Spread-Spectrum Techniques
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1. Overview
Basic Requirements of Spread-Spectrum Systems

Motivations:
- Originally developed and used for military communications.
- Want to provide resistance to intentional jamming. (i.e., anti-jamming protection)
- Want to hide the signal by transmitting it at low power and thus making it difficult for an unintended listener to detect its presence in noise. (i.e., low probability to intercept)

Basic Requirements:
- The transmission bandwidth employed is much greater than the minimum bandwidth required to transmit the information.
- Spreading is accomplished by means of a spreading signal, often called a code signal, which is independent of the data.
- At the receiver, despreading is accomplished by the correlation of the received spread signal with a synchronized replica of the spreading signal used at the transmitter to spread the information.
Basic Structure

- Two identical pseudorandom sequence generators are employed to generate a pseudo-noise (PN) binary sequence for spreading.
- For a typical narrowband signal, only the noise in the signal bandwidth can degrade performance.
Benefits of Spread Spectrum Systems

- Interference suppression/rejection
  - Anti-jam capability

- Energy density reduction
  - Low probability of detection/interception

- Fine time resolution
  - Accurate time-delay measurement

- Multiple Access
  - Code-division multiple access (CDMA)
The world goes wireless!

Interference Suppression / Rejection (1/3)

Goal:
- Better protection against jamming

Assumption:
- The jammer cannot determine the signal subset that is currently in use.
- The noise stems from the jammer has a fixed finite power.

The jammer’s choice will be one of the followings:
- Choice 1:
  - Jam all the signal coordinates (i.e., entire signal bandwidth) of the system, with an equal amount of small power in each one.
- Choice 2:
  - Jam only a few signal coordinates (i.e., a part of the frequency band), with increased power.
Interference Suppression / Rejection (2/3)

- The larger the dimensionality of the signal set (or the more signal coordinates) the communicator can choose from,
  - the greater is the jammer’s uncertainty regarding the effectiveness of the jamming technique, and
  - the better will be the protection against jamming.

\[ J: \text{Jammer power (fixed)} \]
\[ J_0': \text{Jammer noise spectral density before spreading} \]
\[ J_0: \text{Broadband jammer noise spectral density} \]

- Power spectral density reduction factor

- Before spreading
  - \[ G(f) \]
  - \[ J_0 = J/W \]

- After spreading
  - Jammer choice 1
    - \[ G_{ss}(f) \]
    - \[ J_0 = J/W_{ss} = J_0'(W/W_{ss}) \]
  - "The jammer noise spectral density is reduced."

- Jammer choice 2
  - \[ G_{ss}(f) \]
  - \[ J_0/\rho \]
  - 0 < \rho \leq 1
  - "The jammer must make a good guess in the coordinates to be jammed."

- W: Unspread bandwidth
- \( W_{ss}: \text{Spread bandwidth} \)
Interference Suppression / Rejection (3/3)

- The essence behind the interference rejection capability:
  - Multiplication by the spreading signal once spreads the signal bandwidth.
  - Multiplication by the spreading signal twice, followed by filtering, recovers the original signal.
  - The desired signal gets multiplied twice, but the interference signal gets multiplied only once.
The world goes wireless!

**Energy Density Reduction**

- **Goal:**
  - *Low probability of detection (or interception)*

- The spread-spectrum systems are designed to make the detection of their signals as difficult as possible by anyone but the intended receiver.
  - Since, in the spread-spectrum systems, the signal is spread over many more signaling coordinates than in conventional modulation schemes, the resulting signal power is, on average, *spread thinly and uniformly* in the spread domain.
  - To anyone who does not possess a synchronized replica of the spreading signal, the spread-spectrum signal will seem “*buried in the noise.*”
  - Not only the exact location of the source but also the direction of the transmitter will be difficult to pinpoint.
Fine Time Resolution

Goal:

- Accurate ranging or determination of position location

Distance can be determined by measuring the time delay of a pulse as it travels the channel.

- Uncertainty in the delay measurement, $\Delta t$, is inversely proportional to the bandwidth of the signal pulse.
- The larger the bandwidth, the more precisely one can measure range.

The spread-spectrum technique uses a code signal consisting of a long sequence of polarity changes in place of the single pulse.

