UNIT III

FREQUENCY HOPPED SPREAD SPECTRUM SYSTEMS 10 hrs.

Frequency hopped spread spectrum system model with block diagram – Demodulation - Fast hopping versus slow hopping - Advantages and limitations of FHSS systems - Performance of FH/QPSK and FH/DPSK systems in partial band jamming – Time hopping – chirp - Example of SS - Global Positioning System.

FREQUENCY HOPPING SYSTEMS

We now consider a spread-spectrum technique called frequency hopping (FH). The modulation most commonly used with this technique is M-ary frequency shift keying (MFSK), where $k = \log_2 M$ information bits are used to determine which one of M frequencies is to be transmitted. The position of the M-ary signal set is shifted pseudo randomly by the frequency synthesizer over a hopping bandwidth W_{ss}. A typical FH/MFSK system block diagram is shown in Figure 3.1.

In a conventional MFSK system, the data symbol modulates a fixed frequency carrier; in an FH/MFSK system, the data symbol modulates a carrier whose frequency is pseudo-randomly determined. In either case, a single tone is transmitted. The FH system in Figure 3.1 can be thought of as a two-step modulation process data modulation and frequency-hopping modulation even though it can be implemented as a single step whereby the frequency synthesizer produces a transmission tone based on the simultaneous dictates of the PN code and the data. At each frequency hop time, a PN generator feeds the frequency synthesizer a frequency word (a sequence of t chips), which dictates one of 2^f symbol-set positions. The frequency-hopping bandwidth W_{ss} and the minimum frequency spacing between consecutive hop positions Af, dictate the minimum number of chips necessary in the frequency word.

For a given hop, the occupied transmission bandwidth is identical to the bandwidth of conventional MFSK, which is typically much smaller than W_{ss}. However, averaged over many hops, the FH/MFSK spectrum occupies the entire spread-spectrum bandwidth. Spread-spectrum technology permits FH bandwidths of the order of several giga hertz, which is an order of magnitude larger than implementable DS bandwidths, thus allowing for larger processing gains in FH compared to DS systems. Since frequency hopping techniques operate over such wide bandwidths, it is difficult to maintain phase coherence from hop to hop. Therefore, such schemes are usually configured using noncoherent demodulation. Nevertheless, consideration has been given to coherent FH in Reference.

In Figure 3.1 we see that the receiver reverses the signal processing steps of the transmitter. The received signal is first FH demodulated (dehopped) by mixing it with the same sequence of pseudo randomly selected frequency tones that was used for hopping. Then the dehopped signal is applied to a conventional bank of M noncoherent energy detectors to select the most likely symbol.

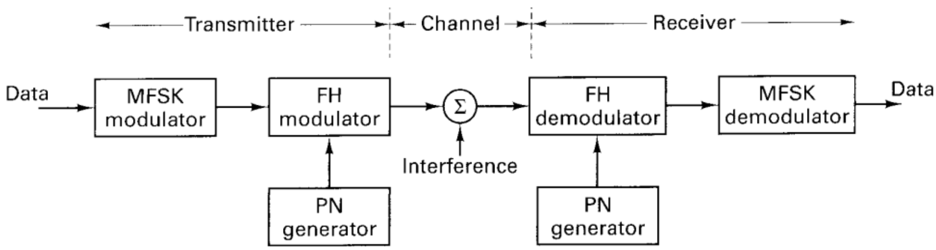

Figure 3.1 FH/MFSK System.

Example 3.1 Frequency Word Size

A hopping bandwidth W_{ss}, of 400 MHz and a frequency step size Δf of 100 Hz are specified. What is the minimum number of PN chips that are required for each frequency word?

Solution:-

Number of Tones contained in $W_{ss} = W_{ss}/\ \Delta f = 400$ MHz/100 Hz

$$= 4 \times 10^6$$

Minimum number of chips — $[\log_2 (4 \times 10^6)]$

$$= 22 \text{ chips}$$

where [x] indicates the smallest integer value not less than x.

Frequency Hopping Example

Consider the frequency hopping example illustrated in Figure 3.2. The input data consist of a binary sequence with a data rate of R = 150 bits/s. The modulation is 8-ary FSK. Therefore, the symbol rate is $R_s = R/(\log_2 8) = 50$

symbols/s (the symbol duration T = 1/50 = 20 ms). The frequency is hopped once per symbol, and the hopping is time synchronous with the symbol boundaries. Thus, the hopping rate is 50 hops/s. Figure 3.2 depicts the time-bandwidth plane of the communication resource; the abscissa represents time, and the ordinate represents the hopping bandwidth, W_{ss}. The legend on the right side of the figure illustrates a set of 8-ary FSK symbol-to-tone assignments. Notice that the tone separation specified is 1/T = 50 Hz, which corresponds to the minimum required tone spacing for the orthogonal signaling of this noncoherent FSK example.

