

DESIGN AND SIMULATION OF FREQUENCY HOPPING TECHNIQUE IN MATLAB

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Abstract

This paper investigates the problems of a frequency hopping spread spectrum (FHSS) and deals with properties and utilization in practice. FHSS is a radio transmission process where user information is sent on a radio channel that regularly changes frequency according to a predetermined code. The FHSS technique is useful for suppressing interference, making interception difficult, accommodating fading and multipath channels, and providing a multiple-access capability. The receiver demodulates the received signal by the carrier frequencies that change synchronously depending on the same frequency hopping sequence and makes a detection of it. Contemporary frequency hopping systems use either noncoherent or differentially coherent demodulators. Also in this paper we describe slow and fast frequency hopping and then, we define their power spectral density (PSD). In the last section of this paper, a simulation procedure of a fast frequency hopping/binary frequency shift keying (FFH/BFSK) spread spectrum system in MATLAB is described.

1 Introduction

The type of spread spectrum in which the carrier hops randomly from one frequency to another is called a frequency hopping spread spectrum (FHSS) [1], [2], [3], [5], [6]. Frequency hopping was first used for military electronic countermeasures, because the transmitted signal that uses frequency hopping is difficult to detect and monitor. In an FHSS system the signal frequency is constant for specified time duration, referred to as a hop period T_h . The hop period is the time spent in transmitting a signal in a particular frequency slot of bandwidth $B \ll W$, where W and B are spread and symbol bandwidth, respectively. The sequence of carrier frequencies is called the frequency hopping pattern. The set of L possible carrier frequencies $\{f_1, f_2, \dots, f_L\}$ is called the hopset. The rate at which the carrier frequency changes is called the hop rate R_h . The carrier frequencies are changed periodically. Hopping occurs over a frequency band called the hopping band that includes L frequency channels. This hopping is typically done in a pseudo-random manner. Each frequency channel is defined as a spectral region that includes a single carrier frequency of the hopset as its center frequency and has a bandwidth B large enough to include most of the power in a signal pulse with a specific carrier frequency. Fig. 1 [6] illustrates the frequency channels associated with a particular frequency hopping pattern.

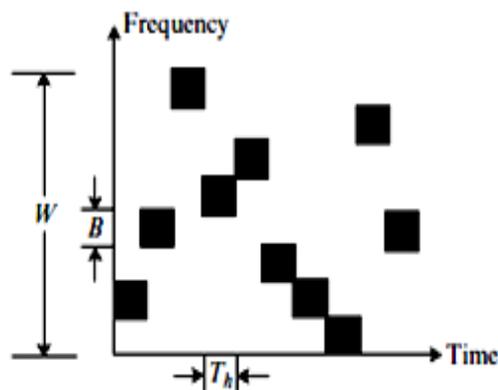


Figure 1: Frequency hopping patterns

2 Description of an FH/MFSK Spread Spectrum System

Fig. 2a shows the block diagram of a frequency hopping/ M -ary frequency shift keying (FH/MFSK) transmitter, which involves frequency modulation followed by mixing.

