CHAPTER

4 Spread Spectrum Techniques and Systems

ACRONYMS

- PN : Pseudonoise
- FH : Frequency Hopping
- DS : Direct Sequence
- CSMA : Carrier Sense Multiple Access
- SFH : Slow Frequency Hopping
- FFH : Fast Frequency Hopping

4.1 INTRODUCTION

As the name 'spread-spectrum' suggests, this technique involves spreading the bandwidth to transmit data with more security.

Spread spectrum technique was initially developed for military applicatios to avoid jamming and interception because a signal spread over a wider bandwidth make jamming more difficult.

Bandwidth expansion is achieved by modulating again the modulated signal with a spreading code. This code is generated by a pseudonoise or pseudorandom number generator. A number of modulated signals (representing a number of users) could be carried over the same bandwidth by using a different code for each user. The first type of spread spectrum that was developed was known as frequency hopping. A new type of spread spectrum is direct sequency. The detail of these spectrums will be discussed further in this chapter.

4.2 ADVANTAGES OF SPREAD SPECTRUM TECHNIQUES

Potential advantages of spread spectrum systems over narrow band systems include the following:

1. Reduced interference
2. Highly secure communication

3. Low density power spectrum for signal hiding
4. Antijamming capability
5. Increased capacity
6. Low cost
7. Immunity to noise and multipath distortion.
8. Several users can transmit the data simultanously.
9. Increased spectral efficiency.

4.3 CLASSIFICATION OF SPREAD SPECTRUM SYSTEMS

Spread spectrum systems have been classified by their architecture and modulation concepts into the following categories as shown in Fig. 4.1.

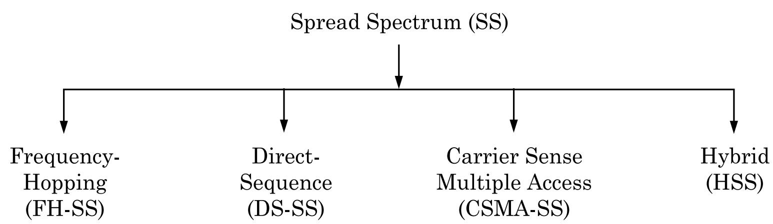


Fig. 4.1 *Classification of Spread Specturm*

The most frequently used spread spectrum techniques, DS and FH requires PN sequences for spreading, synchronization and despreading. The PN sequences are described in next article.

4.4 PSEUDONOISE SEQUENCE

Pseudonoise sequence can simply be defined as a series of bits (1's and 0's) that seems to be random but repeat itself after *n* numbers (or bits) where *n* is the length of a Pseudonise sequence (or PN code).

The major work of pseudonoise sequence in wireless communication is

1. Spread the bandwidth of the user signal.
2. Distinguish between different user signals sharing the same bandwidth by changing the PN sequence.

A random series of binary ones and zeros representing a PN sequence can be produced by PN generator. This PN sequence eventually repeats but appears to be random. PN sequences are generated by an algorithm using some initial value called the '*Seed*'. If the algorithm is good, the resulting sequences will pass many reasonable tests of randomness. Such numbers are referred to as *Pseudonoise sequences* or *Pseudo random numbers*.

At the receiver side, unless you know the algorithm and the seed. It is impractical to predict the sequence. Hence only a receiver that shares this information with a transmitter will be able to decode the signal successfully.

The application of PN sequence in transmitter and receiver side is given as follows—

1. At transmitter side: The correlator yields an encrypted digital representation of the original signal using PN sequence (chipping sequence). This encrypted signal is then spread over a very wide frequency spectrum.

2. At receiving side: The signal is demodulated back to a narrow bandwidth and then fed to a 'decorrelator'. This decorrelator uses its unique PN code (chipping code) to extract only the information intended for it. A signal correlated with a given chipping sequence and decorrelated with the same chipping sequence returns the original signal. Decorrelating the signal with the wrong PN sequence would result in pure noise.

