Introducing Spread Spectrum

In his classic novel, "1984," George Orwell said "Less is more." Spread spectrum advocates say "more is less." What exactly is spread spectrum and why should hams be interested?

Welcome once again to the Digital Data Link. This month, we'll take a look at spread spectrum (S/S): what it is, how it works, and why it's so wonderful. S/S operations aren't new—the idea was developed during World War II by the famous actress, Hedy Lamarr (see "Hedy Lamarr: Spread Spectrum Pioneer?" accompanying this article). However, recent changes in the communications industry and in technology have seen spread spectrum explode into the commercial marketplace.

S/S is just what the name implies: spreading out the spectrum of the transmitted signal to occupy a wider bandwidth than required. Although a wider bandwidth seems to be a bad thing—if you use a wider bandwidth, fewer channels would be available, right?—the reality is that by using spread spectrum, you can fit *more* users into a given spectrum, with no harmful interference.

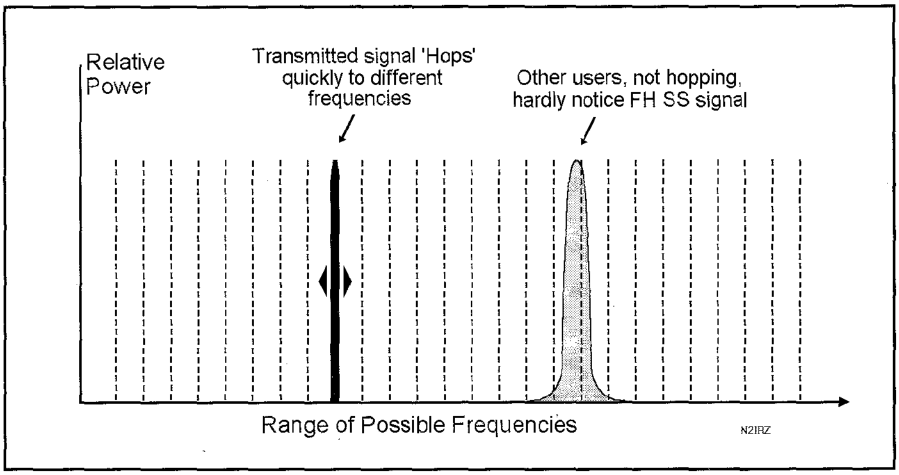

Figure 1. Frequency-hopping spread spectrum. The transmitted signal is sent for brief periods on different frequencies. Other receivers using a different sequence of frequencies, or a receiver on a single frequency, barely notice the occasional signal "blips."

Wider Bandwidth AND More Users?

Now wait a minute...you spread out your signal, and *more* people can use the spectrum? How can that be? To answer that very basic question, we have to look at *how* we spread the spectrum. While there are many S/S techniques, two that show the most promise for amateur radio are known as *frequency-hopping* (FH) and *direct sequence* (DS).

Frequency-hopping is the easiest to understand conceptually. Your transmitter changes frequency very quickly, tuning sort-of randomly around the band. The receiver tunes in exactly the same way, following these little blips of signal, and (as long as everything stays synchronized) the signal appears seamless, as if the frequency wasn't changing.

In contrast, direct sequence spreads the spectrum of the data signal by multiplying the data by a higher-frequency, data-like signal, simply widening the bandwidth (if this makes no sense to you, don't worry; we'll explain it later on). It's also possible to combine these and other techniques to create what's known as a hybrid system, further improving the benefits of S/S. To better understand how these systems work, and why we get improved communications and spectral efficiency, let's look at some examples:

Frequency Hopping

Consider a typical FM mobile radio with, say, 50 memories. First set each memory to a different frequency, choosing them more or less randomly. Find another radio just like it and set all of its memories identically. Now, as you begin speaking, switch from one memory channel to the next, say at about 10 times per second (this is your so-called *hopping rate*). Of course, you couldn't do this manually with much accuracy, but building a circuit to do this automatically isn't very difficult.

