UWB (Ultra Wideband) Communication System

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What is UltraWideBand?

- **FCC**: bandwidth is more than 25% of a center frequency or more than 1.5 GHz
- **Typically implemented in a carrier-less fashion (Base-band modulation)**
  - Directly modulate an “impulse” with a very sharp rise and fall time => a waveform that occupies several GHz.
- **Historically started with radar applications for military use**
FCC UWB Emission Limit for Outdoor Handheld Systems
FCC UWB Emission Limit For Indoor Systems
Information Modulation (continued)

Figure 2. A Monocycle Pulse Train In The Time and Frequency Domains
Theoretical Motivation

- Shannon Channel Capacity Theorem
  - Capacity grows faster as a function of bandwidth than as a function of power

\[ C = B \log_2 \left( 1 + \frac{P}{BN_0} \right) \]

Where:
- \( C \) = Channel Capacity (bits/sec)
- \( B \) = Channel Bandwidth (Hz)
- \( P \) = Received Signal Power (watts)
- \( N_0 \) = Noise Power Spectral Density (watts/Hz)

\( C \) is an increasing function of \( B \)

Capacity of a Gaussian Channel
Information Modulation

Pulse length <1ns; Energy concentrated in 2-6GHz band; Power < 10uW

- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)
- On-Off Keying (OOK)
- Bi-Phase Modulation (BPSK)
Why is UWB attractive?

1. Simplicity: it’s essentially a base-band system (carrier-free), for which the analog front-end complexity is far less than for a traditional sinusoidal radio.
2. High spatial capacity (bps/m²)
3. Low power
   (Bluetooth: 1Mbps, 10m, 1mW   UWB: 1Mbps, 10m, 10 )
4. Low cost, simple implementation
5. Immune to multipath fading as well as multi-user interference
Two main data modulation schemes used for UWB systems

- Time hopping pulse position modulation (TH-PPM)
- Direct spread code division multiple access (DS-CDMA)
Basic Transmitter Model For TH-PPM

- Transmitter Model with typical time hopping format with Pulse-Position Modulation (PPM):
  - Step 1: Define monocycle waveform
    \[ s^{(k)}(t) = \sum_{j} w(t) \]
    - \( S^{(k)} \) is the \( k^{th} \) transmitted signal
    - \( w(t) \) represents the transmitted monocycle waveform
  - Step 2: Shift to the beginning of Time frame
    \[ s^{(k)}(t) = \sum_{j} w(t - jT_f) \]
    - \( T_f \) is the pulse repetition time or frame time
    - \( j \) is the \( j \) th monocycle that sits at the beginning of each time frame.
Figure 7.1  A typical received monocyte $w_{\text{rec}}(t)$ at the output of the antenna subsystem as a function of time in nanoseconds.
Step 3 – Pseudorandom Time Hopping

\[ s^{(k)}(t) = \sum_j w(t - jT_f - c^{(k)}_j T_c) \]

- To eliminate catastrophic collisions in multiple accessing
- \( \{C_j^{(k)}\} \) are time hopping code, periodic pseudorandom codes
- \( T_c \) is the additional time delay that associate with the time hopping code

Step 4 – Data Modulation

\[ s^{(k)}(t) = \sum_j w(t - jT_f - c^{(k)}_j T_c - \delta d^{(k)}_{[j/N_s]}) \]

- \( \{d_j^{(k)}\} \) is the primary data sequence of the transmitter
- Data are transmitted every \( N_s \) monocycles per symbol
- The symbol \( \delta \) is the time shift that applies to the monocycle, and we define such operation happens when 1 is transmitted.
Receiver Block Diagram for the reception of the first user’s signal

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Receiver Model

- **Signal at Receiver**
  
  \[ r(t) = \sum_{k=1}^{Nu} A_k s^{(k)}(t - \tau_k) + n(t) \]
  
  - \( A_k s^{(k)} \) models the attenuation of transmitter k’s signal
  - \( N(t) \) is the white Gaussian noise
  - \( \tau_k \) is time asynchronisms between clocks of transmitter and the receiver

- **Correlation template signal**

  \[ v(t) = w(t) - w(t - \delta) \]

