INFORMATION THEORY OF SPREAD-SPECTRUM COMMUNICATION

SPREAD SPECTRUM SYSTEMS

Since its inception in the mid-1950s, the term *spread spectrum* (SS) has been used to characterize a class of digital modulation techniques which satisfy the following criteria (1):

1. The transmitted signal is characterized by a bandwidth that is much greater than the minimum bandwidth necessary to send the information.
2. Spreading is accomplished prior to transmission using a spreading sequence, or code, that is independent of the information being sent.
3. Detection/demodulation at the receiver is performed by correlating the received signal with a synchronously generated replica of the spreading code used at the transmitter.

Despite what might seem to be an inefficient utilization of resources, that is, increasing bandwidth without gain over noise, the combined process of "spreading" and "despreading" the information-bearing signal offers potential improvement in communications capability that more than offsets the cost incurred in using additional bandwidth. Indeed, SS offers such benefits as

- Interference suppression
- Power spectral density reduction
- Selective addressing capability
- Resistance to multipath fading

Interference suppression refers to the SS system's ability to operate reliably in an environment corrupted or congested by a level of interference that would compromise the utility of conventional digital modulation techniques. In general, SS signaling is considered robust with respect to interference in the sense that the received signal-to-interference power ratio is independent of the time-frequency distribution of the interference energy (2). Accordingly, SS systems have found application in military communications in which hostile sources intentionally jam the channel as well as in civilian settings wherein other users or wireless services inadvertently hinder data transmission through the channel. Due to its effectiveness against a variety of interference sources, including narrowband, wideband, multiple-access and multipath interference, interference suppression has long been considered the primary advantage of SS communications.

The combined advantages of interference suppression and power spectral density reduction go a long way to explain the military's historical involvement in and application of SS research since World War II [although this historical marker contradicts the mid-1950s date previously espoused, the exact origins of SS communications are rather nebulous and defy precise attribution regarding date and source of origin (1)]. While interference suppression facilitates reliable operation in hostile environments, power spectral density reduction is often exploited to produce low probability of intercept (LPI) or low probability of detect (LPD) waveforms. Low power spectral density is a direct result of spreading the power-limited, nominal-bandwidth information signal over a much greater bandwidth. LPI and LPD, combined with appropriate encryption/decryption techniques, effectively establish the basis of military and civilian covert communications.

The transition of interest in SS communications from primarily defense-oriented markets to commercial products and enterprises has been due in part to two commercially recognized deficiencies: (1) a way in which to support multiple users while simultaneously using bandwidth efficiently, and (2) a means of combating multipath fading in mobile communications. As discussed in the following sections, the autocorrelation of the SS waveform closely approximates that of an impulse function. This noiselike quality of the spread signal facilitates the design and implementation of multiuser/multiple-access communications systems in which several users are assigned unique *signature* codes and are allowed to transmit simultaneously. At the receiver, each user's desired signal is extracted from the composite sum of all user signals plus noise through correlation with the appropriate signature sequence—this description delineates the basis of code-division multiple-access (CDMA) systems in use today. In light of the fact that bandwidth is a physically limited commodity, CDMA essentially allows the number of users supported by existing channels to increase independently of bandwidth at the cost of lower performance, that is, higher error rate. Accordingly, bandwidth is conserved and, thus, utilized more efficiently. Robustness to multipath is also realized as a result of the SS waveform's similarity to white noise. Due to the similarity between the autocorrelation response of the SS waveform and an impulse function, multiple time-delayed replicas of the original signal plus noise can be resolved and coherently combined at the receiver to effectively raise the signal-to-noise ratio (SNR).

Spreading Codes

Based on the previous definition of SS systems, it is apparent that some type of code, or sequence, capable of spreading the information bandwidth must be identified. Here, such codes are discussed—the actual mechanisms by which they effect bandwidth spreading are the focus of subsequent sections.

In practice, data-independent pseudorandom, or pseudonoise (PN), sequences govern the spreading and despreading processes. As their name implies, pseudonoise spreading codes have statistical properties closely approximating those of sampled white noise; in fact, to the unintended listener, such sequences appear as random binary sequences. Although spreading codes can be generally categorized into two classes, periodic and aperiodic, the most often used spreading codes in contemporary communications systems are periodic in nature. This is in part due to the limited number of aperiodic, or Barker, sequences with sufficient length for practical applications as well as the availability of simple shift register structures capable of producing pseudorandom periodic sequences (3).

In many applications, maximal length sequences, or *m-sequences*, are often used because of their ease of generation and good randomness properties. These binary-valued, *shift register* sequences are generated as the output of an n-stage maximum-length shift register (MLSR) with a feedback network consisting of modulo-2 adders. Due to its cyclic nature, an n-stage MLSR produces a periodic sequence with period

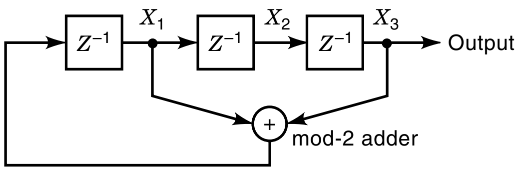

Figure 1. Maximum-length shift register with $n = 3$ and period, $L = 2^n - 1 = 7$.

