signal processing

DSSS vs. FHSS narrowband interference performance issues

An impartial comparison of DSSS and FHSS operation in the presence of narrowband interference for ISM band operation.

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Direct-sequence spread spectrum (DSSS) and frequency-hopping spread spectrum (FHSS) technologies have different physical mechanisms for rejecting narrowband interference. Because of these physical differences, they perform differently in the presence of the same levels of narrowband interference.

This is an important case for successful operation in the ISM bands. After presenting the physical mechanisms by which these spread spectrum methods reject narrowband interferers, measured examples are shown to illustrate DSSS and FHSS interference rejection. Performances of DSSS and FHSS in the presence of a large out-of-band interferer are also measured and compared. Comparisons between the two spread spectrum methods are drawn highlighting the conditions under which they perform identically, and also when one method performs better than the other. The proper choice of direct sequence or frequency hopping as a spread-spectrum technique depends on the actual environment in which the system will be deployed.

Some background

Spread-spectrum communications has enjoyed a surge of interest since the Federal Communications Commission (FCC) allowed its type-approved and unlicensed use under Part-15 regulations in the late 1980s [1]. This FCC allocation is a shared and lower-tier occupant in the industrial, scientific, and medical (ISM) bands around 915, 2,442, and 5,750 MHz.

The fact that this allocation is shared is important. Other users, and therefore other signals, are present in these ISM bands. Successful spread-spectrum products must tolerate the presence of these interfering signals. The FCC has intentionally set up this situation to foster the commercial development of spread-spectrum technology.

By definition, a spread-spectrum system uses a process other than the information signal to expand, or spread, the bandwidth of the signal [2, 3, 4]. There are two fundamental techniques for spectrum spreading: direct sequence and frequency hopping. These achieve the desired spectrum spreading, but that is about all they have in common.

Direct-sequence spectrum spreading combines the information signal with a spreading signal having much wider bandwidth. The net modulation signal effectively handles the wide bandwidth of the spreading signal. This wide modulation is then applied to a fixed frequency carrier signal for transmission. The spreading code directly spreads the information, ahead and independent of the RF modulator. The principle of direct sequence spread spectrum generation, and despreading in the receiver, is shown in Figure 1.

Frequency hopping takes the opposite approach. Rather than spreading the modulation about a fixed carrier, the information is left unchanged and directly modulates a carrier of varying frequency. The principle of frequency-hopping spread spectrum generation is shown in Figure 2. In frequency hopping, the spreading signal is used to change the frequency of the carrier provided by the carrier generator. The data directly modulate this hopping carrier. In essence, the frequency hopping approach is just a collection of conventional narrowband signals.

In the presence of narrowband interference, the performance of direct-sequence and frequency-hopping spread-spectrum techniques differ significantly under certain (likely) operating conditions. Measurements of DSSS and FHSS operation in the 915 MHz ISM band are presented under likely operating conditions. Interference to the intended communication is determined to occur only when the following three criteria are met:

• An interfering signal exists at the demodulation frequency.
• This interfering signal exists at the time demodulation is attempted.
• The interference is strong enough to corrupt the demodulation (issues of circuitry and implementation technology are left to other texts).

The physics of DS interference rejection

Although the interference rejection of DSSS is the cyclic cancellation of the spreading code under consecutive digital multiplications, implemented by the exclusive (or gate). This means that a second spreading operation with the...
same code actually cancels the spreading on an input DSSS signal. The spreading process itself is independent of the data, so by canceling the spreading, the data are left intact. Figure 3

![Figure 3. Cyclic cancellation of direct sequence spreading.](image_url)

demonstrates this process. In a real DSSS system, only the first two stages are actually used. The first stage is in the transmitter, and the second is in the receiver.