Example: Note that binary bits are assumed here are in alphabetical sequence just to understand the transmission and reception more clearly.

$$\text{Transmission Side}\begin{cases}\underset{\text{(Narrow band signal)}}{\text{User}_1\text{ data}} + \underset{\text{(Chipping sequence}_1\text{)}}{\text{ABCD}} \longrightarrow \underset{\text{(Spreaded Signal)}}{\text{APPLE}} \\ \text{User}_2\text{ data} + \underset{\text{(Chipping sequence}_2\text{)}}{\text{XYZW}} \longrightarrow \text{MANGO}\end{cases}$$

Both signals are transmitted at same time. These do not interfare with each other because PN code (chipping sequence) is different.

$$\text{Reception Side}\begin{cases}\text{APPLE} + \text{ABCD} \longrightarrow \text{User}_1\text{ data} \\ \text{MANGO} + \text{XYZW} \longrightarrow \text{User}_2\text{ data}\end{cases}$$

If chipping sequence is not known or incorrect then data cannot be recovered as given

$$\text{APPLE} + \text{XYZW} \longrightarrow \underset{\text{(Wrong information)}}{\text{Noise}}$$

4.5 BLOCK REPRESENTATION OF SPREAD SPECTRUM COMMUNICATION SYSTEM

General model of a spread spectrum digital communication system is shown in Fig. 4.2.

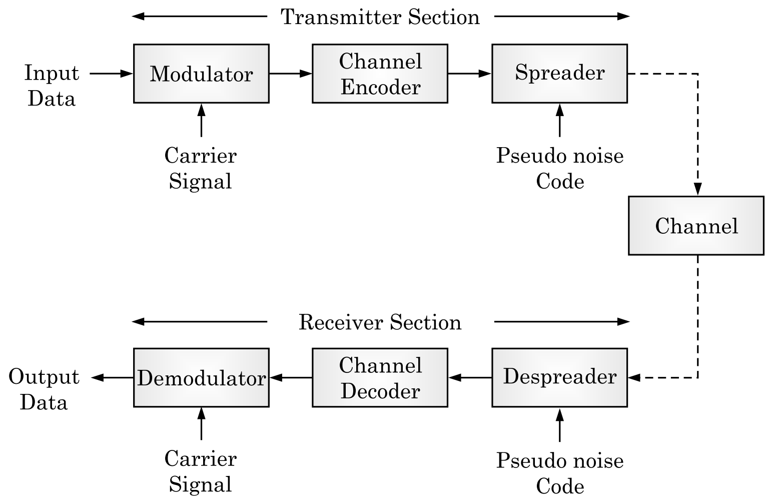


Fig. 4.2 *Block diagram of Spread spectrum digital communication system.*

Working Detail:

Following steps will clear the working of this system:

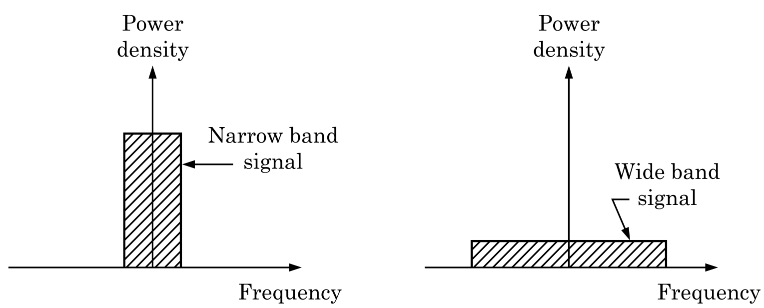
1. Input data alongwith carrier signal is fed to the modulator.
2. This modulated signal is then fed to a channel encoder that produces an analog signal with a relatively narrow bandwidth around some central frequency.
3. After encoding, the signal is further modulated to spread the badnwdith using pseudonoise code i.e. a bandwidth spreading code.
4. This spread spectrum signal is then transmitted over the channel.
5. At the receiver side, the same pseudonoise spreading code is used to demodulate the spread spectrum signal.
6. After demodulation, the spread spectrum signal is converted into narrow band. This signal is fed to channel decoder to recover the narrow band modulated signal.
7. This decoded signal then finally pass again to demodulator where this signal is demodulated using carrier signal to recover the data bits.

Note: The position of both modulators could be interchanged (in transmitter section) in some examples. The input data may be spreaded first via pseudonoise spreading code and then modulated with carrier signal. The process also reverses in receiver section. First demodulats the signal and then despread it.

4.6 CONCEPT OF SPREADING AND DESPREADING

Conversion of a narrowband signal into a wide band spreaded signal has a lot of advantages as discussed in section 4.2. The main advantage is the reduction in narrowband interference.