$L = 2^n - 1$; L is also the length of the corresponding m-sequence. Each sample in the sequence is called a *chip,* meaning that a given m-sequence is $2^n - 1$ chips long. Specific properties of m-sequences include (3):

Balance Property. In each period of a maximal length sequence, the number of 1s is always one more than the number of 0s.

Run Property. Among the runs of 1s and 0s in each period of an m-sequence, one-half of the runs of each kind are of length one, one-fourth are of length two, one-eighth are of length three, and so on, provided these fractions represent meaningful numbers of runs.

Correlation Property. The autocorrelation function of an m-sequence is periodic and binary-valued, that is,

$$R[k] = \begin{cases} +L & k = iL \\ -1 & k \neq iL \end{cases} \tag{1}$$

where i is any integer and L is the length of the code. Note that this expression is valid for all m-sequences regardless of the value of L.

Figure 1 illustrates an n = 3-stage MLSR as an example. Assuming that the MLSR initial state is set to $[X_1, X_2, X_3]$ = [1, 0, 0], the resulting binary output sequence, determined by cycling through successive register states $[X_1, X_2, X_3]$ = [1, 0, 0], [1, 1, 0], [1, 1, 1], [0, 1, 1], [1, 0, 1], [0, 1, 0] and [0, 0, 1], is (0, 0, 1, 1, 1, 0, 1). Successive iterations return the MLSR state to its initial value, [1, 0, 0], wherein the process as well as the resulting output sequence begin to repeat. The MLSR output sequence is thus periodic in the sense that the L = 7-chip m-sequence, (0, 0, 1, 1, 1, 0, 1), is repeated every seven iterations as long as the MLSR is allowed to run. Clearly, the spreading sequence (0, 0, 1, 1, 1, 0, 1) contains four ones and three zeros as is consistent with the balance property. Likewise, the total presence of four runs—two of length one, one of length two, and one of length three essentially meets the specifications of the run property.

As an illustration of the correlation property, Fig. 2 depicts a 7-chip m-sequence and its corresponding autocorrelation

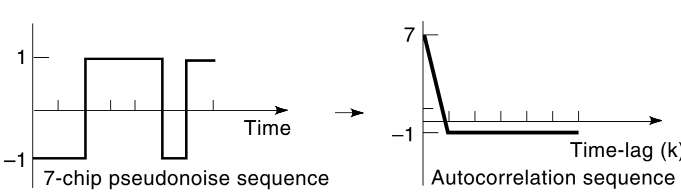

Figure 2. Length L = 7 m-sequence and corresponding cyclic autocorrelation response.

function. In this case, the spreading sequence, (0, 0, 1, 1, 1, 0, 1), which is converted to (−1, −1, 1, 1, 1, −1, 1) for transmission, produces the cyclic autocorrelation response given in Eq. (1) with L = 7. Further details regarding the origin and implementation of m-sequences as well as other potential spreading codes, including Barker, Gold and Kasami sequences, are found in the literature (2–7).

SPREADING THE SPECTRUM

As stated in the definition, spread spectrum is accomplished using a spreading code that is independent of the information being sent. The nature and properties of a common class of spreading waveforms has been addressed in the preceding section. Here, the physical mechanisms by which spectrum spreading is accomplished are discussed. Although there are various approaches to generating spread spectrum waveforms, such as direct-sequence (DS) modulation, frequency-hop (FH) and time-hop (TH) as well as hybrid variants incorporating aspects of each of these, each approach is fundamentally based on the underlying spreading code and endeavors to create a wideband signal from the given information data. Of these techniques, DS and FH spread spectrum are most commonly employed. Information regarding other spread spectrum formats is presented in (5,7).

Direct-Sequence Spread Spectrum

In direct-sequence spread spectrum (DS-SS), the wideband transmitted signal is obtained by multiplying the binary baseband information signal, $b(t)$, by the spreading code as shown in Fig. 3. Note that this figure inherently incorporates the use of binary phase-shift keying (BPSK) modulation and is thus representative of a DS/BPSK spread spectrum system; more generally, the combination of DS-SS with M-ary PSK modulation is referred to as DS/MPSK-SS. Although practical DS/MPSK-SS systems often modulate individual data bits using only a portion of the total m-sequence, it is assumed here, for convenience, that each bit is modulated by a single, full-length m-sequence with the number of chips in the spreading code equal to its length, L. With the bit period defined as T_b, the number of chips per bit is given by the ratio $T_b/T_c = L$ where T_c is the chip duration. The rate of the DS-SS waveform, also called the *chip rate* of the system, is $R_c = 1/T_c$ chips/s.

In practice, the bit duration, T_b, is typically much greater than T_c. Consequently, the chip rate is often orders of magnitude larger than the original bit rate $R_b = 1/T_b$, thus necessitating the increase, or spread, in transmission bandwidth. As shown in Fig. 4, the frequency response of the spread waveform has a $\text{sinc}(x) = \sin(x)/x$ shape with main lobe bandwidth equal to $2R_c$. Pulse shaping can be used to minimize the sidelobes and effectively reduce the DS-SS bandwidth if necessary.