- The received sequence is correlated against a local replica and the results of the correlation are used to perform an accurate time-delay or range measurement.

\[ \Delta t \approx \text{Rise time of pulse} \approx \frac{1}{W} \]
Multiple Access

Goal:
- Want to share a communications resource among numerous users
- Code-division multiple access (CDMA)

By-products of this type of multiple access:
- Ability to provide communication privacy among users with different spreading signals.
- An unauthorized user cannot easily monitor the communications of the authorized users.

\[ \int_0^T g_i(t) g_j(t) \, dt = \begin{cases} 1 & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases} \]
Category of Spread-Spectrum Techniques

- We want to hide the location of signal coordinates from potential enemies, either by spectrum spreading or by time spreading.
  - Direct Sequence (DS)
  - Frequency Hopping (FH)
  - Time Hopping (TH)
  - Hybrids
Transmitted Reference vs. Stored Reference

- Transmitted reference system:
  - Send two versions of an unpredictable wideband carrier on separate channels:
    - One modulated by the data and the other unmodulated.
  - Advantage:
    - No significant synchronization problem at the receiver.
  - Disadvantages:
    - The spreading code is sent in the clear format and thus is available to any listener.
    - The system can be easily spoofed by the jammer.
    - Performance degrades at low signal levels since the noise is present on both the signals.
    - Twice the bandwidth and transmitted power are required.

- Stored reference system:
  - The spreading code is independently and identically generated at both the transmitter and the receiver.
    - Pseudo-noise (PN) or pseudo-random signals
  - Advantage:
    - Cannot be predicted by monitoring the transmission.
  - Disadvantage:
    - Synchronization problems
2. Pseudonoise Sequences
Random Sequence vs. Pseudonoise (PN) Sequence

Random sequence:
- Cannot be predicted.
- Its future variations can only be described in a statistical sense.

Pseudonoise (PN) sequence:
- Not random at all.
- It is deterministic and periodic, known to both the transmitter and receiver.
- It appears to have the statistical properties of sampled white noise, and thus appears to be a truly random signal to an unauthorized listener.

A class of periodic PN sequences:
- Maximal-length linear shift register sequence (or m-sequence):
  - Length: \( N = 2^m - 1 \) (\( m \) = # of shift registers)
- Quadratic residue sequence:
  - Length: \( N = 4k - 1 = \text{prime number} \) (\( k \) is an integer.)
- Hall sequence:
  - Length: \( N = 4k - 1 = 4q^2 + 27 = \text{prime number} \) (both \( k \) and \( q \) are integers.)
- Twin primes:
  - Length: \( N = p (p + 2) \) (both \( p \) and \( p+2 \) are prime numbers.)
Randomness Properties

- **Balance property:**
  - Good balance requires that in each period of the sequence,
    - Number of 1’s = Number of 0’s + 1, or
    - Number of 0’s = Number of 1’s + 1

- **Run property:**
  - Definition of a “run”: a sequence of a single type of binary digit(s).
  - The length of the run is the number of digits in the run.
  - Among the runs of ones and zeros in each period, it is desirable that
    - 1/2 the runs of each type are of length 1
    - 1/4 the runs are of length 2
    - 1/8 the runs are of length 3, and so on.

- **Correlation property:**
  - If a period of the sequence is compared term-by-term with any cyclic shift of itself, it is best if the number of agreements differs from the number of disagreements by not more than one count.

\[
R_g(k) = \frac{1}{N} \sum_{n=1}^{N} g(n) g(n-k) = \begin{cases} 1, & \text{if } k = mN \quad (m: \text{integer}) \\ -\frac{1}{N}, & \text{if } k \neq mN \end{cases}
\]

where \( g(n) = \pm 1 \)
**Linear Feedback Shift Register Sequences (1/2)**

- **Example 1: \( m = 3 \)**
  - Initial state: 1 0 0
  - Then the succession of register states:
    - \( 1 \ 0 \ 0 \rightarrow 1 \ 1 \ 0 \rightarrow 1 \ 1 \ 1 \rightarrow 0 \ 1 \ 1 \rightarrow 1 \ 0 \ 1 \rightarrow 0 \ 1 \ 0 \rightarrow 0 \ 0 \ 1 \rightarrow 1 \ 0 \ 0 \ldots \)
  - The output sequence: 0 0 1 1 1 0 1 \( (N = 2^3 - 1 = 7) \)
    - Balance:
      - \# of ones = 4, and \# of zeros = 3
    - Run:
      - Four runs: \{0 0\}, \{1 1\}, \{0\}, \{1\}
    - Correlation:
      - \( \{g(n)\} = -1, -1, +1, +1, -1, +1 \)

\[
R_g(k) = \begin{cases} 
1, & \text{if } k = 7m \\
-1/7, & \text{if } k \neq 7m \quad (m: \text{integer})
\end{cases}
\]
Linear Feedback Shift Register Sequences (2/2)