An interfering signal appears in the channel between the transmitter and the receiver. In the receiver, the multiplier with the spreading code is the second spreading the DSSS signal encounters, which cancel the original spreading. This is, however, the first spreading that the interference “sees.” The data are recovered as they follow the second stage. The interference behaves as if it is at the transmitter: It is spread, becoming a direct-sequence spread spectrum signal. So the interference simultaneously becomes spread as the data are despread. One possible interpretation of this process is that the spreading process “breaks” the data signal into little pieces. The despread processing, using the same code, “knows” where these pieces are and collects them back together. In this reassembly process, any other signal will not match and so is broken up into pieces of its own.

Narrowband filtering the despread data signal rejects much of the power in the spread interference signal within the receiver. Only a portion of the interfering signal power remains in the bandwidth of the data signal, and this portion appears as a noise floor in the filter passband. As long as there is enough signal-to-noise ratio (SNR) in the receiver to successfully demodulate the despread data signal, the DSSS system completely rejects the narrowband interferer. This continues as long as the above qualifier is met.

The despread process is linear, so that any increases in interference power correspond to equivalent increases in the despread noise floor. At some point the “noise” could be raised such that the detector begins to make mistakes. As long as the filtered spread interferer behaves like noise, conventional noise performance theory can be applied to the detector’s performance. This leads to the well-published concept of the jamming margin [2, 3, 4]. The jamming margin is defined as the difference of the spreading gain and the required detector input signal-to-noise ratio. As long as the interferer power is within the jamming margin, then the direct sequence processing will completely reject it. At higher interference powers, the despread noise floor exceeds the detectors’ ability to make error-free decisions. The DSSS system quickly collapses as the interference exceeds the jamming margin.

For example, assume that a DSSS system is using binary phase-shift keying (BPSK) modulation and a 127 bit maximal length spreading code. More realistically, assume that the packet or frame being sent is 1k bits (125 bytes) long and protected by a cyclic redundancy code (CRC) parity field. If any errors are encountered in reception of the frame/packet, then the CRC should detect it and cause it to be discarded. What is desired is the frame/packet throughput rate in the presence of a narrowband interferer near the DSSS carrier frequency. The results of this example are shown in Figure 4, which compares the DSSS system throughput factor to the interference to signal ratio (ISR).

![Figure 4. DSSS normalized packet/frame throughput vs. interference to signal ratio.](image_url)

As Figure 4 shows, the throughput remains constant and at unity up to the jamming margin. As the noise floor at the despread desired signal is raised by the increasing strength of the spread interferer, more errors are made until the packet/frame error rate nears unity. At this point, the throughput, defined as the ratio of the system bit-rate out to the system input bit-rate, is essentially zero. For a shorter (length 15) spreading code that might be used for high-speed data applications, the jamming margin is smaller and throughput begins to fail at lower interference power levels.

The physics of FH interference rejection

If the operation of direct sequence is viewed as interference suppression, then frequency-hopping can be viewed as performing interference avoidance [4]. The frequency hopping receiver has bandwidth matched to the data modulation, and follows the transmitter as it jumps around the band. If one of those jumps encounters a narrowband interferer, then the communications on that channel can be jammed if all three interference conditions described earlier are met. On the next jump, the narrowband interferer will be moved away from (avoided). This allows the receiver’s selectivity filters to reject the narrowband interferer, essentially independent of its power. The amount of interference rejection is therefore limited by the performance of the receiver selectivity filters.

Channels can, in principle, be overlapped, adjacent, or spaced. Overlapped channels are not allowed for operation in the ISM bands. The total spread of the FH signal must be at least the channel size times the number of hops. This sets the avoidance range of the FH system, in that the FH signal has that much room to move away from a narrowband interferer within that range.

