Spread Spectrum

Chapter 7

Input is fed into a channel encoder
- Produces analog signal with narrow bandwidth

Signal is further modulated using sequence of digits
- Spreading code or spreading sequence
- Generated by pseudo-noise, or pseudo-random number generator

Effect of modulation is to increase bandwidth of signal to be transmitted

On receiving end, digit sequence is used to demodulate the spread spectrum signal
- Signal is fed into a channel decoder to recover data

What can be gained from apparent waste of spectrum?
- Immunity from various kinds of noise and multipath distortion
- Can be used for hiding and encrypting signals
- Several users can independently use the same higher bandwidth with very little interference

Figure 7.1 General Model of Spread Spectrum Digital Communication System

Signal is broadcast over seemingly random series of radio frequencies
- A number of channels allocated for the FH signal
- Width of each channel corresponds to bandwidth of input signal

Signal hops from frequency to frequency at fixed intervals
- Transmitter operates in one channel at a time
- Bits are transmitted using some encoding scheme
- At each successive interval, a new carrier frequency is selected

Frequency Hoping Spread Spectrum (FHSS)
Frequency Hoping Spread Spectrum

- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter, picks up message
- Advantages
  - Eavesdroppers hear only unintelligible blips
  - Attempts to jam signal on one frequency succeed only at knocking out a few bits

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FHSS Using MFSK

- MFSK signal is translated to a new frequency every $T_c$ seconds by modulating the MFSK signal with the FHSS carrier signal
- For data rate of $R$:
  - duration of a bit: $T = 1/R$ seconds
  - duration of signal element: $T_s = LT$ seconds
- $T_c \geq T_s$ - slow-frequency-hop spread spectrum
- $T_c < T_s$ - fast-frequency-hop spread spectrum

FHSS Performance Considerations

- Large number of frequencies used
- Results in a system that is quite resistant to jamming
  - Jammer must jam all frequencies
  - With fixed power, this reduces the jamming power in any one frequency band
Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - Spread is in direct proportion to number of bits used
- One technique combines digital information stream with the spreading code bit stream using exclusive-OR (Figure 7.6)

DSSS Using BPSK

- Multiply BPSK signal, \( s_d(t) = A d(t) \cos(2\pi f_c t) \)
  by \( c(t) \) [takes values +1, -1] to get
  \[ s(t) = A d(t)c(t) \cos(2\pi f_c t) \]
  - \( A \) = amplitude of signal
  - \( f_c \) = carrier frequency
  - \( d(t) \) = discrete function [+1, -1]
- At receiver, incoming signal multiplied by \( c(t) \)
  - Since, \( c(t) \times c(t) = 1 \), incoming signal is recovered

Code-Division Multiple Access (CDMA)

- Basic Principles of CDMA
  - \( D \) = rate of data signal
  - Break each bit into \( k \) chips
    - Chips are a user-specific fixed pattern
  - Chip data rate of new channel = \( kD \)

CDMA Example

- If \( k=6 \) and code is a sequence of 1s and -1s
  - For a ‘1’ bit, A sends code as chip pattern
    - \( \langle c_1, c_2, c_3, c_4, c_5, c_6 \rangle \)
  - For a ‘0’ bit, A sends complement of code
    - \( \langle -c_1, -c_2, -c_3, -c_4, -c_5, -c_6 \rangle \)
- Receiver knows sender’s code and performs electronic decode function
  \[ S_c(d) = d_1 \times c_1 + d_2 \times c_2 + \ldots + d_6 \times c_6 \]
  - \( d_1, d_2, d_3, d_4, d_5, d_6 \) = received chip pattern
  - \( \langle c_1, c_2, c_3, c_4, c_5, c_6 \rangle \) = sender’s code
CDMA Example
- User A code = \(<1, -1, -1, 1, -1, 1>\)
  - To send a 1 bit = \(<1, -1, -1, 1, -1, 1>\)
  - To send a 0 bit = \(<-1, 1, 1, -1, 1, -1>\)
- User B code = \(<1, 1, -1, -1, 1, 1>\)
  - To send a 1 bit = \(<1, 1, -1, -1, 1, 1>\)
  - To send a 0 bit = \(<-1, 1, 1, -1, 1, -1>\)
- Receiver receiving with A’s code
  - \((A’s \ code) \times (\text{received \ chip \ pattern})\)
    - User A ‘1’ bit: 6 \(\rightarrow\) 1
    - User A ‘0’ bit: -6 \(\rightarrow\) 0
    - User B ‘1’ bit: 0 \(\rightarrow\) unwanted signal ignored