Example 2: \( m = 4 \)

- Initial state: \( 1 \, 0 \, 0 \, 0 \)
- Then the succession of register states:
  - \( 100 \, 0 \rightarrow 010 \, 0 \rightarrow 001 \, 0 \rightarrow 100 \, 1 \rightarrow 110 \, 0 \rightarrow 011 \, 0 \rightarrow 101 \, 1 \rightarrow 010 \, 1 \rightarrow 101 \, 0 \rightarrow 110 \, 1 \rightarrow 111 \, 0 \rightarrow 111 \, 1 \rightarrow 011 \, 1 \rightarrow 001 \, 1 \rightarrow 000 \, 1 \rightarrow 100 \, 0 \ldots \)

- The output sequence: \( 0 \, 0 \, 0 \, 1 \, 0 \, 0 \, 1 \, 0 \, 1 \, 0 \, 1 \, 1 \, 1 \, 1 \) \((N = 2^4 \, – \, 1 = 15)\)
  - Balance:
    - \# of ones = 8, and \# of zeros = 7
  - Run:
    - Eight runs: \{0 0 0\}, \{1\}, \{0 0\}, \{1 1\}, \{0\}, \{1\}, \{0\}, \{1 1 1 1\}
  - Correlation:
    - \( \{g(n)\} = -1, -1, +1, -1, -1, +1, +1, +1, -1, +1, +1, +1, +1 \)

\[
R_g(k) = \begin{cases} 
1, & \text{if } k = 15m \\
-\frac{1}{15}, & \text{if } k \neq 15m \ (m : \text{integer})
\end{cases}
\]
Range of PN Sequence Lengths

- The period, $N$, of an $n$-stage linear feedback shift register:
  
  \[ N = 2^n - 1 \]

- Example ($m = 42$):
  - Clock frequency = 1 MHz
  - Chip duration = $10^{-6}$ sec
  - $N = 2^{42} - 1 \approx 4.398 \times 10^{12}$

  - Time interval for one period of the sequence:
    \[ \approx 4.398 \times 10^{12} \times 10^{-6} = 4.398 \times 10^6 \text{ (sec)} \approx 50.903 \text{ (days)} \]

<table>
<thead>
<tr>
<th>$m$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>127</td>
</tr>
<tr>
<td>10</td>
<td>1023</td>
</tr>
<tr>
<td>12</td>
<td>4095</td>
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<td>13</td>
<td>8191</td>
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<tr>
<td>16</td>
<td>65535</td>
</tr>
<tr>
<td>17</td>
<td>131071</td>
</tr>
<tr>
<td>19</td>
<td>524287</td>
</tr>
<tr>
<td>42</td>
<td>$\approx 4.398 \times 10^{12}$</td>
</tr>
</tbody>
</table>
The (normalized) autocorrelation function $R_x(\tau)$ of a periodic waveform $x(t)$ with period $T_0$:
- We call each fundamental pulse of $x(t)$ a PN code symbol or a chip.

\[
R_x(\tau) = \frac{1}{K} \left( \frac{1}{T_0} \right) \int_{-T_0/2}^{T_0/2} x(t)x(t + \tau)dt \quad \text{for} \quad -\infty < \tau < \infty
\]

\[
K = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} x^2(t) \, dt
\]

The normalized autocorrelation for a PN waveform of chip duration 1 and period $p$ chips:
**PN Autocorrelation Function (2/2)**

- **Example:**
  - Pulse waveform of the binary sequence for $m=3$

![Pulse waveform of the binary sequence for m=3](image)

- Autocorrelation function of $g(t)$:

  \[
  R_g(\tau) = \frac{1}{K} \frac{1}{7T_c} \int_0^{7T_c} g(t)g(t+\tau)d\tau
  \]

  where

  \[
  K = \frac{1}{7T_c} \int_0^{7T_c} g^2(t)dt
  \]
3. Direct-Sequence Spread-Spectrum Systems
**Direct-Sequence (DS) Modulator**

- The data-modulated signal $s_x(t)$ is again modulated with a high-speed (wideband) spreading signal $g(t)$.