During a hop in which the interferer is in the current channel, the FH system operates as a conventional narrowband single channel link. The modulation chosen, along with the demodulation method used, sets the interference-to-signal ratio (ISR) that the radio can tolerate. Unfortunately, detailed information on ISR performance is not well documented in the reference literature for general modulations. For purposes of discussion, assume that for binary frequency shift keying (BFSK) modulation demodulated with a limiter-discriminator, the tolerable ISR is −10 dB. Thus, if the interference is 10 dB below the desired signal power or
higher, the interference “wins” and communication on that channel ceases. Communication on the remaining N—1 channels continues unabated.

The net throughput of the FHSS system is shown in Figure 5. Interference in one channel has no effect as long as it is below the ISR limit of the demodulator, –10 dB in this case. Above this limit, the interference controls the demodulator on that channel and the desired communication is lost. Interference is not present on the remaining channels, so normal communication proceeds. The throughput falls to (N—J)/N, where J is the number of jammed channels out of the N available.

**Evaluated system definitions**

It is illustrative to measure these interference-suppression mechanisms in both direct-sequence and frequency-hopping spread-spectrum systems. Evaluation hardware is constructed for a direct-sequence transceiver, and another set is constructed for a frequency-hopping transceiver. Both systems are targeted to a simple cordless telephone application, supporting 50 kbp/s uncoded data transmission using the 902 to 928 MHz ISM band. To put quantitative numbers on these cases, the following system definitions have been made.

**The DSSS system**

Two configurations are used for direct-sequence spread-spectrum evaluation hardware. Both systems use BPSK for their modulation. The first uses a processing gain near the FCC minimum for Part 15.247 applications, using a 15-chips-per-data-bit spreading code. This design has a maximum process gain of 10log(15) = 11.8 dB. For an input bit rate of 50 kbp/s, this results in a mainlobe bandwidth of 15 x 50000 x 2 = 1.5 MHz.

The second DSSS system evaluated...
changes only the spreading code. Instead of using 15 chips per input bit, this system uses 127. The maximum process gain is now $10 \log(127) = 21$ dB. Since the input data rate is not changed, the bandwidth of the main lobe is increased to $127 \times 50000 \times 2 = 12.7$ MHz. Figure 6 shows an overlay of these two DSSS signals, where both signals have the same output power.

Notice that the occupied bandwidth of the DSSS signals of Figure 6 are not absolute. Much of the signal energy is in the main lobe of the spectrum, but there is also energy in many sidelobes. Measurements of the total DSSS bandwidth at –20 dBc, –40 dBc, and –60 dBc, give different values. This characteristic becomes important in some of the later measurements.

**The FHSS system**

Only one system configuration is used for the frequency hopping evaluation. As in the direct-sequence evaluation, the bit rate is set to 50 kbps. Channel spacing is set at 76 kHz, which is a convenient value for the frequency synthesizer used in the test. This sets the channel bandwidth efficiency to $50/76 = 0.66 \text{ bits/sec/Hz}. This value is compatible with binary frequency shift keying, the conventional modulation type for FHSS systems. Using 52 channels for the hopper, which is just over the FCC minimum of 50 required for operation in the 902 MHz ISM band under part 15.247, this provides a total spreading bandwidth of 3.9 MHz. This spread system is placed between 912 and 916 MHz, as shown in Figure 7.

Unlike the DSSS systems, the spread bandwidth of the FHSS signal in Figure 7 is well-bounded. Measurements of the total FHSS bandwidth at –20 dBc, –40 dBc and –60 dBc, give essentially the same value. This behavior is defined as hard-bounded spreading.

**DS narrowband interference rejection performance**

The basic operation of the interference rejection mechanism is illustrated in Figure 8. Figure 8a shows the channel, with the x15 DSSS signal at 915 MHz and an interfering CW tone of equal power at 915.5 MHz. From the earlier discussion, after the receiver’s despreading operation, the DSSS signal should return to its original, unspread form. At the same time, the interference should become spread. This is indeed what happens, as shown in Figure 8b. The original DSSS signal is now a single spike at the 70 MHz intermediate frequency (IF). Centered 500 kHz above the desired signal, at the converted frequency of the interference, is the spread interference.