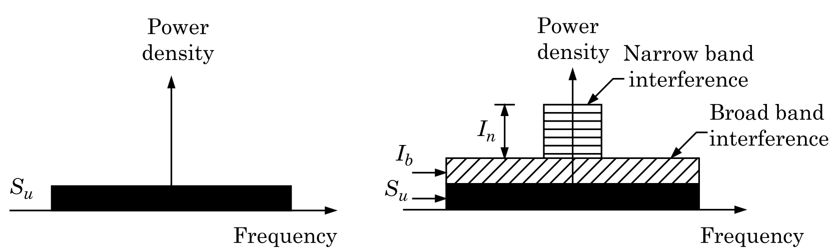
The signal is spreaded from the sender side (transmitter side) and it is desprreaded at the receiver side. Fig. 4.3 shows how a narrowband signal is converted into a wideband signal.



(*a*) Before Spreading (*b*) After Spreading

Fig. 4.3 *Spreading of a narrowband signal.*

Figure 4.3(*a*) and (*b*) show that the energy needed to transmit the signal is the same in both cases (the shaded area shown in fig.) but the signal is now spread over a wider frequency range. The power level of the spread signal can be much lower that of the original narrowband signal withoiut losing any data.



(*a*) Signal at Transmitter side (*b*) Signal at receiver side

Fig. 4.4 *Interference added during transmission.*

When this narrowband signal is transmitted over a channel then some interference (narrowband and wideband) gets added in this signal i.e. received with the narrow-band signal at receiver side, as shown in Fig. 4.4.

Here $I_n \rightarrow$ Narrowband interference

$I_b \rightarrow$ Broadband interference

$S_u \rightarrow$ User Signal

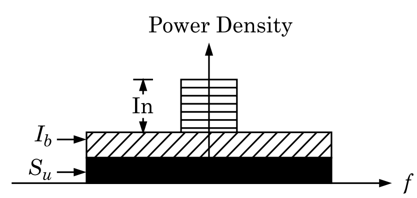
At receiver side, a special process is done to remove the interference and recover the original signal. In the *despreading* steps, the receiver performs the following operators. After these steps, received input [Fig. 4.5(*a*)] changed into its replica [Fig. 4.5(*b*)]

1. Convert the spread user signal into a narrow band signal again.

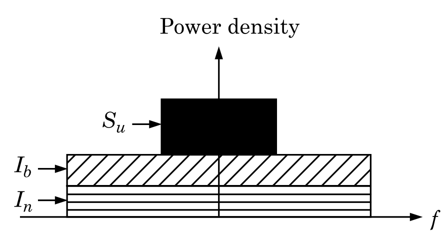
2. Spread the narrow band interference.

3. Remain bandband interference as it is.

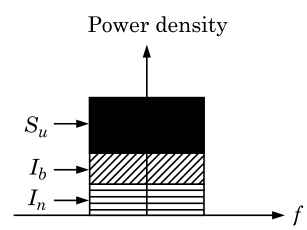
4. After the convertion of broodband signal into narrowband signal, it is passed to bandpass filter to cut the left and right portion except narrow band signal shown in [Fig. 4.5 (*c*)]. By this way the original signal gets recovered because the original signal is much stronger than the remaining interference.



(*a*) *Signal at Receiver input*



(*b*) *Replica of received Signal*



(*c*) *Signal after passing through band pass filter.*

Fig. 4.5 *Despreading of a wideband signal.*

4.7 DIRECT SEQUENCE SPREAD SPECTRUM (DS-SS)

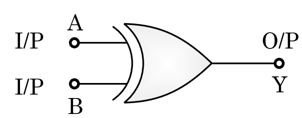
So far we have discussed about spread spectrum now we will understand how spread spectrum is achieved using direct sequence. Direct sequence is a combination of bits (1*s* and 0*s*) that is used to code the user data.

In DS-SS, user bit stream (user data) is exclusive-OR (XOR) with a random number (chipping sequence). Chipping sequence is a set of smaller pulses which repeat with each user bit.

EX-OR function is performed here due to the reason that EX-OR gives an output high at unequal input bits (0 and 1 & 1 and 0) and makes its output low at equal bits (00 and 11). Fig. 4.6 shows the truth table and symbol of EX-OR gate

I/P–1 (A)	*I/P–2 (B)*	*Output* $Y = A \oplus B$
0	0	0
0	1	1
1	0	1
1	1	0

(*a*) *Truth table*



(*b*) *Symbol*

Fig. 4.6 *Truth table and sysmbol of Ex-OR gate.*

The working can be explained by the follows

1. When first input is zero, the output follows the second input.
2. When first input is one, the output is replica of second input.