Given the baseband information signal, $b(t)$, and the spreading code, $c(t)$, the DS-SS waveform is given by

$$m(t) = c(t)b(t) \tag{2}$$

Subsequent transmission over a noisy channel corrupted by interference produces the receiver input

$$r(t) = m(t) + i(t) + n(t) \tag{3}$$

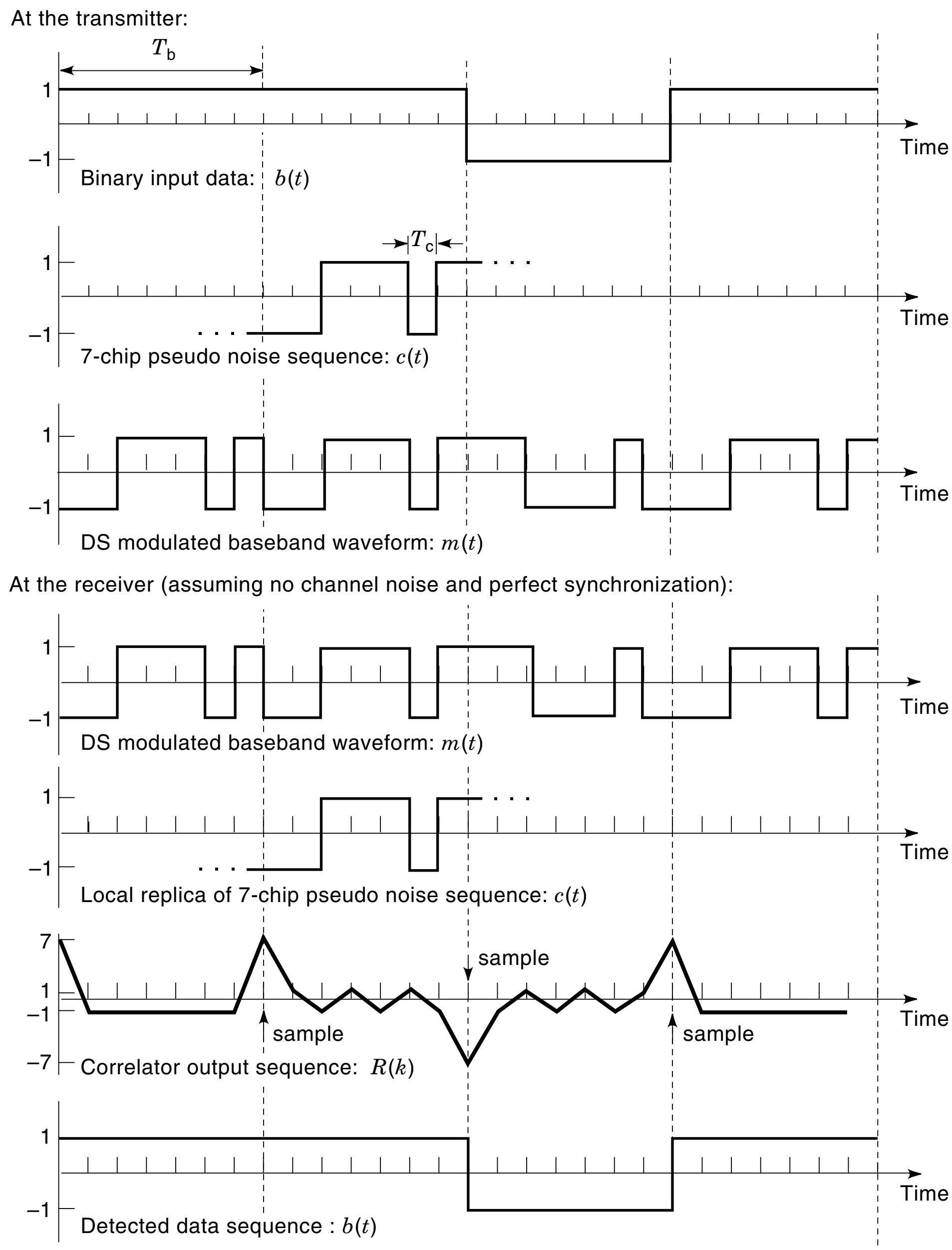

Figure 3. Direct-sequence spread spectrum modulation and demodulation.

where $i(t)$ and $n(t)$ denote interference and white noise, respectively. Often when using SS signaling, the interference power is assumed to be much greater than that of the noise and this expression is simplified as

$$r(t) = m(t) + i(t) \quad (4)$$

$$= c(t)b(t) + i(t) \quad (5)$$

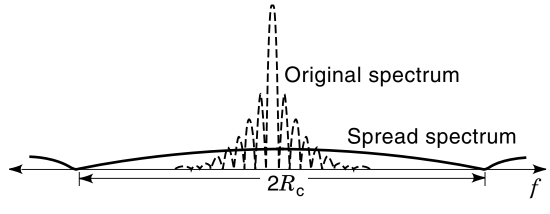

Figure 4. Magnitude-squared frequency response of a DS-SS waveform.