What you're doing is sending a very tiny bit of your signal—^{1}/10th of a second's worth, to be exact—on each of the 50 channels. To anyone listening to any one of those channels, they'll just hear a little "blip" every five seconds or so. It's nothing they could understand as a message, or that would interfere with their QSO, just a brief pulse of RF.

Now, at the receive end, listen on one of the channels for a blip. As soon as you hear one, start running through the memory channels at the same speed, and in the

By Don Rotolo, N2IRZ

Forward Error Correction

If you want to increase the chance of a message getting through under adverse conditions, you use *Forward Error Correction* (*FEC*). A simple method of FEC is to say everything two or three times, or to spell everything using phonetics.

Standard AX.25 packet does not use FEC, but the much simpler technique of *Error Detection*. In AX.25, if an error is detected, the message is not acknowledged by the receiving station, and is thus sent again and again until it gets through. The advantage of FEC is that you don't have to acknowledge every good message, you just send enough information that most probable errors can be corrected at the receiver.

There are a number of methods of implementing FEC, some better at correcting errors but requiring more redundancy, others using less redundancy but less likely to be able to correct certain possible errors. The goal is to use the least redundancy to correct the most errors. Which specific type of FEC you use depends on the type and severity of the expected errors. Theoretical mathematicians who dislike PN Codes get *their* kicks by coming up with better methods for FEC.

For more information on FEC methods and their relative efficiencies, visit Phil Karn, KA9Q's Web page at <http://www.qualcomm.com/people/pkarn/>. This is especially interesting if you have a sound card, as you can hear various signals and the effects of FEC processing.

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same order, as the transmitter. If the signal remains as you tune, then you've locked onto the correct transmitter and are now synchronized with it.

If, on the other hand, the signal disappears as you tune, you probably heard someone else's blip, so stop and wait for another signal and repeat the process. Remember, you programmed the frequencies and their sequence randomly, so the chances of someone else picking all the same frequencies, and in the same order, is very small. If you think about it, you can select sequences that have little chance of being mistaken for one another. Such sets are said to have a low *correlation*, and the sequences used are said to be *orthogonal*.

OK, so now you (or some automatic circuit) have heard the transmitter, locked onto it and synchronized with it after a maximum of five seconds. Since both the transmitter and receiver are scrolling through the same frequencies, in the same order and at the same rate, the transmitted signal—all those blips—are all able to be heard, just as if the frequency weren't changing at all. So, once the receiver is *synchronized*, you can hear the transmitted signal perfectly. The idea behind the frequency-hopping technique is illustrated in Figure 1.

Why Bother?

Why go through the trouble? First of all, frequency-hopping S/S is resistant to interference: losing a blip or two for any reason (another signal's interference, multipath, whatever) makes little difference in understanding the message. A $^1/_{10}$th of a second dropout is insignificant, in terms of the length of the word being spoken, so there's really no interference. In reality, losing even most of the blips makes little difference.

Second, since you aren't using any one channel, others can use the same technique—with a different sequence of channels, of course—to use the same frequencies at the same time you do. A further advantage is that, unless someone else knows your frequency selection and sequence, it's difficult to eavesdrop on, or jam, your conversation.

The main *disadvantage* to this technique is the time it takes for the two stations to synchronize, in this example as long as five seconds. If you increase the hopping rate (the speed at which you change channels), you can reduce this time, but then it becomes more difficult to build a radio that can change channels quickly enough.

To increase the relative value of this S/S technique, try to increase both the number of channels and the hopping rate. The resulting reduction of interference effects is called the *processing gain*, which is the added ability for the communication to "get through" in relation to conventional simplex or some other technique. This processing gain, measured in decibels (dB), is a real gain, just like using more power or a bigger antenna.