Now we can assume user bits as first input and chipping sequence as second input. It means that it user bit is '0' then the result is same as chipping sequence, and if user bit is '1' then the result is complement (or reverse) or chipping sequence.

This operation can be easily understood by the following example—

Say, User bits (I/p-1) = 0 1 1 0

Chipping sequence (I/p-2) = 1010

then the result is either the sequence 1010 (if user bit equals 0) or its complement (if user bit equals 1), as shown in Fig. 4.7

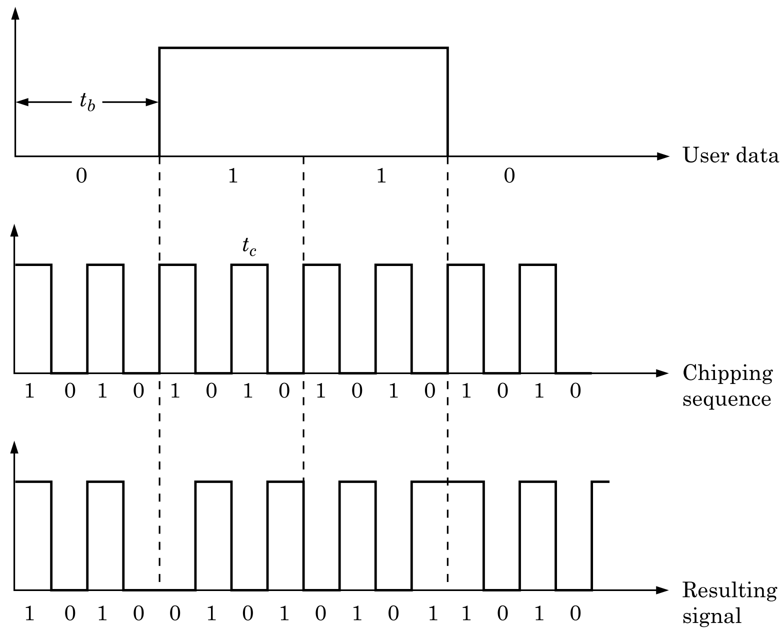


Fig. 4.7 *Spreading the signal with DS-SS.*

Here in Fig. 4.7, t_b represents each user bit duration and t_c represents chipping bit duration. Sometimes the chipping sequence is also known as **Pseudo-noise sequence**.

From the above example (as shown in Fig. 4.7) we may conclude that a 4 bit chipping sequence (spreading code) spreads each user bit 4 time greater than 1 bit spreading code. Therefore, the spreading factor is 4 in this example as spreading factor is given by—

$$\text{Spreading factor } (s) = \frac{t_c}{t_b} \qquad ...(4.1)$$

If the original signal bandwidth is W, then the final signal bandwidth after spreading = $s \times W$.

4.7.1 DS-SS Transmitter

Figure 4.8 shows the transmiter section and its each block of direct sequence spread spectrum system.

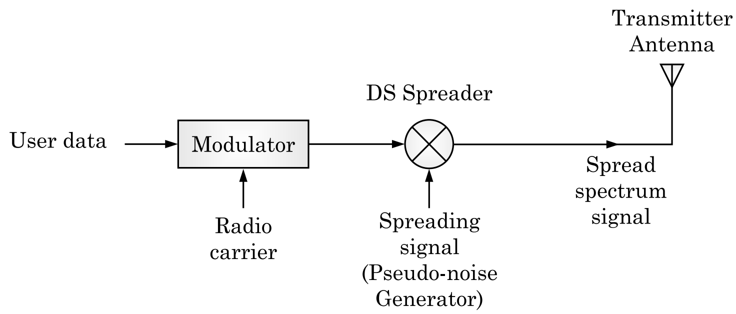


Fig. 4.8 *DS-SS Transmitter.*

The first step that is performed in the transmitter section is modulation of the user data with carrier signal. The modulated signal is then spreaded with the chipping sequence (or spreading signal or pseudonoise signal) that is generated by pseudonise generator. This signal is then transmitted using transmitting antenna.