At the receiver, demodulation, or despreading, as depicted in Fig. 3 in the absence of noise and interference, is accomplished by multiplying $r(t)$ with a synchronized replica of the spreading code, that is,

$$u(t) = c(t)r(t) \quad (6)$$

$$= c^2(t)b(t) + c(t)i(t) \quad (7)$$

$$= b(t) + c(t)i(t) \quad (8)$$

with the final equality a result of the relationship, $c^2(t) = 1$ for all t. Subsequent integration of $u(t)$ over each symbol produces the correlator output which, when sampled at the appropriate instances, yields the detected data sequence. The preceding steps demonstrate that multiplying a signal once by the spreading code spreads its energy across a much larger bandwidth while a second multiplication reverses this process by despreading the energy and restoring the spread waveform

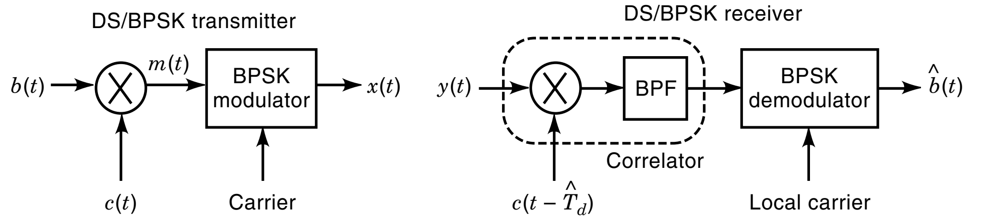

Figure 5. Synchronized DS/BPSK transmitter/receiver structures.

to its original, prespread condition. Equation (8) verifies that the information signal, $b(t)$, which is multiplied twice by the spreading code, is recovered, and returned to its initial state, while the interference, which is multiplied only once, undergoes spreading due to $c(t)$.

Whereas the previous discussion has focused on baseband signals, practical implementations typically modulate the baseband SS waveform onto a sinusoidal carrier as diagrammed in Fig. 5. Here, sinusoidal modulation produces the DS/BPSK SS signal,

$$x(t) = \sqrt{2P}m(t)\cos 2\pi f_c t \tag{9}$$

where P denotes the average power and f_c is the carrier frequency. The receiver input is thus the bandpass waveform

$$y(t) = x(t) + i(t) + n(t) \tag{10}$$

Figure 5 illustrates correlation as performed at the receiver by multiplying the received signal with a synchronized copy of the spreading code, $c(t - \hat{T}_d)$, where $\hat{T}_d$ represents the estimated propagation delay of the transmitted signal, and bandpass filtering to remove out-of-band components. Subsequent BPSK demodulation produces the estimate of the transmitted data sequence, $\hat{b}(t)$.

Synchronization between the received signal and the spreading sequence is typically performed in two stages: (1) an *acquisition* stage, which provides coarse alignment between the two waveforms, typically to within a fraction of a chip, and (2) a *tracking* stage, which maintains fine synchronization and, essentially, the best possible alignment between $y(t)$ and $c(t)$. Rudimentary discussions of synchronization techniques for SS systems are presented in (4,5), while more in-depth expositions are found in (5,8).

As demonstrated in Eq. (8), multiplication of the received signal with a locally generated, synchronized copy of the spreading code simultaneously collapses the spread data signal back to its original bandwidth while spreading any additive noise or interference to the full SS bandwidth or greater. As shown in Fig. 5, a bandpass filter with bandwidth matched to that of the original data is subsequently used to recover the data and reject a large fraction of the spread interference energy. The ratio of the signal-to-noise ratio (SNR) after despreading, SNR_o, to the input signal-to-noise ratio, SNR_i, is defined as the *processing gain, G_p*, that is,

$$G_p \triangleq \frac{\text{SNR}_\text{o}}{\text{SNR}_\text{i}} \tag{11}$$

Note that in both SNR_i and SNR_o the noise term implicitly denotes the sum of additive white Gaussian noise (AWGN) plus any additional interference. Given an input data rate of R_b bits/s, Gp can be approximated in DS-SS systems by the ratio of the chip rate to the data rate,

$$G_p \approx \frac{R_c}{R_b} = \frac{T_b}{T_c} = N \tag{12}$$

where N corresponds to the number of chips per spread data bit; $N = L$ when individual data bits are modulated by the entire spreading sequence. Note that, in practice, the entire spreading code may not be used to modulate each data bit (depending on the application, a subset of $K < L$ chips may be used). In essence, G_p roughly gauges the antijam capability and LPI/D quality of the SS system.

System performance is ultimately a function of SNR_o, which determines the bit-error-rate (BER) experienced by the communication link. For a given data rate, spreading the transmitted signal energy over a larger bandwidth allows the receiver to operate at a lower value of SNR_i. The range of SNR_i for which the receiver can provide acceptable performance is determined by the *jamming margin, M_J*, which is expressed in decibels (dB) as

$$M_J = G_p - [\text{SNR}_{\text{o}_{\text{min}}} + L_{\text{sys}}] \tag{13}$$

where $\text{SNR}_{\text{o}_{\text{min}}}$ is the minimum SNR_o required to support the maximum allowable BER, and L_{sys} accounts for any losses due to receiver implementation. Hence, in addition to G_p, M_J represents another metric available to system designers indicating how much interference can be tolerated while still maintaining a prescribed level of reliability.