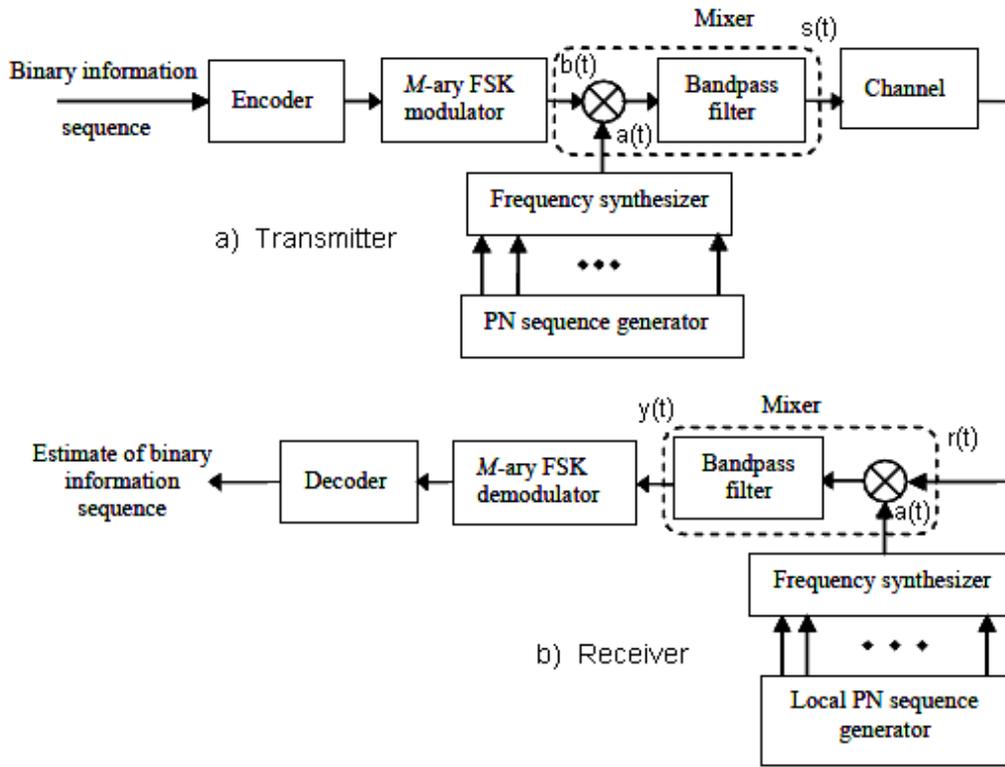


Figure 2: Block diagram of an FH/MFSK spread spectrum system. a) Transmitter; b) Receiver

First, the incoming binary data are applied to an M -ary FSK modulator. For M -ary FSK, the data signal (real bandpass signal) can be expressed as [7]

$$b(t) = \sqrt{2P} \sum_{k=-\infty}^{\infty} p_{T_s}(t - kT_s) \cos(\omega_k t + \phi_k) \quad (1)$$

where $\omega_k \in \{\omega_{s0}, \omega_{s1}, \dots, \omega_{sM-1}\}$. The frequency synthesizer outputs a hopping signal

$$a(t) = 2 \sum_{l=-\infty}^{\infty} p_{T_c}(t - lT_c) \cos(\omega'_l t + \phi'_l) \quad (2)$$

where $p(t)$ is the pulse shape used for the hopping waveform, T_c is the hop period also called the chip period, $\omega'_l \in \{\omega_{c0}, \omega_{c1}, \dots, \omega_{cL-1}\}$ are the L hop frequencies, and ϕ'_l are the phases of each oscillator. The resulting modulated wave and the output from a digital frequency synthesizer generating a signal with a frequency among a predefined set of possible frequencies are then applied to a mixer that consists of a multiplier followed by a bandpass filter (BPF). The resulting frequency hopped transmit signal is then

$$s(t) = [b(t)a(t)]_{BPF} \quad (3)$$

where the bandpass filter is designed to select the sum frequency component resulting from the multiplication process as the transmitted signal.

In the receiver depicted in Fig. 2b, we have an identical PN generator, synchronized with the receiver signal, which is used to control the output of the frequency synthesizer. The despread signal $y(t)$ is obtained by multiplying received signal with the output of a local frequency synthesizer and bandpass filtering out the images:

$$y(t) = [r(t)a(t)]_{BPF} = \left[(s(t) + n(t)) 2 \sum_{l=-\infty}^{\infty} p_{T_c}(t - lT_c) \cos(\omega_l t + \phi_l') \right]_{BPF} \\ = b(t) + n'(t) \quad (4)$$

where $n'(t)$ is the noise process after despreading and filtering. The resulting output signal $y(t)$ is subsequently processed by noncoherent M -ary FSK detector. To implement this M -ary detector, we may use a bank of M noncoherent matched filters, each of which is matched to one of the MFSK tones. An estimate of the original symbol transmitted is obtained by selecting the largest filter output. A signal for maintaining synchronism of the PN generator with the frequency-translated received signal is usually extracted from the received signal.