- A constant-envelope phase-modulated carrier having power $P$:

$$s_x(t) = \sqrt{2P} \cos [\omega_0 t + \theta_x(t)]$$

- The transmitted waveform:

$$s(t) = \sqrt{2P} \cos [\omega_0(t) + \theta_x(t) + \theta_g(t)]$$

- For a BPSK system:

$$s_x(t) = \sqrt{2P} x(t) \cos \omega_0 t$$

$$s(t) = \sqrt{2P} x(t)g(t) \cos \omega_0 t$$

- Phase due to the spreading sequence

- Phase due to the data

- $\theta_x(t)$ and $\theta_g(t) = 0$ or $\pi$

- $\theta_x(t) + \theta_g(t) = \pi$, if $x(t)g(t) = -1$

- $\theta_x(t) + \theta_g(t) = 0$, if $x(t)g(t) = +1$

**Diagram**

- Data pulse waveform $x(t) = \pm 1$

- BPSK data modulator $s_x(t) = \sqrt{2P} x(t) \cos \omega_0 t$

- BPSK code modulator $s(t) = \sqrt{2P} x(t)g(t) \cos \omega_0 t$

- Spreading signal $g(t) = \pm 1$
Example: DS/BPSK Modulation and Demodulation (1/2)

- DS/BPSK Transmitter:

\[
s(t) = \sqrt{2P} x(t) g(t) \cos \omega_0 t
\]

- DS/BPSK Receiver:

\[
r(t) = A \sqrt{2P} x(t - T_d) g(t - T_d) \cos [\omega_0 (t - T_d) + \phi]
\]

\[
g(t - T_d) g(t - T_d) = 1, \text{ if } \hat{T}_d = T_d
\]
Example: DS/BPSK Modulation and Demodulation (2/2)

Binary data waveform to be transmitted

Code sequence

Transmitted sequence

Phase of transmitted carrier

Phase shift produced by receiver code

Phase of received carrier after phase shifted (despread) by receiver code

Demodulated data waveform

Signal hiding effect

\[
x(t)
\]

\[
g(t)
\]

\[
x(t)g(t)
\]

\[
0_x(t) + 0_g(t)
\]

\[
\hat{\theta}_g(t)
\]

\[
\hat{\theta}_x(t)
\]

\[
\hat{x}(t)
\]
Processing Gain (1/2)

- The spread-spectrum techniques enable a relatively low-dimensional signal to be distributed in a large-dimensional signal space, so that the signal can be hidden within the larger signal space.

- Recall that the jammer’s choice is
  - To jam the entire space with its fixed total power, and thus inducing a limited amount of interference in each signal coordinate, or
  - To jam a portion of the signal space with its total power, and thus leaving the remainder of the signal space free of interference.

- A fundamental issue in spread-spectrum systems:
  - “How much protection can the spread-spectrum techniques provide against interfering signals with finite power?”
  - Processing gain!
Processing Gain (2/2)

- Consider a set of $D$ orthogonal signals, $s_i(t)$, $i = 1, 2, \ldots, D$, in an $N$-dimensional space (generally, $D \ll N$).

- Using a PN spreading code, we want to *hide* the $D$-dimensional signal set $\{s_i(t)\}$ in the larger $N$-dimensional space.

- Processing gain (PG), $G_p$:
  - *Performance advantage over the jammer*, i.e., $N/D$, or
  - *Performance advantage over a narrowband system*
  - High PG provides more robust signaling.
  - Since the approximate dimensionality of a signal with bandwidth $W$ and duration $T$ equals to $2WT$, we can write the PG as

\[
G_p = \frac{N}{D} \approx \frac{2W_{ss}T}{2W_{\text{min}}T} = \frac{W_{ss}}{R} \\
\text{or} \quad G_p = \frac{R_{\text{ch}}}{R} \quad \text{or} \quad 10 \log(G_p) \text{ in dB}
\]

- $W_{ss}$: The spread-spectrum bandwidth ($\approx$ code chip rate, $R_{\text{ch}}$)
- $W_{\text{min}}$: The minimum bandwidth of the data ($\approx$ data rate, $R$)
4. Frequency-Hopping Systems
**FH/MFSK System**

- Frequency-hopping (FH) most commonly works with MFSK:
  - The position of the $M$-ary signal set is shifted *pseudorandomly* by the frequency synthesizer over a hopping bandwidth $W_{ss}$.
  - At each frequency hop time, a PN generator feeds the frequency synthesizer a frequency word (say, a sequence of $l$ chips), which dictates one of $2^l$ symbol-set positions.
  - The *minimum number of chips necessary in the frequency word* can be determined by the frequency hopping bandwidth, $W_{ss}$, and the *minimum frequency spacing* between consecutive hop positions, $\Delta f$.
  - *Bandwidth for FH >> bandwidth for DS*, and thus has a larger PG.
  - It is difficult to maintain phase coherence from hop to hop, and thus FH is usually demodulated *noncoherently*.