Frequency-Hop Spread Spectrum

In contrast to DS-SS, which directly employs the spreading sequence to modulate a phase-shift-keyed version of the information bearing waveform, frequency-hop spread spectrum (FH-SS) utilizes the spreading code to determine the carrier frequency, or frequency slot, used to transmit data over a specific period of time. In this manner, a broadband signal is generated by sequentially moving, or *hopping*, a *fixed-frequency* data-modulated carrier throughout the frequency spectrum as directed by a pseudorandom pattern known (ideally) only to the transmitter and its intended receivers. Figure 6 shows the idealized frequency spectrum of a FH-SS sig-

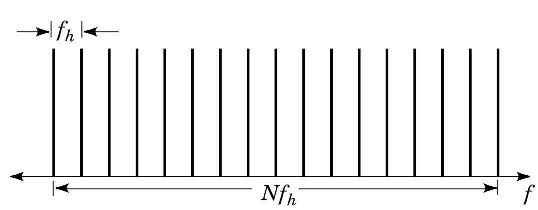

Figure 6. Idealized frequency spectrum of a FH-SS waveform.

nal in which the N hop frequencies are equally spaced at intervals of f_h Hz—the spread bandwidth of this signal is thus Nf_h Hz; in practice, each of the illustrated tones is replaced by the actual narrowband signal spectrum associated with the underlying narrowband modulation scheme employed.

The modulation format most often used in conjunction with FH-SS is M-ary FSK (MFSK); this combination is simply referred to as FH/MFSK. Figure 7 depicts typical FH/MFSK transmitter and receiver block diagrams. In the FH/MFSK transmitter, $k = \log_2 M$ information bits determine which of the M frequencies of the MFSK modulator is to be transmitted. The function of the frequency synthesizer is to produce a sinusoidal waveform, or tone, which when *mixed* with the MFSK modulator output effectively shifts its position in frequency. Note that the mixing operation as well as the required bandpass filtering is performed by the up-converter. As might be surmised, the frequency of the synthesizer output is pseudorandomly determined by the PN generator driving it. Typically, $j = \log_2 N$ chips of the spreading code are fed into the frequency synthesizer to select one of N possible tones. The FH/MFSK receiver shown in Fig. 7 simply reverses the processes performed in the transmitter by down-converting the received signal with a locally generated copy of the tone used at the transmitter and subsequently performing conventional MFSK demodulation to produce the estimated information signal, $\hat{b}(t)$.

As discussed above, at any instant in time, the actual amount of bandwidth used in FH/MFSK signaling is identical to that of conventional MFSK. This bandwidth is much less than the effective FH-SS bandwidth realized by averaging over many hops. Recognizing that the total number of possible tones is $N = 2^j$, the FH/MFSK-SS bandwidth is roughly Nf_h and, in practice, is limited primarily by the operational range of the frequency synthesizer. Frequency hopping over very large bandwidths typically precludes the use of coherent demodulation techniques due to the inability of most frequency synthesizers to maintain phase coherence over successive hops. Consequently, noncoherent demodulation is usually performed at the receiver (5).

Whereas the term *chip* in DS-SS corresponds to the samples of the spreading sequence, in FH-SS, it refers to the FH/MFSK tone with the shortest duration. The amount of time spent at each hop determines whether the FH/MFSK system is classified as *slow frequency-hopping* (SFH/MFSK) or *fast frequency-hopping* (FFH/MFSK). In SFH/MFSK systems, several MFSK symbols are transmitted per hop with the chip rate, R_c, equal to the MFSK symbol rate, R_s. The converse is true in FFH/MFSK-SS, wherein several hops are performed per MFSK symbol, with the resulting chip rate equal to the hopping rate, R_h.

In the example of SFH/MFSK-SS shown in Fig. 8, the information signal $b(t)$, whose bit rate, R_b, is related to the bit duration, T_b, via $R_b = 1/T_b$, is segmented into two-bit pairs which select the frequency (one out of four possible frequencies assuming M = 4-FSK modulation) to be transmitted. Since two bits are required per MFSK output, the duration of each symbol is $T_s = 2T_b$ yielding the symbol rate, $R_s = 1/T_s = \frac{1}{2}T_b$ (note that R_s is equivalent to f_h of Fig. 6). Using the periodically repeated m-sequence generated by the MLSR in Fig. 1, that is, the sequence (**0**, **0**, **1**, **1**, **1**, **0**, **1**, 0, . . .) with boldface type denoting the first period, the output of the MFSK modulator is hopped through N = 8 different frequency slots. To determine the hopping pattern, the PN sequence is divided into successive (not necessarily disjoint) k = 3 bit segments, each indicating the particular frequency slot to be used; in this case, frequency assignment is unique since $N = 2^k$. Below the resulting SFH/MFSK waveform diagram in Fig. 8 are the corresponding 3-bit segments, **001**, **110**, **100**, **111**, **010**, . . . governing the hopping pattern. Note that in this example the 000 sequence never appears and thus N is effectively only seven; such an aberration is seldom encountered in practice and, even if it were, the general principle illustrated here would still be valid. In this example, two symbols are transmitted per hop. Thus, the hop duration, $T_h = 2T_s$ with the corresponding hop rate given by $R_h = 1/T_h = R_s/2$. The effective FH-SS bandwidth is $B_{ss} = NR_s$.