3 Slow and Fast Hopping FHSS

3.1 Description of Slow Frequency Hopping

First, let us consider the case where $T_c > T_s$, which is called slow frequency hopping. A slow FH/MFSK signal is characterized by having multiple symbols transmitted per hop. Hence, each symbol of a slow FH/MFSK signal is a chip. We impose the constraint that $T_c = NT_s$ for slow frequency hopping. For the case of slow frequency hopping, the FHSS signal is given by [7]

$$s(t) = \sqrt{2P} \sum_{k=-\infty}^{\infty} p_{T_s}(t - kT_s - \Delta) \cos[(\omega_k + \omega'_{[k/N]}) (t - \Delta) + \phi_k + \phi'_{[k/N]}] \quad (5)$$

where $[x]$ is the largest integer which is smaller than or equal to x and the delay Δ is assumed to be uniformly distributed on $[0, T_s)$. The orthogonality requirement for the FSK signals forces the separation between adjacent FSK symbol frequencies be at least $2\pi/T_s$. Hence, the minimum separation between adjacent hopping frequencies is $2\pi M/T_s$.

Fig. 3 [1] depicts the operation of a slow FHSS system with 4-FSK modulation ($M = 4$), 6 hop frequencies ($L = 6$), and 4 symbols per hop ($T_c = 4T_s$, $N = 4$).

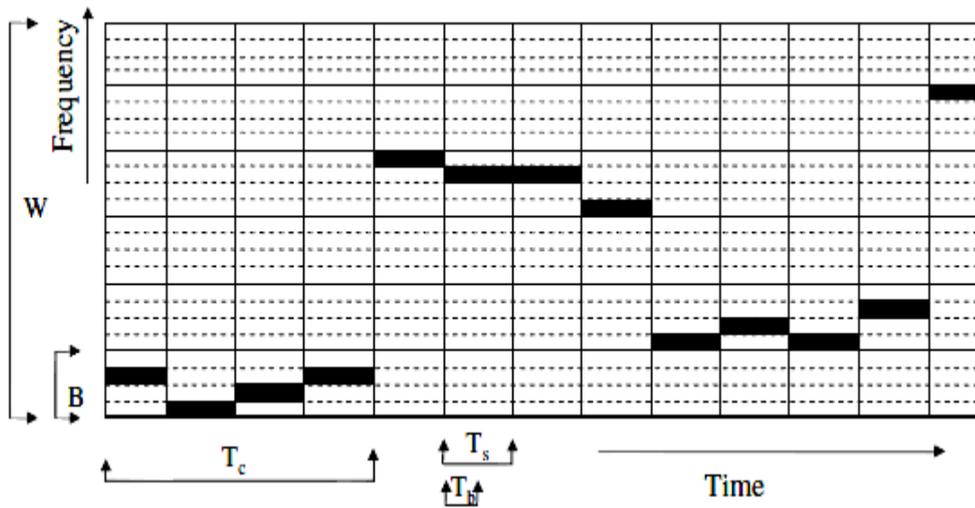


Figure 3: Time-frequency plot for slow frequency hopping ($T_c =$ hop period, $T_s =$ symbol period, $T_b =$ bit period, $W =$ spread bandwidth, $B =$ symbol bandwidth)

As can be seen, every T_s seconds, the frequency is changed to one of 4 symbols based on the data. Additionally, every T_c seconds, the center frequency of these symbols is changed on the basis of the frequency hopping pattern. At the receiver, the pseudo-random hopping is removed, leaving only the data modulation as shown in Fig. 4.