A typical binary data sequence is shown at the top of Figure 3.2. Since the modulation is 8-ary FSK, the bits are grouped three at a time to form symbols. In a conventional 8-ary FSK scheme, a single-sideband tone (offset from f_0, the fixed center frequency of the data band), would be transmitted according to an assignment like the one shown in the legend. The only difference in this FH/MFSK example is that the center frequency of the data band f_o is not fixed. For each new symbol, f_0 hops to a new position in the hop bandwidth, and the entire data-band structure moves with it. In the example of Figure 3.2, the first symbol in the data sequence, 0 1 1, yields a tone 25 Hz above f_o. The diagram depicts f_o with a dashed line and the symbol tone with a solid line. During the second symbol interval, f_0 has hopped to a new spectral location, as indicated by the dashed line. The second symbol, 1 1 0, dictates that a tone indicated by the solid line, 125 Hz below f_o, shall be transmitted. Similarly, the final symbol in this example, 0 0 1, calls for a tone 125 Hz above f_o. Again, the center frequency has moved, but the relative positions of the symbol tones remain fixed.

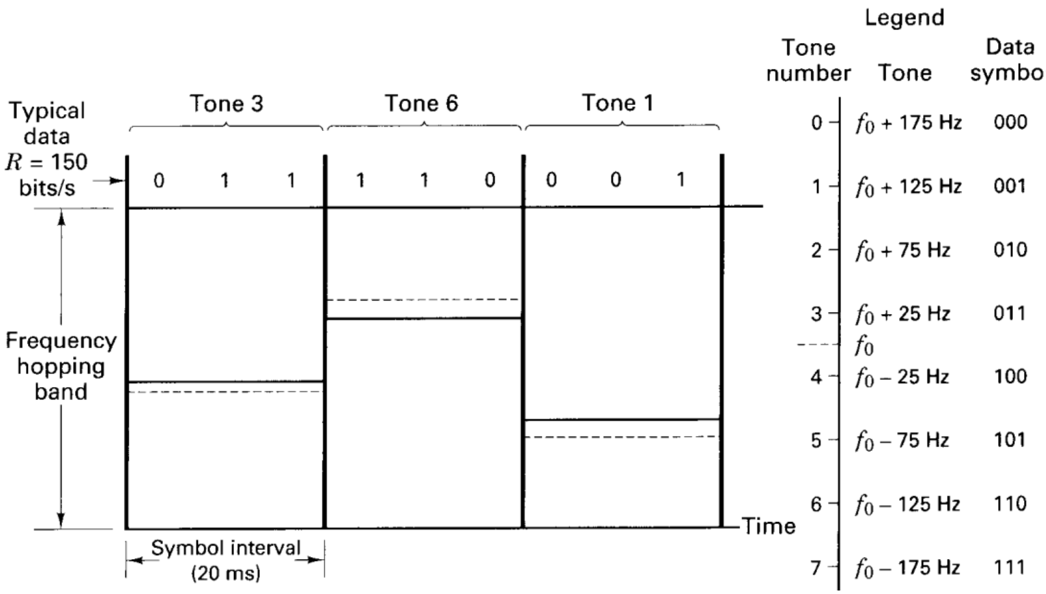

Figure 3.2 Frequency-hopping example using 8-ary FSK modulation.

bandwidth, and the entire data-band structure moves with it. In the example of Figure 3.2, the first symbol in the data sequence, 0 1 1, yields a tone 25 Hz above f_o. The diagram depicts f_o with a dashed line and the symbol tone with a solid line. During the second symbol interval, f_0 has hopped to a new spectral location, as indicated by the dashed line. The second symbol, 1 1 0, dictates that a tone indicated by the solid line, 125 Hz below f_o, shall be transmitted. Similarly, the final symbol in this example, 0 0 1, calls for a tone 125 Hz above f_o. Again, the center frequency has moved, but the relative positions of the symbol tones remain fixed.

Robustness

A common dictionary definition describes the term robustness as the state of being strong and healthy; full of vigor; hardy. In the context of communications, the usage is not too different. Robustness characterizes a signal's ability to withstand impairments from the channel, such as noise, jamming, fading, and so on. A signal configured with multiple replicate copies, each transmitted on a different frequency, has a greater likelihood of survival than does a single such signal with equal total power. The greater the diversity (multiple transmissions, at different frequencies, spread in time), the more robust the signal against random interference.