Figure 9 illustrates FFH/MFSK-SS signaling. As in the SFH/MFSK example, two-bit pairs from $b(t)$ drive the MFSK modulator thus again yielding the symbol duration, $T_s = 2T_b$. In contrast to the previous example, however, multiple hops in frequency occur per MFSK symbol. Although frequency hop assignment is again governed by the periodic PN sequence segmented into the 3-bit patterns, **001**, **110**, **100**, **111**, **010**, **011**, **101**, 001, . . . (boldface denotes initial register states associated with the 7-chip m-sequence), in this example, *two* 3-bit patterns are used per symbol; the actual 3-bit pairs used per symbol are listed below the FFH/MFSK waveform diagram. Accordingly, the hop duration, $T_h = T_s/2$, with $R_h = R_b$. The overall FH-SS bandwidth, which is independent of the hop rate, is again $B_{ss} = NR_s$.

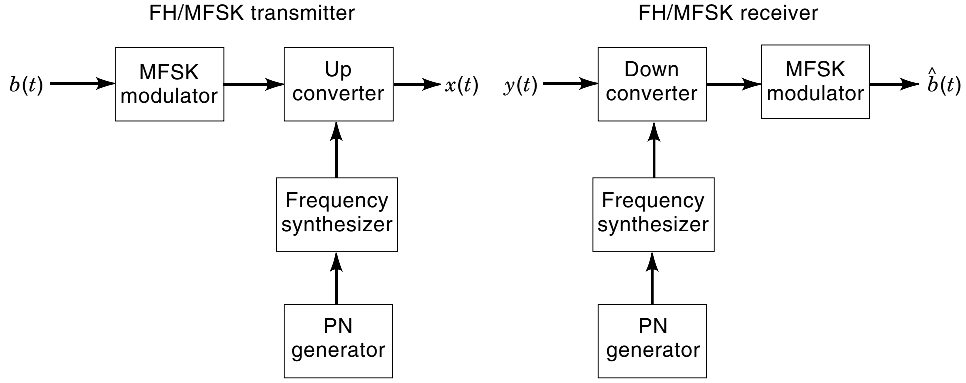

Figure 7. Synchronized FH/MFSK transmitter/receiver structures.