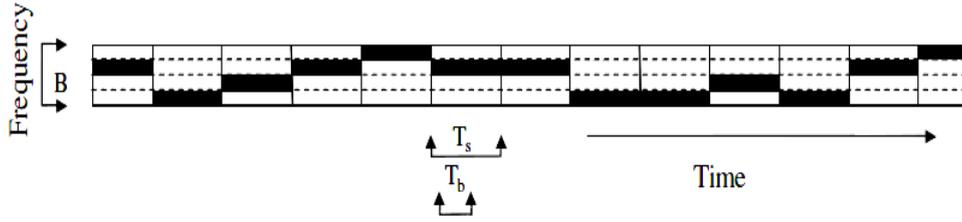


Figure 4: Time-frequency plot after despreading

3.2 Description of Fast Frequency Hopping

In contrast to slow frequency hopping, with fast frequency hopping, $T_c < T_s$, i.e., frequency hopping occurs faster than the modulation. A fast FH/MFSK system differs from a slow FH/MFSK system in that there are multiple hops per M -ary symbol. Hence, each hop of a fast FH/MFSK signal is a chip. We impose the constraint that $T_s = NT_c$ for fast frequency hopping. For the case of fast frequency hopping, the FHSS signal is given by [7]

$$s(t) = \sqrt{2P} \sum_{l=-\infty}^{\infty} pT_c(t - lT_c - \Delta) \cos[(\omega_{|l/N|} + \omega'_l)(t - \Delta) + \phi_{|l/N|} + \phi'_l] \quad (6)$$

where $[x]$ is the largest integer which is smaller than or equal to x and the delay Δ is assumed to be uniformly distributed on $[0, T_c)$. The orthogonality requirement for the FSK signals forces the separation between adjacent FSK symbol frequencies be at least $2\pi/T_c$. Hence, the minimum separation between adjacent hopping frequencies is $2\pi M/T_c$.

Fig. 5 [1] depicts the operation of a fast FHSS system with 4-FSK modulation ($M = 4$), 6 hop frequencies ($L = 6$), and 2 hops per symbol ($T_s = 2T_c$, $N = 2$).

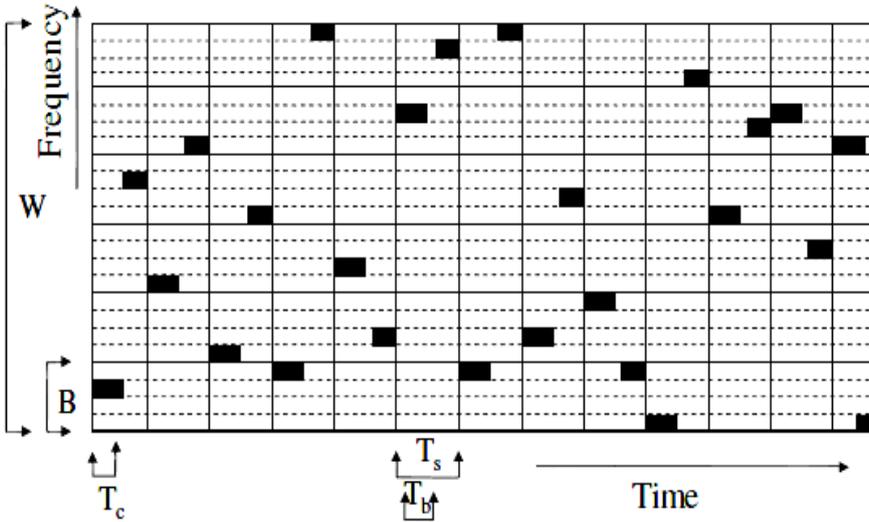


Figure 5: Time-frequency plot for fast frequency hopping (T_c = hop period, T_s = symbol period, T_b = bit period, W = spread bandwidth, B = symbol bandwidth)

In this case, coherent modulation is extremely difficult since it would require extremely fast carrier synchronization and therefore noncoherent detection is used for data recovery at the receiver. However, the detection procedure is quite different from that used in a slow FH/MFSK receiver. The despread or dehopped signal is plotted in Fig. 4, which shows that the despread data is the same as in slow frequency hopping.