The following example should clarify the concept. Consider a message consisting of four symbols: s_1, s_2, s_3, s_4. The introduction of diversity starts by repeating the message N times. Let us choose N = 8. Then, the repeated symbols, called chips, can be written.

SI S1 Sl S1 S1 S1 S1 S1 S2 S2 S2 S2 S2 S2 S2 S2 S3 S3 S3 S3 S3 S3 S3 S3 S4 S4 S4 S4 S4 S4 S4 S4

Each chip is transmitted at a different hopping frequency (the center of the data bandwidth is changed for each chip). The resulting transmissions at frequencies f_i, f_i, f_k,... yield a more robust signal than without such diversity. A target-shooting analogy is that a pellet from a barrage of shotgun pellets has a better chance of hitting a target, compared with the action of a single bullet.

Frequency Hopping with Diversity

In Figure 3.3 we extend the example illustrated in Figure 3.2, with the additional feature of a chip repeat factor of N = 4. During each 20-ms symbol interval, there are now four columns, corresponding to the four separate chips to be transmitted for each symbol. At the top of the figure we see the same data sequence, with R = 150 bps, as in the earlier example; and we see the same 3-bit partitioning to form the 8-ary symbols. Each symbol is transmitted four times, and for each transmission the center frequency of the data band is hopped to a new region of the hopping band, under the control of a PN code generator. Therefore, for this example, each chip interval, T_c, is equal to T/N = 20 ms/4 = 5 ms in duration, and the hopping rate is now

$$NR/\log_2^8 = 200 \text{ hops/s}$$

Notice that the spacing between frequency tones must change to meet the changed requirement for orthogonality. Since the duration of each FSK tone is now equal to the chip duration, that is, T_c, = T/N, the minimum separation between tones is $1/T_c$ = N/T = 200 Hz. As in the earlier example, Figure 3.3 illustrates that the center of the data band (plus the modulation structure) is shifted at each new chip time. The position of the solid line (transmission frequency) has the same relationship to the dashed line (center of the data band) for each of the chips associated with a given symbol.

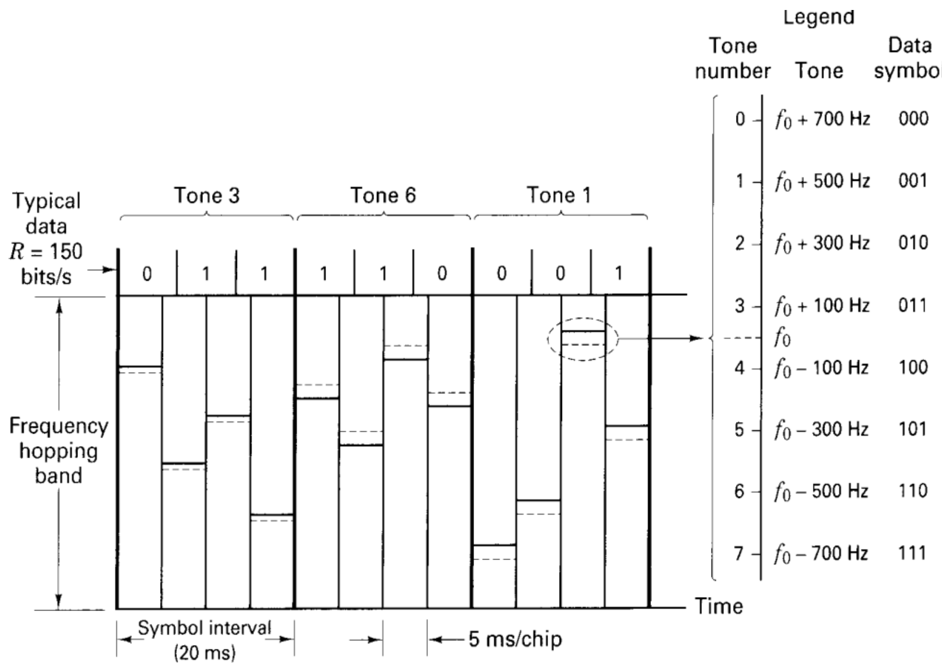

Figure 3.3 Frequency hopping example with diversity (N= 4).