  - \( V(t) \) is the pulse shape defined as the difference between two pulses shifted by the modulation parameter \( \delta \). It will then be correlated with the received signal for a statistical test
Figure 7.2  The template signal $v(t)$ with the modulation parameter $\delta$ chosen to be 0.156 ns. Since the template is a difference of two pulses shifted by $\delta$, the non-zero extent of the template signal is approximately $\delta$ plus the monocycle width, i.e., about 0.86 ns.
The optimal decision rule (one monocycle)

\[ H_0 \iff \int_{t \in T_i} r(t) v_{bit} (t - jT_f - c_j^{(k)} T_c) dt > 0 \]

- Pulse correlator output = \( \alpha_j \)

\[ H_0 \iff \sum_{j=0}^{Ns-1} \int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} r(t) v_{bit} (t - jT_f - c_j^{(k)} T_c) dt > 0 \]

- Test statistic = \( \alpha \) (one symbol)
- if \( \alpha > 0 \), the symbol transmitted is 0, else it is 1
What is EC signal sets?

Generating EC sequences.
- The simplest method is using Hadamard matrix and removing first row and column with constraining number of frames per bit to be $2^{m-1}, p, p(p+2)$ (p is prime number).
- Each row is an a sequence of bits corresponding to one of the M symbols.

the modulated signal for 1 bit is represented by

$$s(t) = \sum_{k=0}^{N_t-1} p(t - kT_f - b_j^k \tau_2), i = 1, 2, ..., M$$
EC signal sets parameters

- $\tau_2$ is the time delay that corresponds to the minimum autocorrelation between $p(t)$ and $p(t - \tau_2)$.
- The correlation of the EC signals is given by:

$$\lambda = \frac{N_s - 1}{2} \gamma_w(0) + \frac{N_s + 1}{2} \gamma_w(\tau_2).$$

$$\lambda \approx \frac{1 + \gamma_w(\tau_2)}{2}.$$
Receiver Simplification using EC signals

Instead of using M correlators for each user, by using the properties of the EC signals, the receiver can be simplified to the use of two correlators and M store and sum circuits, the function is given by:

\[ y_j = \sum_{k=0}^{N_z-1} \left[ (b_j^k - 1)z_1(k) + b_j^k z_2(k) \right], \]

where

\[ z_m(k) \triangleq \int_{kT_j}^{kT_j+T_p+\tau_2} x(t)p(t-kT_j-\tau_m)dt, \quad m = 1, 2. \]
Receiver Schematic (1 correlator)

\[ x(t) \xrightarrow{\text{Multiply}} (kT_f + T_p + \tau_z) \xrightarrow{\text{Store and Sum}} y_1 \]

\[ p(t - kT_f - \tau_m) \]

\[ z_m(k) \xrightarrow{\text{Store and Sum}} y_2 \]

\[ k = 0, 1, 2, ..., N_s - 1 \]

\[ m = 1, 2 \]
Multi access performance limits for EC signals

- Degradation factor as a function of the number of users:

\[
DF(N_u) = \frac{1}{1 - \text{SNR}_{b_{spec}} \left[ \frac{1}{R_b} \frac{\mu / T_f}{(N_u - 1)} \right]^{-1}}.
\]

- Maximum bit transmission rate:

\[
R_{\text{max}} \triangleq \lim_{DF \to \infty} N_u(DF) = \frac{1}{\text{SNR}_{b_{spec}}} \frac{1}{N_u - 1} \frac{\mu}{T_f}.
\]
Multi access performance limits for EC signals (cont.)

- Maximum Number of users:
  \[ N_{\text{max}} \triangleq \lim_{DF \to \infty} N_u(DF) = \frac{1}{\text{SNR}_{b_{\text{spec}}}} \frac{1}{R_b} \frac{\mu}{T_f} + 1. \]

- The multiple-access transmission capacity:
  \[ C(B) \approx \frac{1}{\log(2)} \frac{\mu/T_f}{N_u - 1} = C_{IR}(N_u) \]

- where:
  \[ \mu = \frac{(E_w[1 - \gamma_w(\tau_2)])^2}{2\sigma_w^2} \quad \sigma_w^2 = \frac{1}{T_f} \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} w(t-s)[w(t) - w(t - \tau_2)] dt \right]^2 ds, \]

where SNR_{b_{\text{spec}}} is the specified operating snr to achieve the desired probability of error.
Degradation Factor

