the parking frequency, the hopper will not be able to hop at all. And once it hops, it will be very difficult, if not impossible to re-synchronize if the receiver ever lost the sync.

The frequency hopper, however, is better than the direct-sequence radio when dealing with multipath. Since the hopper does not stay at the same frequency and a null at one frequency is usually not a null at another frequency if it is not too close to the original frequency. So a hopper can usually deal with multipath fading issues better than direct-sequence radio.

The hopper itself, however, could suffer performance problems if it interferes with another radio. In these scenarios, the system that survives depends upon which can suffer more data loss. In general, a voice system can survive an error rate as high as 10^{-2} while a data system must have an error rate better than 10^{-4}. Voice system can tolerate more data loss because human brain can "guess" between the words while a dumb microprocessor can't.

Modulation and Demodulation

For direct-sequence systems the encoding signal is used to modulate a carrier, usually by phase-shift keying (PSK; for example, bi-phase or quad-phase) at the code rate. Frequency-hopping systems generate their wide band by transmitting at different frequencies, hopping from one frequency to another according to the code sequence. Typically such a system may have a few thousand frequencies to choose from, and unlike direct sequence signal, it has only one output rather than symmetrically distributed outputs.

It's important to note that for both direct-sequencing and frequency-hopping systems generate wideband signals controlled by the code sequence generator. For one the code is the direct carrier modulation (direct sequence) and the other commands the carrier frequency (frequency hopping).

There are several different modulation techniques that designers can employ when developing frequency-hop or direct-sequence systems. Information modulation can be accomplished using amplitude (AM) or frequency modulation (FM) techniques. AM is normally used because it tends to be detectable when examining the spectrum. FM is more useful because it is a constant-envelope signal, but information is still readily observed. In both AM and FM, no knowledge of the code is needed to receive the transmitted information.

Clock modulation, which is actually frequency modulation of the code clock, is another option in spread-spectrum designs. In most cases (including frequency hopping), clock modulation is not used because the loss in correlation due to phase slippage between received and local clocks, could cause degraded performance.

Code modification is another modulation technique that designers can use when building a spread-spectrum system. Under this approach, the code is changed in such a way that the information is embedded in it, then modulated by phase transitions on a RF carrier.

In direct-sequence designs, balance modulation can be used in any suppressed carrier system used to generate the transmitted signal. Balanced modulation helps to hide the signal, as well as there are no power wasted in transmitting a carrier that would contribute to interference rejection or information transfer. When a signal has poor balance in either code or carrier, spikes are seen in its spectrum. With these spikes, or spurs, the signal is easily detectable, since these spikes are noticed above the noise and thus provide a path for detecting the hidden signal.

Once the signal is coded, modulated and then sent, the receiver must demodulate the signal. This is usually done in two steps. The first step entails removing the spectrum-spreading modulation. Then, the remaining information-bearing signal is demodulated by multiplying with a local reference identical in structure and synchronized with the received signal.

Coding Techniques

In order to transmit anything, codes used for data transmission have to be considered. However, this section will not discuss the coding of information (like error correction coding) but those that act as noise-like carriers for the information being transferred. These codes are of much greater length than those for the usual areas of data transfer, since it is intended for bandwidth spreading.

Codes in a spread-spectrum system are used for:

1. Protection against interference: Coding enables a bandwidth trade for processing gain against interfering signals.
2. Provision for privacy: Coding enables protection of signals from eaves dropping, so that even the code is secure.
3. Noise-effect reduction: error-detection and correction codes can reduce the effects of noise and interference.

Maximal sequencing is one of the more popular coding methods in a spread-spectrum system. Maximal codes can be generated by a given shift register or a delay element of given length. In binary shift register sequence generators, the maximum length sequence is (2^n-1) chips, where n is the number of stages in the shift register.

A shift register generator consists of a shift register in conjunction with the appropriate logic, which feeds back a logical combination of the state of two or more of its stages to its input. The output, and its contents of its n stages at any clock time, is its function of the outputs of the stages fed back at the proceeding sample time. Some maximal codes can be of length 7 to [(2^{36}-1] chips.

Error detection and correction codes (EDAC) must be used in frequency-hopping systems in order to overcome the high rates of error induced by partial band jamming. These codes usefulness has a threshold that must be exceeded before satisfactory performance is achieved.

In direct-sequence systems, EDACs may not be advisable because of the effect it has on the code, increasing the apparent data transmission rate, and may increase jamming threshold. Some demodulators can operate detecting errors at approximately the same accuracy as an EDAC, so it may not be worthwhile to include a complex coding/decoding scheme in the system.

Advantages of Spread Spectrum

Spread-spectrum systems provide some clear advantages to designers. As a recap, here are nine benefits that designers can expect when using a spread-spectrum-based wireless system.

1. Reduced crosstalk interference: In spread-spectrum systems, crosstalk interference is greatly attenuated due to the processing gain of the spread spectrum system as described earlier. The effect of the suppressed crosstalk interference can be essentially removed with digital processing where noise below certain threshold results in negligible bit errors. These negligible bit errors will have little effect on voice transmissions.

2. Better voice quality/data integrity and less static noise: Due to the processing gain and digital processing nature of spread spectrum technology, a spread-spectrum-based system is more immune to interference and noise. This greatly reduces consumer electronic device-induced static noise that is commonly experienced by conventional analog wireless system users.