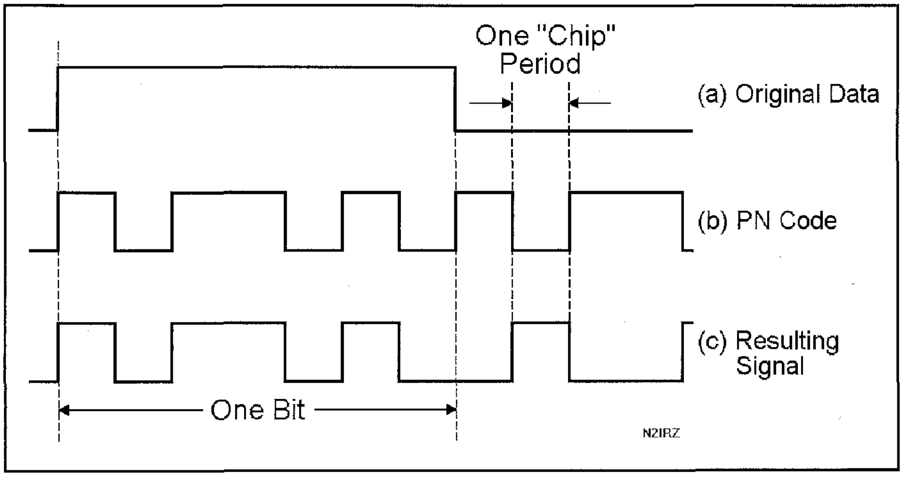

Figure 2. Direct sequence spread spectrum. The data signal (a) is multiplied by a repeating pseudo-random spreading code, PN Code (b), which increases the bandwidth of the resulting signal (c). Due to the effects of the PN Code, the signal resembles background noise. Receivers using the same PN Code can decode the signal, while those using different PN Codes, or narrowband receivers, see the signal as only noise.

Direct Sequence

Direct sequence S/S works differently. Instead of spreading out the transmitted RF onto many different frequencies, it multiplies the data signal by another signal of much higher frequency, making the signal's bandwidth much wider. Let's try another example to illustrate this since it's a difficult concept to understand.

First, it's important to know that *the bandwidth of a signal, after modulation, is related to the highest frequency in the signal, and as the highest frequency increases, so does the bandwidth*[1]. So, you take a data signal and multiply it by another data-like signal, as shown in Figure 2. This higher-frequency, data-like signal repeats itself for every single bit. This added signal is called a *pseudo-random noise code* (PN code).

A PN code is just a repeating collection of ones and zeros, chosen more or less at random[2]. The PN code is characterized by the length of the code, or how many times it changes per bit. Each data bit is multiplied by the whole PN code, so longer PN codes result in higher frequencies and thus wider bandwidths.

What's interesting is that, unless your receiver divides the incoming signal by the same PN code, the signal is essentially random noise. Even if other S/S signals are heard by the receiver, the use of different PN codes means that the receiver "listens" to only your signal. An occasional overlap of the PN codes is possible (and likely), but since PN codes are carefully chosen, there's usually no effect upon the received signal. Recognizing such a signal on the air is also unlikely, simply because the bandwidth is so wide and the signal somewhat randomized, so it sounds like noise. In fact, the effect of a direct sequence S/S transmission is to slightly raise the noise floor at the frequencies of interest. *(See "Weak-Signal Worries About S/S," elsewhere in this article.—ed.)*

With its noise-like characteristics, the signal is immune to narrowband interference, multipath effects, jamming, and casual eavesdropping. Again, the processing gain thus realized is real gain, like you get from a power amplifier. For direct sequence systems, the processing gain increases with the length of the PN code, up to the point where the bandwidth is a little more than a megahertz, after which you begin to see a diminishing return due to wideband noise effects at the receiver.

The main disadvantage to this technique is the problems created by the *FM Capture effect* (see Figure 3). An FM receiver tends to demodulate only the strongest signal it receives, ignoring all others. If the desired signal is weaker at the receiver than some other signal sharing the bandwidth, then the desired signal is lost, even though the stronger signal cannot be decoded.