3.3 Power spectral density of Slow and Fast Frequency Hopping

To obtain the power spectral density (PSD) of the M -ary FHSS signal, we model the phases ϕ_k and ϕ'_l as independent identically distributed random variables uniformly distributed on $[0, 2\pi)$. The hopping frequencies ω'_l are modeled as independent identically distributed random variables taking values from the set $\{\omega_{c0}, \omega_{c1}, \dots, \omega_{cL-1}\}$ with equal probabilities. The FSK symbol frequencies ω_k are independent identically distributed random variables taking values from the set $\{\omega_{s0}, \omega_{s1}, \dots, \omega_{sM-1}\}$ with equal probabilities. The PSD of the FHSS signal $s(t)$ is given by [2]

$$\Phi_s(\omega) = \frac{PT_s}{2ML} \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} \left\{ \left[\frac{\sin(\omega - \omega_{cl} - \omega_{sm}) T_s/2}{(\omega - \omega_{cl} - \omega_{sm}) T_s/2} \right]^2 + \left[\frac{\sin(\omega + \omega_{cl} + \omega_{sm}) T_s/2}{(\omega + \omega_{cl} + \omega_{sm}) T_s/2} \right]^2 \right\} \quad (7)$$

for slow frequency hopping (see Fig. 6), or

$$\Phi_s(\omega) = \frac{PT_c}{2ML} \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} \left\{ \left[\frac{\sin(\omega - \omega_{cl} - \omega_{sm}) T_c/2}{(\omega - \omega_{cl} - \omega_{sm}) T_c/2} \right]^2 + \left[\frac{\sin(\omega + \omega_{cl} + \omega_{sm}) T_c/2}{(\omega + \omega_{cl} + \omega_{sm}) T_c/2} \right]^2 \right\} \quad (8)$$

for fast frequency hopping (see Fig. 7). Therefore, the spectrum of the original data signal $b(t)$ is approximately spread by a factor of L for slow frequency hopping, or by a factor of LN for fast frequency hopping.

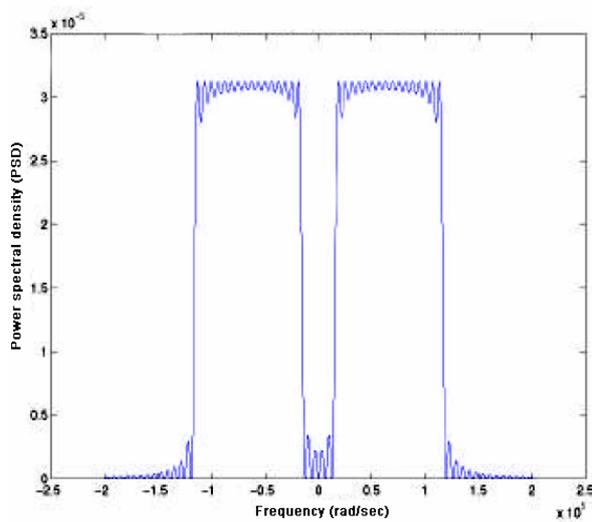


Figure 6: PSD of slow frequency hopping

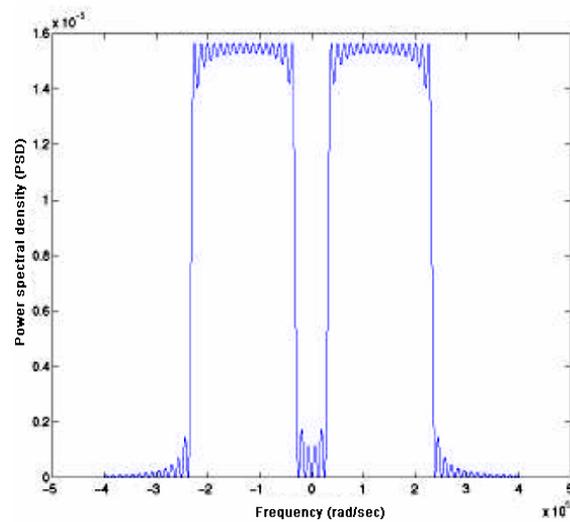


Figure 7: PSD of fast frequency hopping

4 Simulation of an FH/BFSK spread spectrum system in MATLAB

In this section we describe a fast frequency hopping/binary frequency shift keying (FFH/BFSK) spread spectrum system shown in Fig. 8 [8] and we simulate its important characteristics in MATLAB.