Example: User signal bandwidth = 1 MHz
Radio carrier bandwidth = 1 GHz
Spreading signal = 10 bit PN code,

then the resulting modulated signal after spreading would have 10 GHz bandwidth. We may also change the positioin of spreader and modulator. Then spreaded signal = 1 MHz × 10 bit code = 10 MHz. This signal is then shifted at carrier frequency of 1 GHz.

4.7.2 DS-SS Receiver

DS-SS Receiver performs just the inverse function of the transmitter. The reconstruction process of the original data in the receiving path is more complex than that in transmitting path due to addition of the noises and multipath propagation.

The very first step in the detection is that the receiver has to know the original chipping sequence that was used in transmitter to spread the signal. Sequences at the transmitter and receiver have to be precisely synchronized. This chipping sequence is then finally producted with the incoming signal received from antenna and given to integrator section that add all these products. This process is also known as correlation and the device performing this function is 'correlator'. Then the despreaded signal is given to demodulator where the radio carrier is detected and original data (that was sent during transmission) is received.

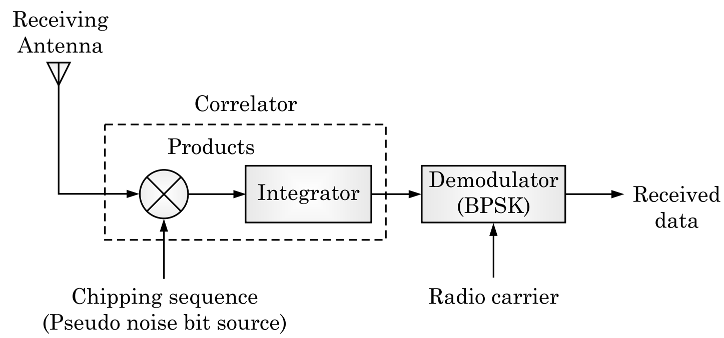


Fig. 4.9 *DS-SS Receiver.*

4.8 FREQUENCY HOPPING SPREAD SPECTRUM (FH-SS)

In the previous type of spread spectrum hopping technique (i.e. DS-SS), we have studied that the user data is spreaded in bandwidth with the chipping sequence via digital modulation. The FH-SS scheme as an implementation concept similar to DH-SS system.

In FH-SS, the signal is broadcasted over a random series of radio frequencies, hopping from one frequency to another fixed intervals. At receiver side, the message is reconstructed by hopping between same frequencies in synchronization with the transmitter.

The total available bandwidth of the system is divided into many smaller bandwidths plus guard spaces between each bandwidth. Each division of badnwidths represents a channel. Transmitter and receiver stay on one of these channels at one time and then hop on to another channel.

Let us assume, the frequeency separtion between adjacent frequencies is Δf and the total number of channels are N, then the processing gain of FH-SS system is—

$$G = \frac{\text{Radio-Frequency bandwidth}}{\text{Message bandwidth}} = \frac{N \cdot \Delta f}{\Delta f} \quad ...(4.2)$$

$$\boxed{G = N} \quad ...(4.3)$$

Therefore, the FH-SS system produces a spreading effect by pseudorandomly hopping the RF carrier frequency over the available RF carrier frequencies, f_1, f_2 ... f_N where N could be several thousands or more.

The pattern of channel usage is called the '*hopping sequence*'. According to hopping sequence the FH-SS system is divided into two parts.

1. Slow Frequency Hopping (SFH)

2. Fast Frequency Hopping (FFH)

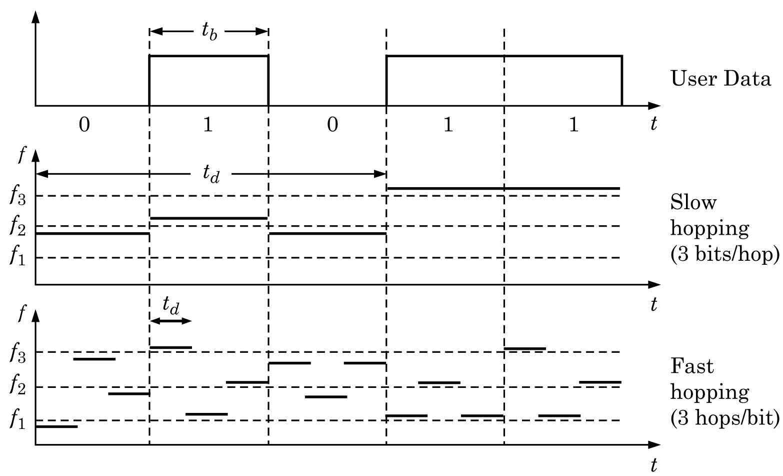


Fig. 4.10 *Slow and Fast frequency hopping.*

In Fig. 4.10, let hopping rate is denoted by t_h and data rate is denoted by t_d then