Hybrid Systems

Note that frequency-hopping systems are not affected by the FM capture effect, but it is difficult to get high processing gain in a frequency-hopping system. So, to get the advantages of both systems, while reducing the disadvantages, you simply combine them to achieve a direct sequence signal that hops to a number of different frequencies. This is called a *hybrid spread spectrum system*, and, because of its further improved noise immunity, the processing gain is even higher. You can even change the PN code at each frequency hop, further increasing the processing gain.

Further Gains

As a side note, if you use a Forward Error Correcting (FEC) technique (see sidebar) to allow minor bit errors to be corrected at the receiver, you further increase the processing gain, because even a slightly faulty signal still carries the information. In other words, it doesn't matter whether 95% of the data gets through because of large signal strength (dB of power) or because of processing gain (dB of software)—the effect is the same. Anyone who thinks that Morse code is the best mode for adverse conditions has never heard of processing gain. You can actually get a usable signal that is *under the noise floor*! Try doing *that* with CW.

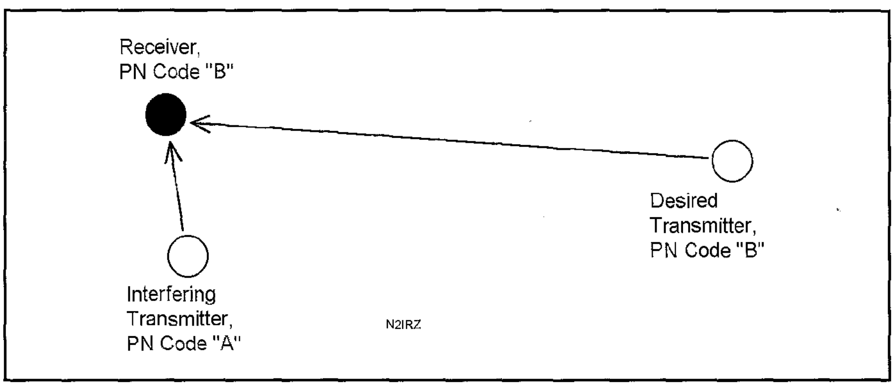

Figure 3. The FM capture effect. The stronger signal from the transmitter (a) "captures" the receiver's demodulator, effectively shutting out the desired signal from transmitter (b). This effect is well known from narrowband FM repeater operations, but it also affects direct sequence spread spectrum systems.

FCC limits and the TAPR STA

At this time, Part 97 of the FCC Rules limits the number and length of PN codes used by amateurs to a selected few, as

Hedy Lamarr, Spread Spectrum Pioneer?

It's hard to make people believe that the actress called "the most beautiful woman in the world" in 1940 was the first to hold an S/S patent—even when you show them the patent. But it's true!

Hedy Lamarr, for those of you who are baby boomers or younger, was a very popular and talented actress in the 1940s. Strongly anti-Nazi and concerned about the coming Hitler threat, she left her native Austria and her pro-Nazi arms-merchant husband in the late 1930s and came to America.

While making a career for herself in film, Ms. Lamarr and George Antheil, an accomplished American composer and musical innovator, got the idea for a "Secret Communications System" in which radio transmitters changed frequency rapidly to prevent the interception of messages. The 88-frequency system of frequency-hopping they sketched out was controlled by piano-roll strips (a piano has 88 keys). They were awarded U.S. Patent Number 2,292,387 on August 11, 1942.

Because the technology to implement the system did not exist, they let their patent rights lapse after the 17-year protection period had expired. A few years later, the Navy finally figured out a way to do it, and it wasn't until some 40 years after the war that the patent was declassified and the FCC allowed non-military use of S/S.