To actually achieve rejection of the interference, the desired signal is now passed through a bandpass filter. Since most of the interference energy is now outside the filter bandwidth designed to pass only the despread signal, this energy is blocked from continuing into the receiver. As long as there is a significant amount of spreading, then there will be an equally significant amount of interference power rejection from the receiver. This is clearly shown in Figure 9, where signals are presented after despreading in the receiver. For these measurements, the equal power interference was moved to be right on the carrier frequency. This is the condition used in the mathematical models predicting process gain and jamming margin.

Figure 8a. Direct-sequence interference transformations using a x15 DSSS signal with CW interferer at 915.5 MHz.

Figure 8b. Direct-sequence interference transformations using a despread IF signal showing compressed DSSS signal and spread interference.

Figure 9a. Direct-sequence process gain effects at the receiver, with equal power CW interferers on the carrier frequency at x15 DSSS.

Figure 9b. Direct-sequence process gain effects at the receiver, with equal power CW interferers on the carrier frequency at x127 DSSS.
The x15 DSSS system. There is 12 dB from the top of the despread signal to the peak of the spread interferer. It is no accident that this distance essentially matches the process gain for this configuration. Figure 9b shows the same measurement except that now, the wider spread factor of x127 is used. The distance to the peak of the spread interference is now 20 dB. Wider spreading improves the rejection of near-frequency interference, as expected.

The 902 MHz ISM band has large pager transmitter signals located just above it, at around 935 MHz. It is important to also check the behavior of the DSSS systems in the presence of such large, out-of-band signals. These measurements are shown in Figure 10. Figure 10a is the channel test setup, showing the DSSS signal at 915 MHz, which for this photograph is the x15 version, and the

 interpoler at 935 MHz with an amplitude that is 40 dB greater than the DSSS signal. Figure 10b is the receiver after despreading this channel signal arrangement. Notice that there is spreading energy from the interferer present in the signal passband. The receiver filters will still reject the interference power, but now there is much more interference power to reject. In the photograph of Figure 10c the DSSS system behavior with
x127 spreading is more striking. There is actually more interference from the out-of-band interferer with the wider spreading in use. The very feature that improved the in-band interference rejection is exacerbating the out-of-band interference rejection. This is a direct result of soft bounded spreading. Because the spreading fac-

tor is nearly eight times wider, the rolloff of the spread sidebands is eight times slower.

FH narrowband interference rejection performance

Like direct-sequence spread spectrum, frequency hopping achieves its interference tolerance by spreading the interfering signal over a wide frequency range at the same time as it collects and despreads the desired signal. The physical process, however, is different. Figure 11 illustrates the FH process. In Figure 11a, the FH signal covering 912-916 MHz is shown with an equal power interferer at 915 MHz. Compare this with Figure 8a, where the same conditions are applied to a DSSS signal. Two major differences are noted: 1) the FH system applies all of its output power at whatever frequency it is operating at during a hop, unlike the DS system that uses all frequencies simultaneously, and 2) the soft-bounded nature of the DS spread compared to the hard-bounded nature of the FH spread.

Figure 11a. FHSS signal with equal power CW interferer at 915 MHz.

Figure 11b. Despread IF signal showing compressed FHSS signal and spread interference.

Figure 12a. Frequency-hopper large in-band interferer performance with a +40dB CW interferer at 914 MHz.

Figure 12b. Frequency-hopper large in-band interferer performance despread IF signal showing compressed FHSS signal and spread interference.

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Figure 13a. Frequency-hopping out-of-band interference performance with an interferer at +20 MHz and +40 dB from the FHSS signal.

Figure 13b. FHSS after receiver despreading.

Figure 13c. Wider band measurement of the FHSS following despreading.

that uses all frequencies simultaneously, and 2) the soft-bounded nature of the DS spread compared to the hard-bounded nature of the FH spread.