![Diagram of FH/MFSK System]

- $k = \log_2 M$ information bits
- $l$ chips
- PN generator
- Interference
- Frequency Synthesizer
- FH modulator
- FH demodulator
- MFSK modulator
- MFSK demodulator
- Transmitter
- Channel
- Receiver
Frequency Word Size

Example:

- Hopping bandwidth, \( W_{ss} = 400 \) MHz
- Frequency step size, \( \Delta f = 100 \) Hz
- What is the minimum number of PN chips required for each frequency word?

Number of tones contained in \( W_{ss} \) = \( \frac{W_{ss}}{\Delta f} = \frac{400 \text{ MHz}}{100 \text{ Hz}} \)

= \( 4 \times 10^6 \)

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

= 22 chips

where \([x]\) indicates the smallest integer value not less than \(x\).
**FH/MFSK Example (1/2)**

8-ary FSK system:
- Data rate, $R = 150$ bits/s
- Symbol rate, $R_s = R/\log_2 8 = 150/3 = 50$ symbols/s
- Symbol duration, $T = 1/50 = 20$ ms
- Hop once per symbol, i.e., hop rate = 50 hops/s
- Frequency spacing, $\Delta f = 1/T = 50$ Hz

**For every symbol interval, the center frequency $f_0$ is shifted pseudorandomly according to the PN code generator output.**

### 8Δf = 400 Hz
- $f_0 + 175$ Hz
- $f_0 + 125$ Hz
- $f_0 + 75$ Hz
- $f_0 + 25$ Hz
- $f_0$
- $f_0 - 25$ Hz
- $f_0 - 75$ Hz
- $f_0 - 125$ Hz
- $f_0 - 175$ Hz

### 400 Hz
- $f_0 + 125$ Hz
- $f_0 + 75$ Hz
- $f_0 + 25$ Hz
- $f_0$
- $f_0 - 25$ Hz
- $f_0 - 75$ Hz
- $f_0 - 125$ Hz
- $f_0 - 175$ Hz

### Δf = 50 Hz
- $f_0 + 25$ Hz
- $f_0 - 25$ Hz
- $f_0 - 75$ Hz
- $f_0 - 125$ Hz
- $f_0 - 175$ Hz
4-ary FSK system:
- $k = 2$
- $M = 4$
- Length of PN segment/hop, $l = 2$
- Total # of frequency hops = $2^l = 4$

The frequency is hopped once per symbol.
The world goes wireless!

Robustness

- The greater the *diversity*, the more robust the signal against random interference.
  - Multiple transmissions at different frequencies, and spread in time

- Example:
  - Want to transmit 4 symbols: \[ s_1 s_2 s_3 s_4 \]
  - Repeating factor for diversity, \( N = 8 \)
  - Repeated symbol (i.e., *chip*):
    \[
    s_1 s_1 s_1 s_1 s_1 s_1 s_1 s_1 s_2 s_2 s_2 s_2 s_2 s_2 s_2 s_2 s_2 s_2 s_3 s_3 s_3 s_3 s_3 s_3 s_3 s_3 s_4 s_4 s_4 s_4 s_4 s_4 s_4 s_4
    \]
    \[ f_i \quad f_j \quad f_k \]
  - We transmit each chip at a different hop frequency (i.e., the center frequency of the data bandwidth is changed for each chip).
  - The resulting transmissions yield a more robust signal than without such diversity.
Frequency-Hopping with Diversity

- FH Example with diversity:
  - 8-ary FSK system:
  - Data rate, $R = 150$ bits/s
  - Symbol rate, $R_s = R / \log_2 8 = 150 / 3 = 50$ symbols/s
  - Symbol duration, $T = 1 / 50 = 20$ ms
  - Frequency spacing, $\Delta f = 1 / T = 50$ Hz
  - Chip repeat factor, $N = 4$

Frequency hopping band

Frequency hopping

Symbol interval (20 ms)