Fast Hopping versus Slow Hopping

In the case of direct-sequence spread-spectrum systems, the term "chip" refers to the PN code symbol (the symbol of shortest duration in a DS system). In a similar sense for frequency hopping systems, the term "chip" is used to characterize the shortest uninterrupted waveform in the system. Frequency hopping systems are classified as slow frequency hopping (SFH), which means there are several modulation symbols per hop, or as fast-frequency hopping (FFH), which means that there are several frequency hops per modulation symbol. For SFH, the shortest uninterrupted waveform in the system is that of the data symbol; however, for FFH, the shortest uninterrupted waveform is that of the hop. Figure 3.4a illustrates an example of FFH; the data symbol rate is 30 symbols/s and the frequency hopping rate is 60 hops/s. The figure illustrates the waveform s(t) over one symbol duration (1/30s). The waveform change in (the middle of) s(t) is due to a new frequency hop. In this example, a chip corresponds to a hop since the hop duration is shorter than the symbol duration. Each chip corresponds to half a symbol. Figure 3.4b illustrates an example of SFH; the data symbol rate is still 30 symbols/s, but the frequency hopping rate has been reduced to 10 hops/s. The waveform s(t) is shown over a duration of three symbols (1/10 S). In this example, the hopping boundaries appear only at the beginning and end of the three-symbol duration. Here, the changes in the waveform are due to the modulation state changes; therefore, in this

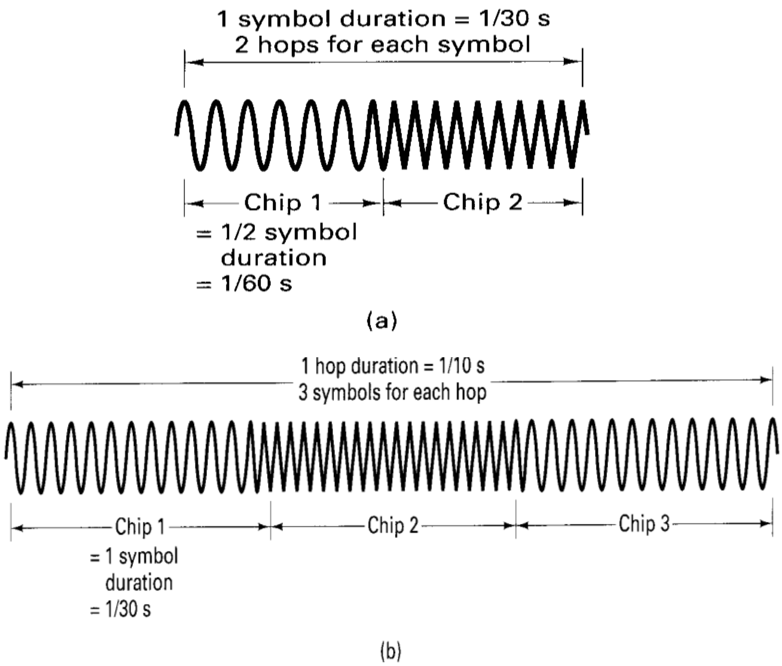

Figure 3.4 Chip-in the context of an FH/MFSK system. (a) Example 1: Frequency hopping MFSK system with symbol rate = 30 symbols/s and hopping rate = 60 hops/s. 1 chip = 1 hop. (b) Example 2: Same as part (a) except hopping rate = 10 hops/s. 1 chip = 1 symbol.

example a chip corresponds to a data symbol, since the data symbol is shorter than the hop duration.

Figure 3.5a illustrates an FFH example of a binary FSK system. The diversity is N = 4. There are 4 chips transmitted per bit. As in Figure 3.3, the dashed line in each column corresponds to the center of the data band and the solid line corresponds to the symbol frequency. Here, for FFH, the chip duration is the hop duration. Figure 3.5b illustrates an example of an SFH binary FSK system. In this case, there are 3 bits transmitted during the time duration of a single hop. Here, for SFH, the chip duration is the bit duration. If this SFH example were changed from a binary system to an 8-ary system, what would the chip duration then correspond to? If the system were implemented as an 8-ary scheme, each 3 bits would be transmitted as a single data symbol. The symbol boundaries and the hop boundaries would then be the same, and the chip duration, the hop duration, and the symbol duration would all be the same.