This information is based upon an Internet posting by David R. Hughes of Colorado Springs, Colorado. You can find out more about the S/S-Hedy Lamarr connection by visiting Phil Karn, KA9Q's Web page (see address elsewhere in this article) or "The Hedy Lamarr Page" at <http://www.geocities.com/hollywood/hills/1797/>.

well as the number of hopping frequencies. Ostensibly to allow the FCC to monitor communications for enforcement purposes, it really cripples our ability to use and experiment with S/S. Recognizing this, the FCC has granted Tucson Amateur Packet Radio (TAPR) a Special Temporary Authorization (STA) to experiment with S/S techniques presently prohibited on amateur frequencies. For more information on this project, including a list of presently-scheduled experiments and an application to be included on the STA (you have to be a TAPR member), visit the TAPR home page on the World Wide Web at <http://www.tapr.org>.

Some Problems

One problem, especially with direct sequence systems, is the FM capture effect discussed earlier. While this effect can be somewhat reduced by using a hybrid technique, this considerably complicates transceiver design. In cases where fixed stations are operating, the problem can be overcome by frequency (and PN code) coordination, judicious power levels, directional antennas, and plain old cooperation. However, where mobile operations are involved, the signal strengths vary wildly, and conventional control techniques are impractical. The answer is deceptively simple: *automatic power control.*

In a manner similar to the AMPS cellular telephone system used in North America, each receiver measures the signal-to-noise (S/N) ratio, and commands the other station's transmitter to increase or decrease its power. This ensures that the minimum power for effective communications is always used (that's in Part 97!), thus reducing the chance for, but not eliminating, the negative influences of the FM capture effect.

Power control is easier to implement than you think, especially with data communications. Some time ago, adding some power control bits to the AX.25 protocol was proposed, and work is in progress on that and many other improvements to AX.25.

Not Just for Data

It's important to remember that, while S/S is used for data transmissions, just about anything can be represented by data bits. One obvious application of S/S would be for dramatically increasing the

Dayton Weak-Signal Banquet

The VHF Weak Signal Group that meets Monday nights at 0200 UTC on 3.843 MHz would like to invite everyone who is coming to the Dayton Hamvention to our annual banquet. We have reserved a room, which will seat 150, for Friday night, May 16th, from 7:00 p.m. until 11:00 p.m. at the Holiday Inn North, Wagoner Ford Rd, Dayton, Ohio. There will be a cash bar as well as plenty of seating to allow you to mix and mingle with other VHFers from all over the country and the world. There will be over 50 prizes, including two grand prizes worth $300 dollars each. Drawings begin at 9:00 p.m. Also, there will be a guest speaker who will provide a short talk on VHF activity, plus a noise figure measuring table, so bring along your preamps for tweaking.

Tickets include the two-entree banquet dinner, and are $29.00 per person, limited to 150. You may order your tickets by sending $29.00 plus an SASE to either Tony Emanuele, WA8RJF, 7156 Kory Court, Concord Township, Ohio 44077, or Tom Whitted, WA8WZG, 4641 Port Clinton, East Rd., Port Clinton, Ohio 43452. Website info is at <http://WWW. WA8WZG.COM>.

This is one of the largest gatherings of VHF Weak-Signal enthusiasts in the U.S. so make sure to get your ticket early and join us for an enjoyable evening at the Dayton Hamvention!

"Anyone who thinks that Morse code is the best mode for adverse conditions has never heard of processing gain. You can actually get a usable signal that is under the noise floor! Try doing that *with CW."*

capacity of a voice repeater. Users could be on different, non-interfering "PN code channels" on the same machine, talking at the same time. High-efficiency *voice coding* techniques could considerably reduce the quantity required, and processing gain would reduce power requirements. Just think of how many "virtual" repeaters could exist, all on a single, wide-bandwidth machine! Of course it's somewhat complicated, both technically and politically, to actually do that, but it remains possible.