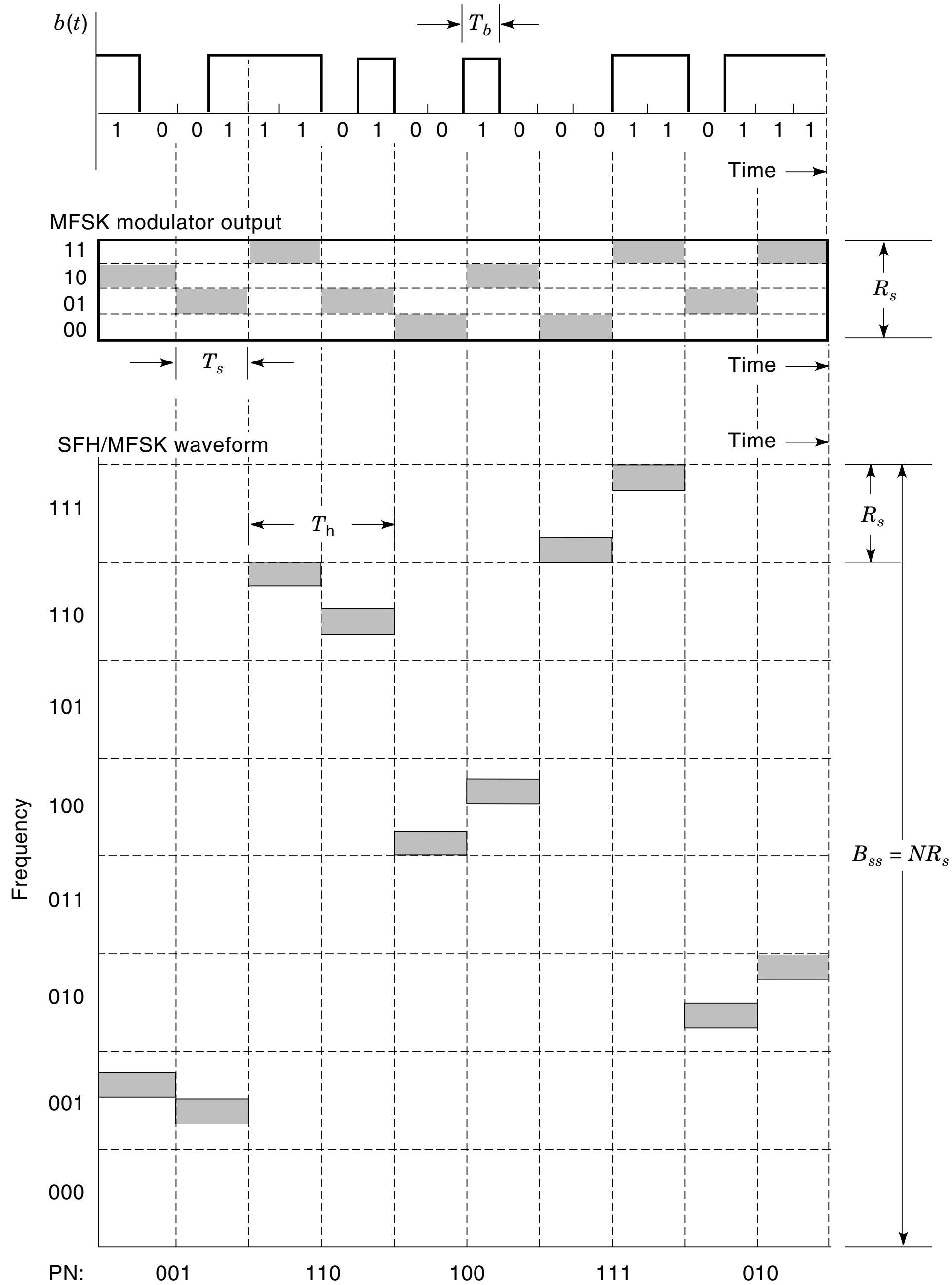

Figure 8. SFH/MFSK modulation with $M = 4$, $N = 8$, and a dwell time of $2T_b$ s.

In general, FFH/MFSK-SS is an effective means of combating certain types of jammers called *follower* and *repeat-back* jammers which attempt to intercept the frequency of the transmitted waveform and retransmit it along with additional frequencies so as to degrade receiver performance (4). When using FFH/MFSK-SS, the jammers do not typically have sufficient time to intercept and jam the spread waveform before it hops to another frequency. The price paid for such evasion, however, is the need for fast-frequency synthesizers capable of changing frequency at the required hopping rates.

As in DS-SS, the processing gain, G_p, serves as a metric indicating the signaling scheme's robustness with respect to interference. For either fast-FH or slow-FH, the effective processing gain can be approximated as the ratio of the spread spectrum bandwidth, B_{ss}, to the original data rate, R_b, that is,

$$G_p \approx \frac{B_{ss}}{R_b} \tag{14}$$

Assuming that the interference energy is spread over the entire FH bandwidth and that the original data rate is approximately equal to the symbol rate, $R_b = R_s$, the processing gain for either FH-SS system shown in Fig. 8 and Fig. 9 is approximately equal to N, the number of different frequencies over which the MFSK modulator output is hopped. The expression for the jamming margin, M_J, as given in Eq. (13), holds.

APPLICATIONS

Primary applications of spread spectrum in contemporary communications include antijam (AJ) communications, code-division multiple-access (CDMA), and multipath interference rejection. Not surprisingly, each of these applications has been directly foreshadowed by the list of attributes associated with SS signaling presented at the beginning of this topic.

AntiJam Communications

As previously discussed, the AJ capability of a SS system is directly related to its overall processing gain, G_p. Although in theory the processing gain associated with a DS-SS waveform can be arbitrarily increased by using longer spreading codes, stringent synchronization requirements and practical bandwidth considerations limit its availability. FH-SS, on the other hand, is limited in spread bandwidth and, thus, processing gain, only by the operational limits of the frequency synthesizer. In practice, physical implementations of FH-SS are typically capable of sustaining wider bandwidth signals than practical DS-SS systems.

Even though SS systems possess a fundamental level of inherent interference immunity, different types of interference pose threats to DS-SS and FH-SS systems. In particular, pulsed-noise jammers are especially effective against DS/MPSK systems, while partial-band and multitone interference, perhaps due to CDMA *overlay* and/or narrowband services present within the SS bandwidth, represent significant threats to reliable FH/MFSK systems. Additional sources of interference, as well as their effects on SS communications, are found throughout the literature (4–7).