$$\text{In SFH} \rightarrow t_h < t_d$$
$$\text{In FFH} \rightarrow t_h > t_d$$

(*i*) Slow Frequency Hopping: In slow frequency hopping system, the hopping rate (switching from frequency to frequency) is slower than the user data rate. It means that there are several or many bits per frequency hop. Fig. 4.10 shows that the transmitter uses frequency f_2 for transmitting the first three bits. After transmitting these three bits, the transmittter hops to the next frequency f_z.

(*ii*) Fast Frequency Hopping: In FFH system, the hopping rate is higher than user data rate. Therefore there are many hops per frequency bit. In the example of Fig. 4.10, the transmitter hops three times during a bit period. At the transmission of next bit, transmitter again hops three times (frequency changes three times).

4.8.1 FH-SS Transmitter

The block diagram of FH-SS transmitter section is shown in Fig. 4.11.

The first step in FH-SS transmitter is the modulation of user data (binary data) using some digital to analog encoding scheme, such as FSK or BPSK. For example, the modulating scheme uses FSK that generate—

1. f_0 frequency for binary 0, and

2. f_1 frequency for binary 1.

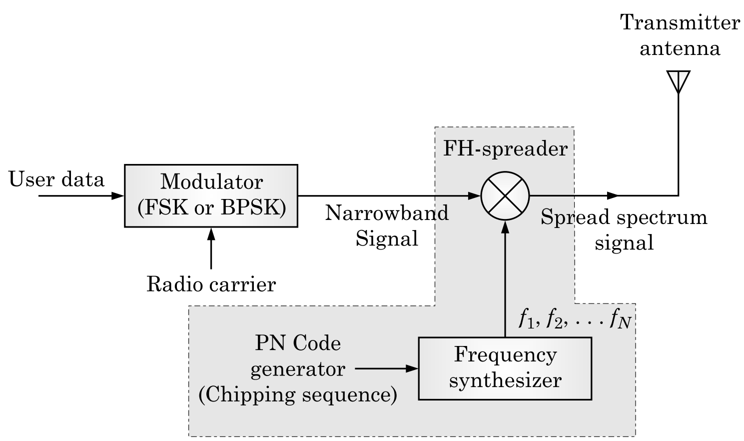


Fig. 4.11 *FH-SS Transmitter.*

This modulated signal is then fed to FH-SS spreader for spreading of modulated signal. In FH-spreader section, the chipping/ hopping sequence (i.e. generated by PN code generator) is fed into a frequency synthesizer. Here, each bits of the PN code generator specifies one of the 2^n carrier frequencies. At next n^k bit sequence, a new carrier frequency is generated. Let, the frequency synthesizer generate the carrier frequency f_C. Now, in FH-spreader, a second modulation takes place that spreads the signal with the frequency,

1. $f_c + f_0$ for binary 0, and

2. $f_c + f_1$ for binary 1 respectively.

This spreaded signal over frequency f_c is transmitted through transmitting antenna.

Key Note: Two FH-SS transmitters should never use the same carrier frequency, f_c at the same time. This precaution is taken to avoid overlapping or interference. Therefore, all transmitters and their hopping sequences should be in coordination.

4.8.2 FH-SS Receiver

The receiver section of FH-SS system should work in synchronization with the transmitter section. A simplified block diagram of FH-SS receiver is shown in Fig. 4.12.

Receiver section performs just the inverse function of transmitter to reconstruct the user data. Several fitters are also required for this operation (not shown in Fig. 4.12). On reception, the spread spectrum signal is demodulated using the same PN code (chipping sequence), that is why the receiver and transmitter should always work in synchronization. After passing through FH-despreader the spreaded signal is converted into narrow-band signal. Here, it is again demodulated to reproduce the original user data.