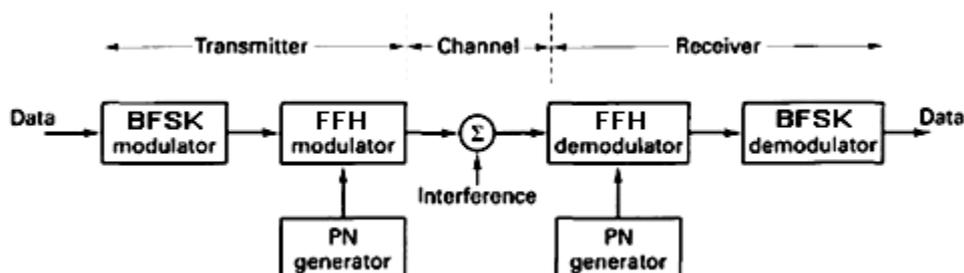


Figure 8: Block diagram of an FFH/BFSK spread spectrum system

The FH spread spectrum system can be thought of as a two-step modulation process-data modulation and frequency-hopping modulation. BFSK modulation scheme is used in a simulated FHSS system. The BFSK modulator selects one of two frequencies corresponding to the transmission of either 1 or 0. The resulting BFSK signal is translated in frequency by an amount that is determined by the output sequence from the PN generator, which is used to select a frequency that is synthesized by the frequency synthesizer. This frequency is FFH modulated by mixing it with the output of the BFSK modulator and the resultant fast frequency hopped spread spectrum (FFHSS) signal is transmitted over the channel. The receiver reverses the signal processing steps of the transmitter. At the receiver, we have an identical PN generator, synchronized with the receiver signal, which is used to control the output of the frequency synthesizer. The received signal is first FFH demodulated (dehopped) by mixing it with the same sequence of pseudo-randomly selected frequency tones that was used for hopping. Finally, the resultant dehopped signal is data demodulated by means of the BFSK demodulator.

In Fig. 9 we can see the flow chart of the simulation procedure of an FFH/BFSK spread spectrum system. Fig. 10 illustrates the simulation results of an FFH/BFSK spread spectrum system in MATLAB.