Figure 11b shows the signals in the FH receiver following the despread operation. The desired FH signal is now compressed into a single tone at the 70 MHz IF, and the interference is spread. Like the DS system, the use of a narrowband bandpass filter to select the despread FH signal will cause the rejection of most of the interference power. Unlike the DS system, when the interfering signal overlays the desired signal is not a noise signal, but a real jamming signal. That particular hop communication is likely to be impossible. This characteristic is expanded on in Figure 12. The interfering power is increased by 40 dB. Figure 12a shows the channel with the large interferer. In Figure 12b, the signals following the FH despreader are shown. The interferer is now spread. Notice that if the narrowband bandpass filter has sufficient selectivity, this large interferer will be rejected when it is shifted outside the filter. Communications is jammed completely when the frequencies align.

Evaluation of the FHSS system performance in the presence of a large out-of-band interferer is the last comparison measurement. The results are presented in Figure 13. Figure 13a shows the channel configuration, which uses the same conditions as those used in the DSSS evaluation, namely, the large out-of-band interferer is 20 MHz above the spread signal, with +40 dB more signal power. The despread signal is shown in Figure 13b. This shows only the despread FHSS signal, with no effect from the interferer. The wider band measurement of Figure 13c shows the entire story. The spread interferer is present, but all of its energy is removed in frequency by 20 MHz. Filter selectivity can be used to
completely reject this interference. This is a direct consequence of the hard-bounded nature of the frequency-hopped spreading process.

Comparison discussion

These measurements show that the differing physical processes used in direct sequence and frequency hopping do perform differently in the presence of narrowband interference. In fact, these two spread-spectrum approaches can be considered duals. If the interferer is within the spreading band, then the DSSS system can tolerate and completely reject it while the FHSS system can be completely jammed on that channel. For a large out-of-band interferer, the opposite is true. The DSSS process is sensitive to such interferers, where the FHSS system is not.

For the DSSS system, this sensitivity to large out-of-band interferers is a direct consequence of the switched mixer method of generating BPSK. Remember that this modulation method is used twice; once in the transmitter, and once in the receiver for the despreader (Figure 1). The problem is in the receiver despreader, where the spreading of the interference takes place. There are two ways to address this problem. First is to use a rooftop bandpass filter to eliminate out-of-band signals. This works, but because it is not inherently required by the FHSS system (Figure 13) it puts a DSSS system at a complexity disadvantage in this instance. The other method is to examine the real source of the problem, the receiver despreader, and to address it directly.

The remaining points of comparison relate to Figures 4 and 5. Considering the system frame error probability (FEP) in the presence of a narrowband interferer, Figure 4 shows that the direct-sequence system initially completely rejects its presence. For signals lower than the jamming margin, the DSSS system throughput is unity, which means that every packet sent can be accurately received. When the jamming margin is reached, within 5 dB of additional interference power the throughput of the DSSS system has gone to zero. This happens because noise from the spread interferer in the receiver is now large enough to completely dominate the detector. As the interference level continues to grow, so does the noise following the despreader, and the throughput remains at zero.

The frequency hopper shows a degradation in performance at a significantly lower level of interfering signal power. Once the interference is large enough to disturb the detector on that channel, communications through that channel is lost. Any packets sent on that channel must be present on a different channel. A major difference here is that once that channel is lost due to the narrowband interference, then it remains lost. This remains true irrespective of the level of the interfering signal power, to first order. At large interference levels, other effects such as ultimate filter rejec-
tion levels and front-end compression come into effect.

**Conclusion**

The proper choice of direct sequence or frequency hopping as a spread spectrum technique depends on the actual environment in which the system will be deployed. If there are narrowband interferers of moderate level, then a DSSS system that will completely reject them may be desirable. Should there be any large interfering signals, then a DSSS link may completely fail while FHSS is likely to continue operating, even though the interference is not completely rejected.

**References**


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