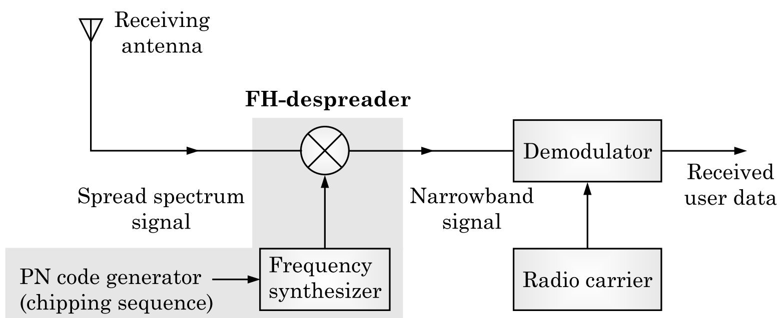


Fig. 4.12 *FH-SS Receiver.*

4.9 DS-SS SYSTEMS VS. FH-SS SYSTEMS

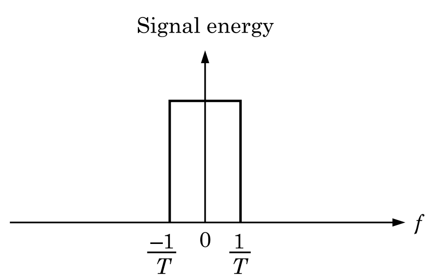
S.No.	*DS-SS Systems*	*FH-SS Systems*
1.	Spreading process is complex	Spreading process is simple
2.	DS-SS systems always use the total bandwidth available.	FH-SS systems use only a portion of the total band at any time
3.	More resistant to fading and multipath effects.	Less resisted to fading and multipath effects.

S.No.	*DS-SS Systems*	*FH-SS Systems*
4.	No need of frequency synthesizer.	Frequency synthesizer is required.
5.	Rejection capabilities to cancel out interferences and noise, are good.	Interference rejection capability is poor.

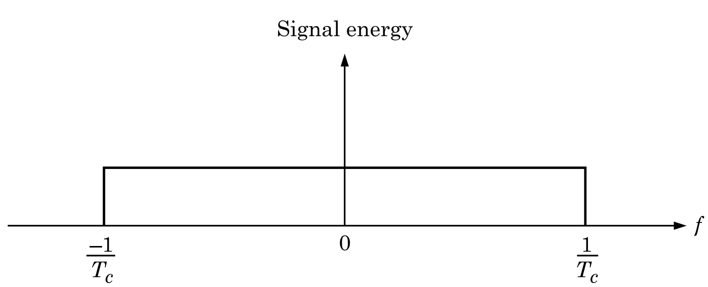
4.10 PERFORMANCE OF DS-SS SYSTEMS

The major advantage of spread spectrum system is the ability of these systems to cancel out the interference that may create ambiguity and noise in the communication. To check the performance of DS-SS system, we study its rejection capabilities in additive white gaussian noise (AWGN) and jamming signal environment.

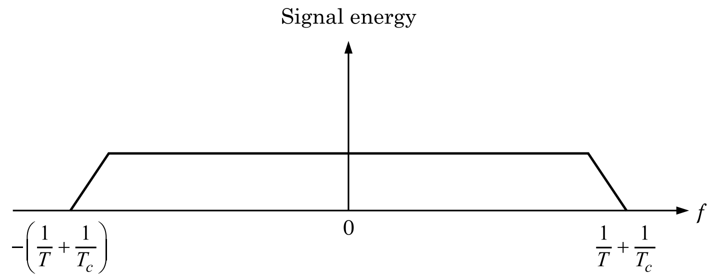
Let us concentrate on the given example (shown in Fig. 4.13). Assume that the information signal has bit width of T, which is equivalent to a data rate of $1/T$. In that case, the spectrum of the signal, dependingon the encoding technique, is roughly $2/T$. Similarly, the spectrum of the PN sequence (having frequency f_C) is $2/T_C$. The amount of spreading achieved is a direct result of the data rate of the PN stream.



(*a*) Spectrum of data signal



(*b*) Spectrum of pseudo noise signal



(*c*) Spectrum of combined signal

Fig. 4.13 *Approximate spectrum of DS-SS Signal.*

Let us assume a simple jamming signal at the center frequency of the DS-SS system. The jamming signal has the form

$$S_j(t) = \sqrt{2 \cdot S_j}\cos(2\pi f_c t) \quad \text{...(4.4)}$$

and $S(t)$ is the transmitted signal then the received signal is

$$S_r(t) = S(t) + S_j(t) + n(t) \quad \text{...(4.5)}$$

where $n(t)$ is additive white gaussian noise.