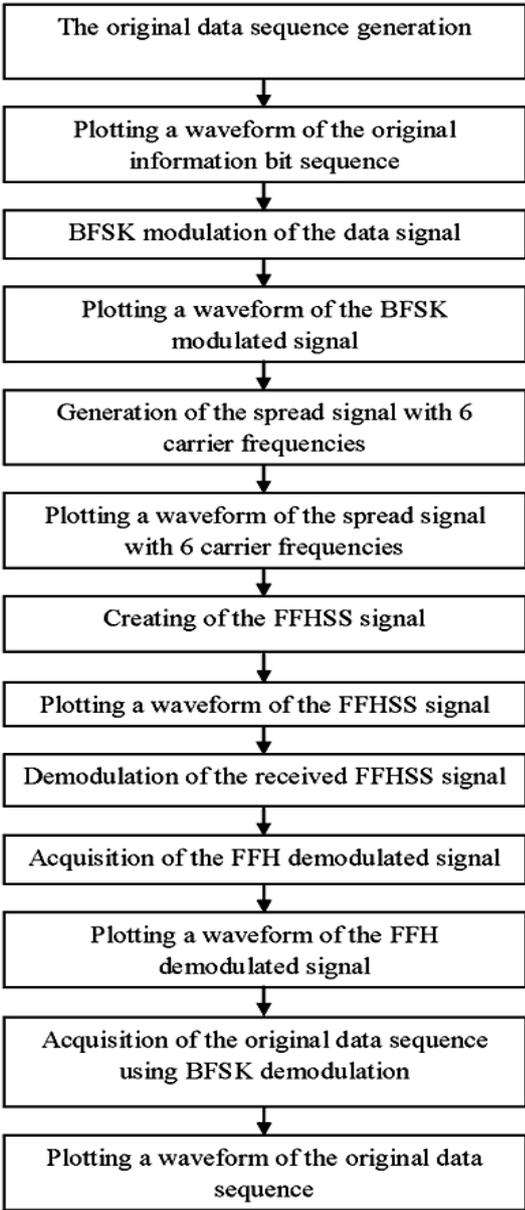
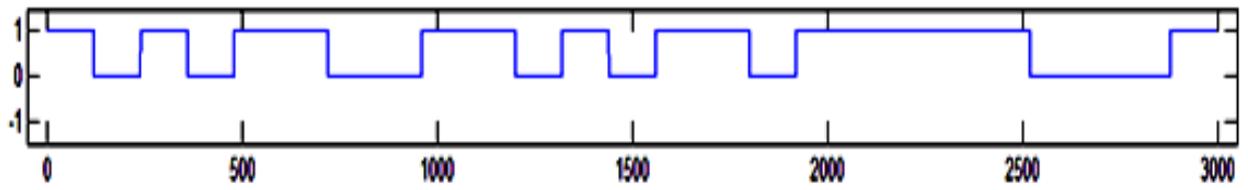
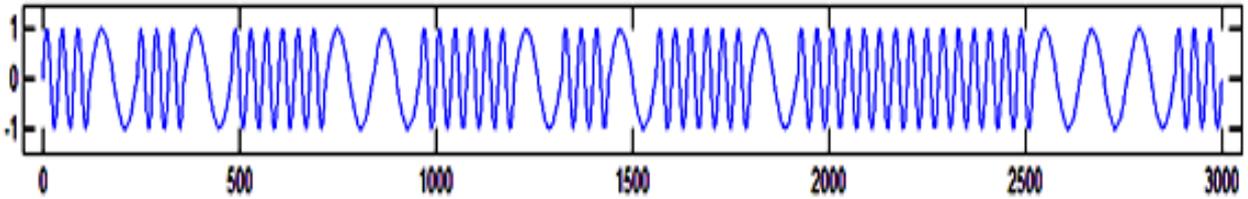


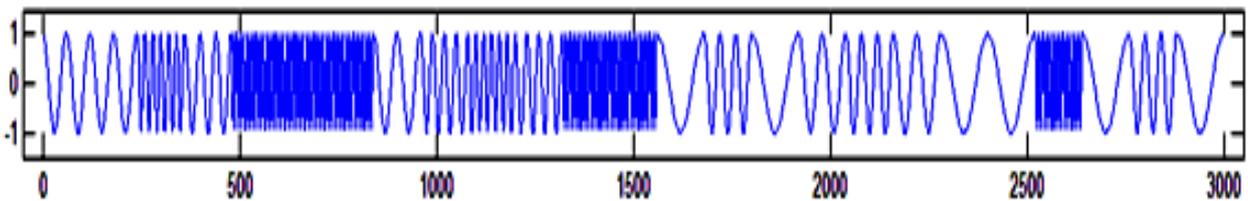
Figure 9: Flow chart of the MATLAB simulation procedure of a FFH/BFSK spread spectrum system