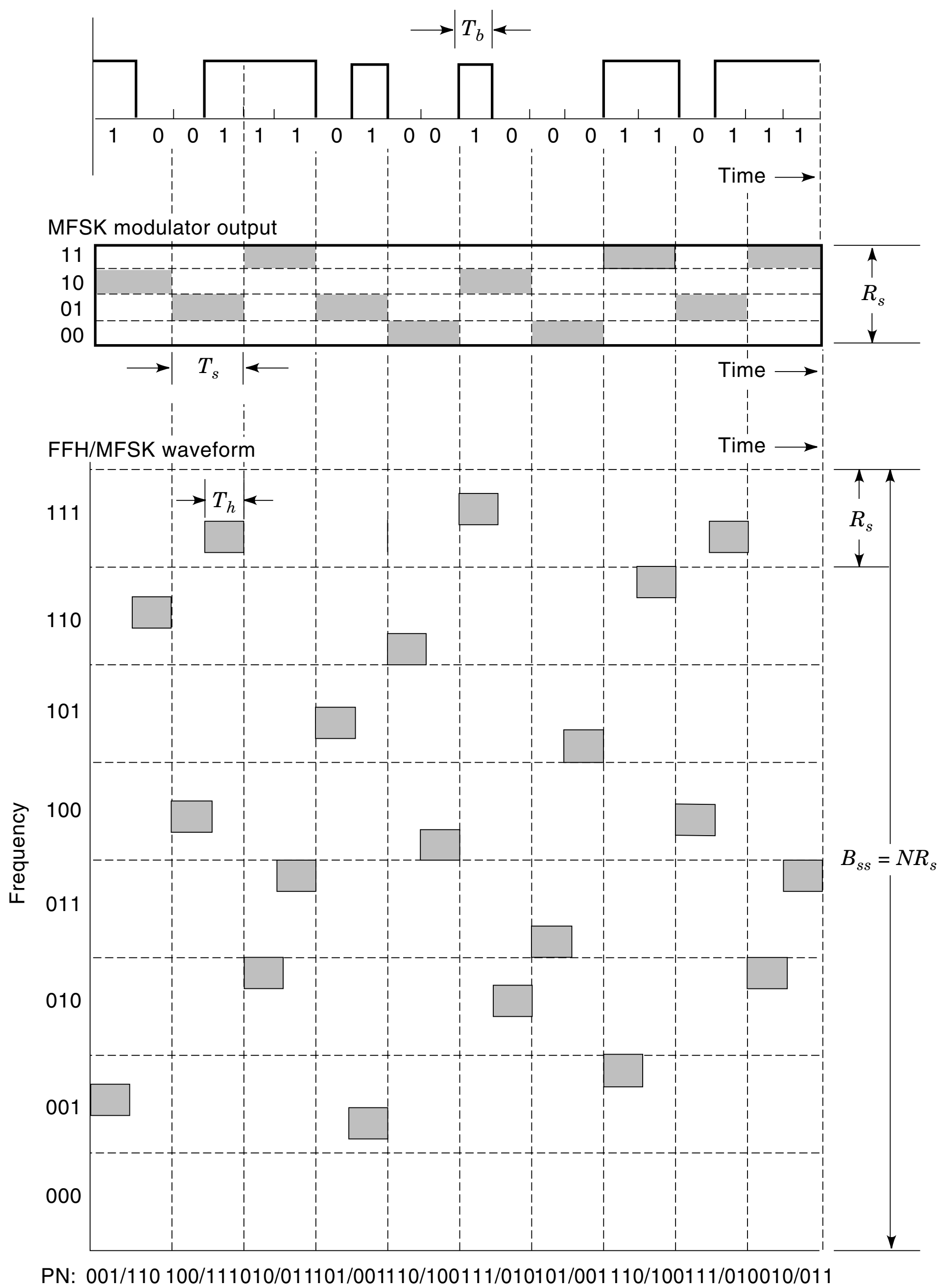

Figure 9. FFH/MFSK modulation with $M = 4$, $N = 8$, and a dwell time of T_b s.

Code-Division Multiple-Access

Prior to the introduction of code-division multiple-access (CDMA), conventional multiple-access techniques focused on dividing the available time or frequency space into disjoint partitions and assigning them to individual users. In time-division multiple-access (TDMA), users are multiplexed in time and allowed to transmit sequentially over a given channel. In contrast, in frequency-division multiple-access (FDMA), each user is assigned a portion of the channel bandwidth, separated from other users by a guard band, and allowed to use the channel simultaneously without interfering with one another. As opposed to partitioning either the time or frequency plane, CDMA provides both time and frequency diversity to its users through the use of spread spectrum modulation techniques.

In CDMA, each user is assigned a pseudorandom signature code, or sequence, similar in structure to the m-sequences discussed earlier. Gold codes and Kasami sequences, like m-sequences, have impulselike autocorrelation responses and are frequently used in such applications. Unlike m-sequences, however, these codes are generated as a set of spreading codes whose members possess minimal cross-correlation properties (4). Low cross-correlation among multiple users allows them to communicate simultaneously without significantly degrading each other's performance. In contrast to TDMA, CDMA does not require an external synchronization network and it offers graceful degradation as more users are added to the channel (due to the fact that since the spreading codes approximate wideband noise, each additional CDMA user appears as an additional noise source which incrementally raises the noise floor of the channel). In addition, CDMA also offers the benefits of SS communications including resistance to multipath as well as jamming.

Multipath Suppression

In many communications systems, actual data transmission occurs along direct, line-of-sight paths, as well as from a number of physical paths which are the result of reflections of the transmitted signal off of various scatterers such as buildings, trees, and mobile vehicles. Multipath interference is a result of the combination of these direct and indirect signal transmissions arriving at the receiver at a slight delay relative to each other. When the direct path signal is substantially stronger than the reflected components, multipath does not represent much of a challenge, if any, to reliable communications. When the direct path signal is either nonexistent or, more likely, comparable in strength to the indirect, delayed components, however, multipath interference results in variations in the received signal's amplitude, which is called *fading.*

Under slow fading conditions, multipath can be combatted directly through the use of DS-SS. Due to the noiselike property of the DS-SS waveform, multipath signal components, when correlated with the local reference code, can be resolved in time (provided the multipath spread is greater than a chip duration) and combined coherently to improve data detection. Under these conditions, the degradation in receiver performance due to multipath is directly related to the chip rate associated with DS modulation—the greater the chip rate, the less effect multipath will have on performance.

FH-SS can also be used to combat multipath interference provided that the transmitted signal hops fast enough relative to the differential time delay between the direct path and multipath signal components. In this case, much of the multipath energy falls into frequency slots vacated by the FH-SS waveform and, thus, its effect on the demodulated signal is minimized (3).

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INFORMATION VISUALIZATION. See DATA VISUALIZATION.

INFRARED. See PHOTODETECTORS QUANTUM WELL.