Let the chipping sequence is represented by $C(t)$. At receiving side, the despreader multiplies $S_r(t)$ by $C(t)$, so the signal component due to the jamming signal is

$$y_j(t) = \sqrt{2S_j}\, C(t)\cos(2\pi f_c t) \quad \text{...(4.6)}$$

This is simply BPSK modulation of the carrier tone. ?Thus, the carrier power S_j is spread over a badnwidth of approximately $2/T_c$. However the BPSK demodulator following the DS-SS despreader includes a bandpass filter matched to the BPSK data, with bandwidth of $2/T$. Thus most of the jamming power is filtered. Although a number of factors come into play. As an approximation, we can say that the jamming power passed by the filter is,

$$S_{jF} = \frac{S_j(2/T)}{(2/T_c)} = S_j(T_c/T)$$

$$S_{jF} = S_j(T_c/T) \quad \text{...(4.7)}$$

Equation 4.7 illustrates that the jamming power has been reduced by a factor of (T_c/T) through the use of spread spectrum.

The inverse of this factor is the gain in signal-to-noise ratio.

$$\boxed{G_p = \frac{T}{T_c} = \frac{R_c}{R} \simeq \frac{W_s}{W_d}} \quad \text{...(4.8)}$$

where, R_c = Spreading bit rate

R = Data rate

W_d = Signal bandwidth

W_s = Spread spectrum signal bandwidth

4.11 PERFORMANCE OF FH-SS SYSTEMS

As we know that a large number of frequencies are used in FH-SS system so that spread spectrum signal bandwidth (W_S) is much larger than original signal bandwidth (W_d). One major advantage of this is that a large number of channels results in a system that is quite resistance to noise and jamming.

Example: Assume that we have an MFSK transmitter with bandwidth W_d and noise jammer of the same bandwidth, and fixed power S_j on the signal carrier frequency. Then we have a ratio of signal energy per bit to noise power density per hertz of,

$$\frac{E_b}{N_j} = \frac{E_b \cdot W_d}{S_j} \quad \text{...(4.9)}$$

If frequency hopping is used, the jammer must jam all 2^K frequencies. With a fixed power, this reduces the jamming power in any one frequency band to $S_j/2^K$. The gain in signal to noise ratio (or processing gain) is similar to the result for DS-SS system, i.e.

$$G_p = 2^K = \frac{W_s}{W_d} \quad \text{...(4.10)}$$

SUMMARY

- Spread spectrum is a technique used to convert narrow band signal into wide band signal.
- Main advatnage of spread spectrum system is antijamming capability and secure communication with reduced interference.
- Pseudo noise code (PN code) is a code word i.e. used to spread the bandwidth of a signal.
- A signal correlated with a given PN sequence and de-correlated with the same PN sequence returns the original signal.
- Spread spectrum systems are divided into two main parts—

  1. Direct Sequence Spread Spectrum (DS-SS)

  2. Frequency Hopping Spread Spectrum (FH-SS)
- DS-SS systems worked on total available bandwidth available and FH-SS systems uses only a portion of the total bandwidth available at given time.
- Chipping sequence is a set of smaller pulses which repeat with each user bit.
- Spreaded signal bandwidth is a product of user signal bandwidth and PN code.

  Spreaded Signal = user signal × PN code
- In slow-frequency hopping, the hopping rate is slower than the user data rate.
- In fast-frequency hopping, the hopping rate is higher than user data rate.
- Frequency synthesizer is required in FH-SS systems.

REVIEW QUESTIONS

1. What do you understand by 'Spread Spectrum technique'? What are the benefits in this technique.
2. What is direct sequence spread spectrum?
3. What is the basic principle of frequency hopping spread spectrum? How many types of frequency hopping are possible?
4. Draw the block diagram of FH-SS transmitter system and explain each block in detail.
5. Draw the block diagram of a basic spread spectrum digital communication system and explain its working detail.
6. What is the concept of spreading and despreading? Explain in brief.
7. What do you understand by pseudonoise sequence?
8. Explain the difference between DS-SS systems and FH-SS systems.
9. Explain the performance of DS-SS systems.
10. Explain the performance of FH-SS systems.
11. What are the advatnages of spread spectrum systems over narrow band spectrum systems?

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