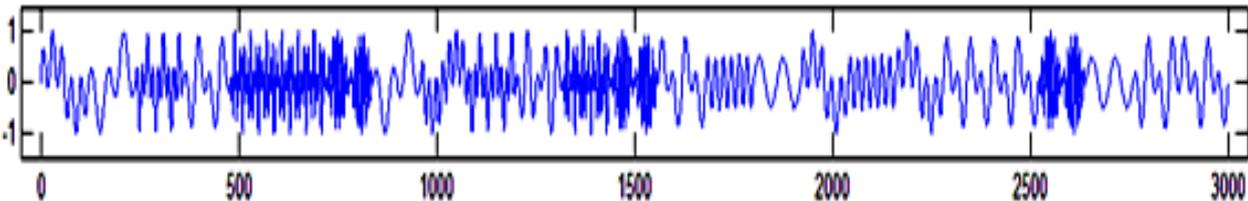
a) The original data sequence



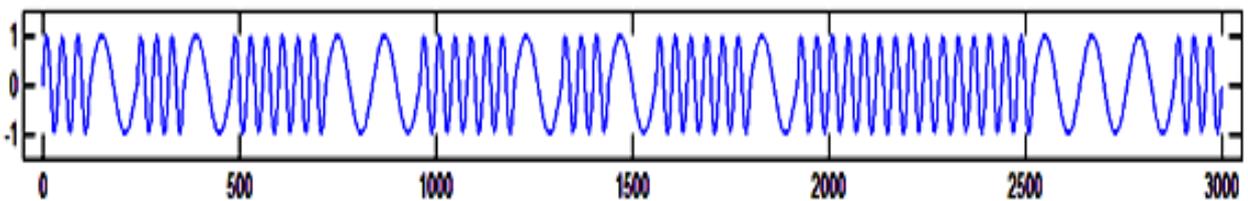
b) The BFSK modulated signal



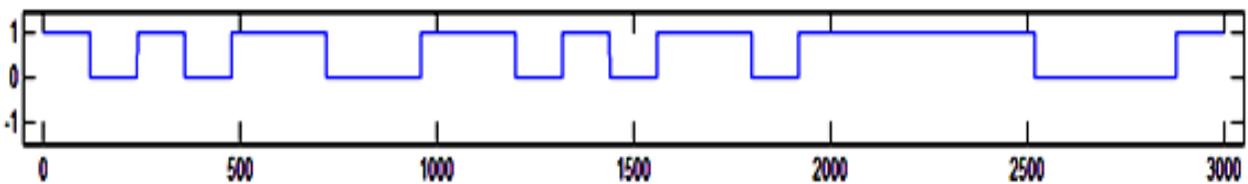
c) The spread signal with 6 frequencies



d) The FFHSS signal



e) The FFH demodulated signal



f) The original data sequence

Figure 10: The simulation results of an FFH/BFSK spread spectrum system in MATLAB

5 Conclusion

In this paper, we have presented FHSS signals and finally, we have described a simulation procedure of an FFH/BFSK spread spectrum communication system in MATLAB. First, we have briefly discussed the characteristic properties FHSS, and consequently we have mathematically described signals in an FH/MFSK spread spectrum communication system. This system is usually configured using noncoherent demodulation since frequency hopping technique operates over a wide bandwidth and it is difficult to maintain phase coherence from hop to hop. In the next section of this paper, we have discussed slow frequency hopping (there are several modulation symbols per hop) and fast frequency hopping (there are several frequency hops per modulation symbol). Although fast frequency hopping is more difficult to implement, offers some advantages over slow frequency hopping. Fast hopping provides frequency diversity at the symbol level, which provides a substantial benefit in fading channels or versus narrowband jamming. On the other hand, slow frequency hopping can obtain these same benefits through error correction coding, but fast hopping offers this benefit before coding, which can provide better performance. In the last section of this paper, a simulation procedure of an FFH/BFSK spread spectrum communication system in MATLAB was described.

References

- [1] R. M. Buehrer. *Code Division Multiple Access (CDMA)*. Morgan & Claypool Publishers, 2006.
 - [2] R. L. Peterson, R. E. Ziemer, and D. E. Borth. *Introduction to Spread Spectrum Communications*. Prentice Hall, Inc., 1995.
 - [3] R. Dixon. *Spread Spectrum Systems with Commercial Applications*. John Wiley & Sons, Inc., third edition, 1994.
 - [4] Ir. J. Meel. *Spread Spectrum (SS) introduction*. In Studiedag Spread Spectrum, 1999.
 - [5] R. L. Pickholtz, D. L. Shilling, L. B. Milstein. *Theory of Spread-Spectrum Communications - A Tutorial*. In IEEE Transactions on Communications, 1982.
 - [6] D. Torrieri. *Principles of Spread-Spectrum Communication Systems*. Springer, second edition, 2011.
 - [7] H. Hrasnica, A. Haidine, and R. Lehnert. *Broadband Powerline Communications: Network Design*. John Wiley & Sons Ltd, 2004.
 - [8] B. Sklar. *Digital Communications: Fundamentals and Applications*. Prentice Hall, second edition, 2001.
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