- Degradation Factor is the additional amount of Snr required by user 1 to overcome the MAI:
Behavior of the prob(SNR(out)) as a function of Number of users
Simulation Results
NOTE:
Each user is 100 times more powerful than the transmitter of interest.
Model Example
Bit error performance for M-ary UWB TH-PPM using EC signals
Multi user behavior of UWB TH-PPM using EC signals
Direct Sequence, DS-UWB

- Similar to conventional CDMA carrier based radios
- Spreading sequence is multiplied by an impulse sequence
- Modulation is provided as in CDMA
Basic signal model for UWB DS-CDMA

- Transmitted waveform is defined as,

\[ s_k(t) = \sqrt{P_k} \sum_{i=\infty}^{\infty} \sum_{n=0}^{N_r-1} b_i^k a_n^k z(t - iT_r - nT_c) \]

- Where \( z(t) \) is the transmitted monocycle waveform,
  - \( b_i^k \) are the modulated data symbols for the \( k^{th} \) user,
  - \( a_n^k \) are the spreading chips,
  - \( T_r \) is the bit period, \( T_c \) is the chip period,
  - \( N_r = T_r / T_c \) is the spread spectrum processing gain, and
  - \( P_k \) is the transmitted power
The Received signal

- \( r(t) = s(t) + M(t) + I(t) + n(t) \)
- \( M(t) \) is the multiple access interference
- \( I(t) \) is the narrow band interference assuming raised cosine wave
- The receiver is correlator
DS-CDMA simulation

- Binary spreading
- Ternary spreading
Episodic Transmission (Ternary Spreading)

- Send n pulses for per information bit
- Allow for off time separation
- Modeled as random ternary with pmf,

\[ p_b(b_i) = (1 - 2\alpha)\delta(b_i) + \alpha \cdot \delta(b_i - 1) + \alpha \cdot \delta(b_i + 1) \]

- Chernoff Bound on the probability of bit error,

\[ P_e < \exp \left( \frac{-n\mathcal{E}_k}{2I_0} \right) \]

where \( \varepsilon \) is the chip energy,

\[ I_0 = \sigma_v^2 + 2\alpha \sum_{j=1, j\neq k}^{K} \mathcal{E}_j \]

K is the number of users, \( \sigma_v^2 \) is the AWGN variance
Ternary Spreading Cont,

- As $\alpha$ becomes smaller, MUI may be significantly reduced (with a corresponding reduction in bit rate).
- Demonstrate the performance of such a sequence by using ternary sequences with aperiodic zero correlation zones (ZCZ).
ZCZ Sequences

- These are the sequences which have a zero valued window around the zero shift, in the autocorrelation (AC) and crosscorrelation (CC) function.

\[ Z_{\text{CZ}} = \min \{ Z_{\text{ACZ}}, Z_{\text{CCZ}} \} \]

- Interference between users separated by delays that are within this window or interference due to delayed replicas of a user's signal due to the multipath channel will be eliminated.
A simple way to create ternary ZCZ sequences

- Take M orthogonal binary sets
- Insert zero padding of length $Z_0$ between the elements of the sets
- Shift each subset a different number of chips
The performance of one user system for Binary DS-UWB (AWGN and NB Interference)
Multiuser performance of Binary DS-UWB (1-8 users, AWGN & NB Interference)
Ternary Spreading Multiuser Performance in AWGN (69Mbit/s)
Performance of 1 watt Ternary DS-UWB with NBI (69Mbit/s, SNR=7dB)
Conclusion

- By using EC signals in TH-PPM with large values of M it is possible to increase number of users supported by the system for given multiple access performance and bit transmission rate.
- The analysis shows that impulse radio using TH-PPM is potentially able to provide multiple-access communications with combined transmission capacity of over 500 Mbps at bit error rate in the range of $10^{-4}$ to $10^{-8}$
- The graphs show that UWB CDMA reduces the impact of the multi-user interference
- Increasing the number of users does not affect the probability of error as it should be for any other system