Categories of Spreading Sequences
- Spreading Sequence Categories
  - PN sequences
  - Orthogonal codes
- For FHSS systems
  - PN sequences most common
- For DSSS systems not employing CDMA
  - PN sequences most common
- For DSSS CDMA systems
  - PN sequences
  - Orthogonal codes

PN Sequences
- PN generator produces periodic sequence that appears to be random
- PN Sequences
  - Generated by an algorithm using initial seed
  - Sequence isn’t statistically random but will pass many test of randomness
  - Sequences referred to as pseudorandom numbers or pseudonoise sequences
  - Unless algorithm and seed are known, the sequence is impractical to predict

Important PN Properties
- Randomness
  - Uniform distribution
  - Balance property
  - Run property
  - Independence
  - Correlation property
- Unpredictability

Linear Feedback Shift Register Implementation
- PN Sequences
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Properties of M-Sequences

Property 1:
- Has $2^n$ ones and $2^{n-1}$ zeros

Property 2:
- For a window of length $n$ slid along output for $N=(2^n-1)$ shifts, each $n$-tuple appears once, except for the all zeros sequence

Property 3:
- Sequence contains one run of ones, length $n$
- One run of zeros, length $n-1$
- One run of ones and one run of zeros, length $n-2$
- Two runs of ones and two runs of zeros, length $n-3$
- $2^{n-3}$ runs of ones and $2^{n-3}$ runs of zeros, length 1

Property 4:
- The periodic autocorrelation of a ±1 m-sequence is

\[
R(\tau) = \begin{cases} 
1 & \tau = 0, N, 2N, \ldots \\
-\frac{1}{N} & \text{otherwise}
\end{cases}
\]

Definitions

Correlation
- The concept of determining how much similarity one set of data has with another
- Range between –1 and 1
  - 1 The second sequence matches the first sequence
  - 0 There is no relation at all between the two sequences
  - -1 The two sequences are mirror images

Cross correlation
- The comparison between two sequences from different sources rather than a shifted copy of a sequence with itself

Advantages of Cross Correlation

- The cross correlation between an m-sequence and noise is low
  - This property is useful to the receiver in filtering out noise
- The cross correlation between two different m-sequences is low
  - This property is useful for CDMA applications
  - Enables a receiver to discriminate among spread spectrum signals generated by different m-sequences

Gold Sequences

- Gold sequences constructed by the XOR of two m-sequences with the same clocking
- Codes have well-defined cross correlation properties
- Only simple circuitry needed to generate large number of unique codes
- In following example (Figure 7.16a) two shift registers generate the two m-sequences and these are then bitwise XORed

Gold Sequences

(a) Shift-register implementation
Orthogonal Codes

- Orthogonal codes
  - All pairwise cross correlations are zero
  - Fixed- and variable-length codes used in CDMA systems
  - For CDMA application, each mobile user uses one sequence in the set as a spreading code
    - Provides zero cross correlation among all users
- Types
  - Welsh codes
  - Variable-Length Orthogonal codes

Walsh Codes

- Set of Walsh codes of length \( n \) consists of the \( n \) rows of an \( n \times n \) Walsh matrix:
  \[
  w_i = (0), \quad W_n = \begin{pmatrix} w_0 & w_2 & \cdots & w_{2^n} \\ W_u & W_w & \cdots & W_{2^n} \\ \end{pmatrix}
  \]
  - \( n \) = dimension of the matrix
  - Every row is orthogonal to every other row and to the logical not of every other row
  - Requires tight synchronization
    - Cross correlation between different shifts of Walsh sequences is not zero

Typical Multiple Spreading Approach

- Spread data rate by an orthogonal code (channelization code)
  - Provides mutual orthogonality among all users in the same cell
- Further spread result by a PN sequence (scrambling code)
  - Provides mutual randomness (low cross correlation) between users in different cells