Less Interference AND Increased Efficiency

S/S is more than just a better way to pack more data into a given bandwidth. We have to not only be able to use the allocated bands when faced with interfering signals, but we must avoid interfering with the primary users of the band. S/S techniques offer a way of doing this, while giving us the added benefits of processing gain and greatly increased spectral efficiency.

I urge you to look further into S/S. The TAPR home page is a good start, as is any college library that has an engineering department. You can also take a look at some of the S/S-related links from Phil Karn, KA9Q's Web page, <http://www.qualcomm.com/people/pkarn/>. With the explosion of unlicensed Part 15 S/S transceivers in the commercial world, prices have plummeted for some S/S transceivers, often offering data rates of 115 kBaud or higher. These make perfect building blocks for high-speed data networks. Unfortunately, FCC rules make it difficult, even with the STA, to use these under Part 97, but they remain perfectly usable under Part 15, sometimes having a range of 15 miles or more!

The tools that we need for a high-speed digital network are out there. While they're still a little expensive, now is the time to experiment to find the best techniques, so that as prices fall, the amateur community will be ready to employ S/S to its fullest advantage.

"One obvious application of S/S would be for dramatically increasing the capacity of a voice repeater."

Weak-Signal Worries about Spread Spectrum... and a Response

From the Editor:

The TAPR S/S experiments have been the subject of contentious debate, on the air, on the Internet, and even in the "Op-Ed" pages of this magazine. Many weak-signal operators, in particular, are worried that the increased noise floor caused by direct sequence S/S or by the every-five-seconds data "blip" of frequency-hopping will wreak havoc with their ability to copy signals that are barely above the noise level.

EME (Earth-Moon-Earth) communications, for example, routinely have path losses of nearly 300 dB and every additional dB of noise makes successful EME contacts more difficult. Meteor scatter (MS) contacts are made using extremely brief bursts of signal bouncing off an ionized meteor trail. An every-five-seconds data signal on an MS operating frequency would likely wipe out any chance of successful MS contacts.

S/S proponents counter that interference is not a given, and that one purpose of conducting the experiments under the TAPR STA is to determine what interference might result from S/S use on, say, 2 meters. Phil Karn, KA9Q, and Tom Clark, W3IWI, even presented a forum at last year's Central States VHF Society conference showing weak-signal operators how the processing gain of S/S could be used to improve such things as EME contacts.

We think Phil and Tom and CSVHFS are on the right track—there's certainly the potential for interference problems, but working together and respecting the value of all types of amateur communication greatly increases the chances that a compromise can be worked out that not only won't hurt either group's operating goals, but may enhance both in the process.

N2IRZ's Point of View:

While S/S *could* be operated in the weak signal portions of any given band, that's really impractically close to the band edges in most cases. In practice, the lower kHz of each band, where the weak-signal ops generally work, won't be affected at all. I envision that most S/S work will be in the repeater subbands, with frequency-hopping channels being between repeater channels. Most direct sequence channels, being about 1.25 MHz wide, would be confined to the centers of each band. So the potential for interference with weak-signal operations would be avoided.

Looking Ahead

That's all the room we have for this month. Next month, I'll switch tracks a little and introduce you to FlexNet—the most popular packet networking system in Europe. It has numerous advantages over what we use in North America, and it can be considered another building block for higher-speed data networks. Until then, remember that this is a hobby and you should be having fun while learning new things with it.

73, N2IRZ

Notes

1. According to Carson's rule (*not* Johnny), the bandwidth of an FM system can be calculated with the equation BW = 2 (Fdev + Fh), where Fh is the highest frequency in the modulating signal, Fdev is the deviation of the FM signal, and BW is the resulting bandwidth.

2. Actually, PN Codes are carefully selected from groups of possible codes. They always have an equal (or nearly equal) number of ones and zeros, to preserve their noise-like quality, and are chosen to have a minimal chance of being misinterpreted as another code; in other words, they're selected to be highly orthogonal. Theoretical mathematicians like to amuse themselves by developing new families of PN codes.