Hop rate

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

Symbol interval (5 ms/chip)
Slow Hopping vs. Fast Hopping

- Slow frequency-hopping (SFH):
  - There are several modulation symbols per hop
  - For an $M$-ary FSK signaling: $R_s > R_h$
    - $R_s = \text{symbol rate (symbols/s)}$
    - $R_h = \text{hop rate (hops/s)}$

- Fast frequency-hopping (FFH):
  - There are several frequency hops per modulation symbol
  - For an $M$-ary FSK signaling: $R_h > R_s$

- Chip rate: $R_c = \max (R_s, R_h)$
Example: Waveforms for Slow vs. Fast Hopping

- Slow frequency-hopping (SFH):
  - Symbol rate, $R_s = 30$ symbols/s
  - Hop rate, $R_h = 10$ hops/s
  - 1 chip = 1 symbol

![Waveform diagram for SFH]

- Fast frequency-hopping (FFH):
  - Symbol rate, $R_s = 30$ symbols/s
  - Hop rate, $R_h = 60$ hops/s
  - 1 chip = 1 hop

![Waveform diagram for FFH]
**Example: Slow vs. Fast Hopping in a Binary System**

- **Slow frequency-hopping:**
  - 3 bits/hop

- **Fast frequency-hopping:**
  - 4 hops/bit
4-ary FSK system:
- $R_s = 2R_h$
- # of shift registers, $m = 4$
- $N = 2^4 - 1 = 15$
- Length of PN segment per hop, $l = 3$
- Total # of frequency hops, $L = 2^l = 8$
4-ary FSK system:
- $R_h = 2R_s$
- # of shift registers, $m = 4$
- $N = 24 – 1 = 15$
- Length of PN segment per hop, $l = 3$
- Total # of frequency hops, $L = 2l = 8$

Input binary data

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>110</td>
<td>011</td>
<td>001</td>
<td>001</td>
<td>001</td>
<td>110</td>
<td>011</td>
<td>001</td>
<td>001</td>
</tr>
</tbody>
</table>

PN seq.

$N = 15$
5. Synchronization
Two Basic Steps for Synchronization

- Acquisition:
  - A problem of searching throughout a region of time and frequency uncertainty in order to synchronize the received SS signal with the locally generated spreading signal.
  - Coarse alignment
  - Coherent or noncoherent
    - Coherent acquisition scheme requires exact and a priori knowledge of the carrier frequency and phase. \( \rightarrow \) Not easy!
    - Most acquisition schemes utilize noncoherent detection.
    - Moreover, we want to make acquisition operate on a baseband signal.
  - Parallel or sequential

- Tracking:
  - Once acquisition is completed, tracking takes place.
  - Fine alignment
  - Coherent or noncoherent
Uncertainties in Synchronization

- Uncertainty in the *distance* between the Tx and Rx:
  - Uncertainty in the amount of propagation delay.

- Relative *clock instabilities* between the Tx and Rx:
  - Phase differences between Tx/Rx spreading signals.

- Uncertainty of the Rx’s *relative velocity* with respect to the Tx:
  - Uncertainty in the value of Doppler frequency offset of the incoming signal.

- Relative *oscillator instabilities* between the Tx and Rx:
  - Frequency offset between the two signals.
6. Applications
CDMA (Code-Division Multiple Access)

- Each code is approximately orthogonal with all other codes.
- Share the full spectrum of resource asynchronously.
- Three attractive features over TDMA:
  - CDMA does not require an external synchronization network, which is essential in TDMA.
  - CDMA offers a gradual degradation in performance as the number of users is increased.
  - CDMA offers an external interference rejection capacity. (i.e., multipath rejection or resistance to deliberate jamming)
Multipath Suppression

- Multipath channel due to
  - Atmospheric reflection or refraction, or
  - Reflections from buildings or other objects.

- May results in fluctuation in the received signal level.

- The DS-SS can be applied in a slow-fading channel.

- If frequency hopping (FH) is used against the frequency-selective multipath problems, improvement in system performance is possible.
**DS-SS vs. FH-SS**

**DS-SS**
- **Good:**
  - Best noise and anti-jam performance
  - Most difficult to detect
  - Best discrimination against multipath
- **Bad:**
  - Requires wideband channel with little phase distortion
  - Long acquisition time
  - Requires a fast code generator
  - Near-far problem

**FS-SS**
- **Good:**
  - Great amount of spreading
  - Can be programmed to avoid portions of spectrum
  - Relatively short acquisition time
  - Less affected by near-far problem
- **Bad:**
  - Complex frequency synthesizer
  - More vulnerable to multipath
  - Error correction required