3. Lowered susceptibility to multipath fading: Because of its inherent frequency diversity properties (thanks to wide spectrum spread), a spread spectrum system is much less susceptible to multipath fading.

4. Inherent security: In a spread spectrum system, a PN sequence is used to either modulate the signal in the time domain (direct sequence systems) or select the carrier frequency (frequency hopping systems). Due to the pseudo-random nature of the PN sequence, the signal in the air has been "randomized". Only the receiver having the exact same pseudo-random sequence and synchronous timing can de-spread and retrieve the original signal. Consequently, a spread spectrum system provides signal security that is not available to conventional analog wireless systems.

5. Co-existence: A spread spectrum system is less susceptible to interference than other non-spread spectrum systems. In addition, with the proper designing of pseudo-random sequences, multiple spread spectrum systems can co-exist without creating severe interference to other systems. This further increases the system capacity for spread spectrum systems or devices.

6. Longer operating distances: A spread spectrum device operated in the ISM band is allowed to have higher transmit power due to its non-interfering nature. Because of the higher transmit power, the operating distance of such a device can be significantly longer than that of a traditional analog wireless communication device.

7. Hard to detect: Spread-spectrum signals are much wider than conventional narrowband transmission (of the order of 20 to 254 times the bandwidth of narrowband transmissions). Since the communication band is spread, it can be transmitted at a low power without being detrimentally affected by background noise. This is because when de-spreading takes place, the noise at one frequency is rejected, leaving the desired signal.

8. Hard to intercept or demodulate: The very foundation of the spreading technique is the code use to spread the signal. Without knowing the code it is impossible to decipher the transmission. Also, because the codes are so long (and quick) simply viewing the code would still be next to impossible to solve the code, hence interception is very hard.

9. Harder to jam: The most important feature of spread spectrum is its ability to reject interference. At first glance, it may be considered that spread spectrum would be most affected by interference. However, any signal is spread in the bandwidth, and after it passes through the correlator, the bandwidth signal is equal to its original bandwidth, plus the bandwidth of the local interference. An interference signal with 2 MHz bandwidth being input into a direct-sequence receiver whose signal is 10 MHz wide gives an output from the correlator of 12 MHz. The wider the interference bandwidth, the wider the output signal. Thus the wider the input signal, the less its effect on the system because the power density of the signal after processing is lower, and less power falls in the band pass filter.

Code-Division Multiple Access (CDMA)

CDMA (Code-Division Multiple Access) refers to any of several protocols used in so-called second-generation (2G) and third-generation (3G) wireless communications. As the term implies, CDMA is a form of multiplexing, which allows numerous signals to occupy a single transmission channel, optimizing the use of available bandwidth. The technology is used in ultra-high-frequency (UHF) cellular telephone systems in the 800-MHz and 1.9-GHz bands. CDMA employs analog-to-digital conversion (ADC) in combination with spread spectrum technology. Audio input is first digitized into binary elements. CDMA can either use DSSS of FHSS.

In FHSS based CDMA, after the ADC conversion, the frequency of the transmitted signal is made to vary according to a defined pattern (code), so it can be intercepted only by a receiver whose frequency response is programmed with the same code so that it follows exactly along with the transmitter frequency. There are trillions of possible frequency-sequencing codes, which enhance privacy and makes cloning difficult.

CDMA can also be implemented using *Direct-Sequence Spread-Spectrum* (DSSS) and radio technology that originally achieved prominence in military communications systems, and then in early wireless LANs. The idea in DSSS is simple -- instead of sending 0s and 1s over the air directly, we convert each 0 and 1 to a longer string of bits, which is the "code." This may appear to waste bandwidth, but the technique in fact improves reliability because damage to one or two bits during transmission need not require that the entire packet of data be resent. Rather, when the signal is de-spread by the receiver, we can use statistical techniques to guess what the original bit was. Using the right codes, we can often guess correctly (and we still use error-checking codes at the end of each packet, regardless). Now, suppose we pick the codes that are *orthogonal* to one another, meaning that two properly designed orthogonal codes can actually exist in the same spectrum at the same time and not -- really! -- interfere with each other. We'd give one code to one user and another to a second user and so on, and then, assuming everyone transmits at the same power level relative to one another so that no one station drowns out the others. This is how the DSSS based CDMA is implemented.

The CDMA channel is nominally 1.23 MHz wide. CDMA networks use a scheme called soft handoff, which minimizes signal breakup as a handset passes from one cell to another. The combination of digital and spread-spectrum modes supports several times as many signals per unit bandwidth as analog modes. CDMA is compatible with other cellular technologies; this allows for nationwide roaming.

The original CDMA standard, also known as CDMA One and still common in cellular telephones in the U.S., offers a transmission speed of only up to 14.4 Kbps in its single channel form and up to 115 Kbps in an eight-channel form. CDMA2000 and Wideband CDMA deliver data many times faster.

References

1. ISSCE—Circuits Systems. "Principles of Spread Spectrum Communication", target="_new">http://olt.et.tudelf.nl/~glas/ssc/techn/techniques.html
2. Dixon, Robert C. "Spread Spectrum Techniques". John Wiley & Sons.
3. Internet Magazine. "Spread Spectrum Scene: ABC's of Spread Spectrum", http://sss-mag.com/ss.html
4. http://searchtelecom.techtarget.com/definition/CDMA
5. http://searchtelecom.techtarget.com/tip/3G-The-CDMA-alternative