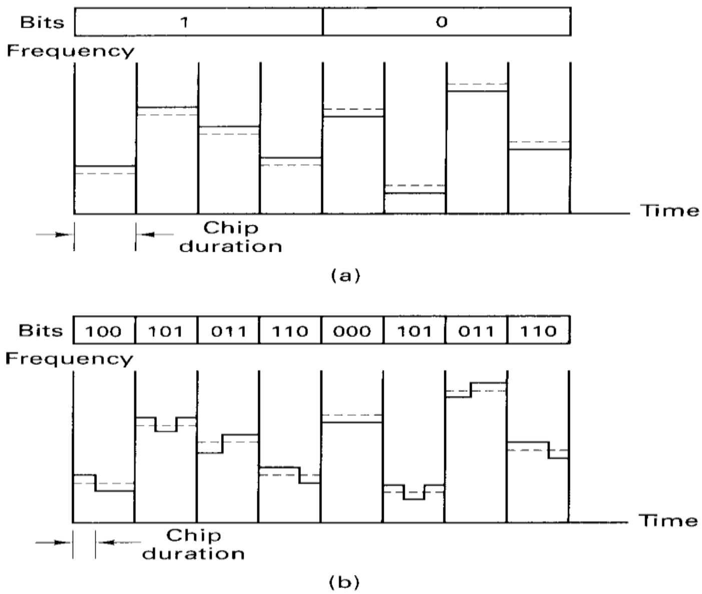

Figure 3.5 Fast hopping versus slow hopping in a binary system **(a)** Fast-hopping example: 4 hops/bit. **(b)** Slow- hopping example: 3 bits/hop

FFH/MFSK Demodulator

Figure 3.6 illustrates the schematic for a typical fast frequency hopping MFSK (FFH/MFSK) demodulator. First, the signal is dehopped using a PN generator identical to the one used for hopping. Then, after filtering with a low-pass filter that has a bandwidth equal to the data bandwidth, the signal is demodulated using a bank of M envelope or energy detectors. Each envelope detector is followed by a clipping circuit and an accumulator. The clipping circuit serves an important function in the presence of an intentional jammer or other strong unpredictable interference; it is treated in a later section. The demodulator does not make symbol

decisions on a chip-by-chip basis. Instead, the energy from the N chips are accumulated, and after the energy from the Nth chip is added to the N-1 earlier ones, the demodulator makes a symbol decision by choosing the symbol that corresponds to the accumulator, z, (i = 1, 2, . . . , M), with maximum energy.

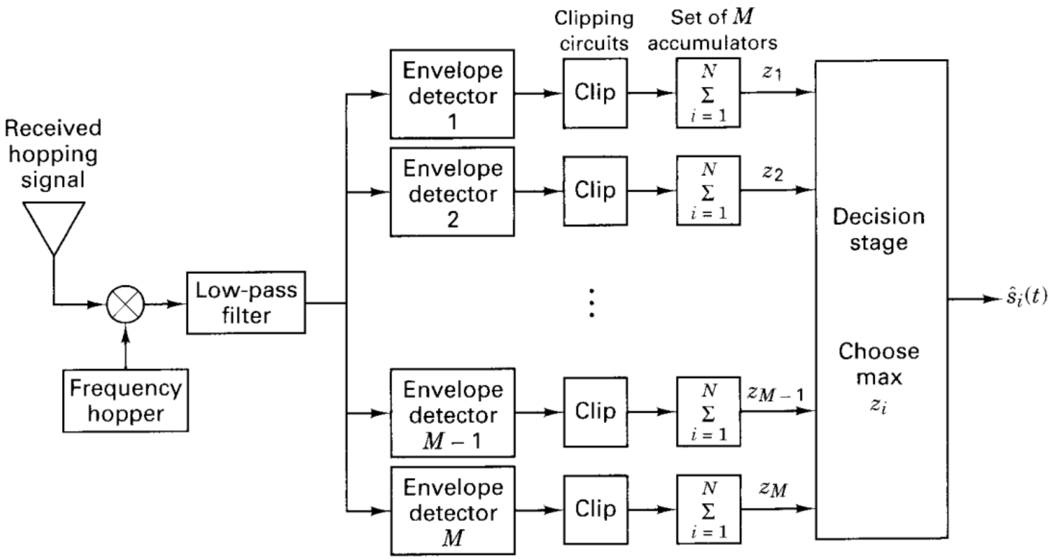

Figure 3.6 FFH/MFSK demodulator.

Processing Gain

Equation shows the general expression for processing gain as $G_p = W_{ss}/R$. In the case of direct-sequence spread-spectrum, W_{ss} was set equal to the chip rate R_{ch}. In the case of frequency hopping, Equation still expresses the processing gain, but here we set W_{ss} equal to the frequency band over which the system may hop. We designate this band as the hopping band $W_{hopping}$, and thus the processing gain for frequency hopping systems is written as

$$G_p = \frac{W_{\text{hopping}}}{R}$$