Ultra Wide Band Communications

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Lesson 2

Generation of UWB radio signals
• The UWB radio signal
• Generation of TH-UWB signals
• Generation of DS-UWB signals
• Generation of MB-UWB signals
The UWB radio signal (1/4)

• A traditional way of emitting an UWB signal is by radiating pulses that are very short in time.

• This transmission technique goes under the name of Impulse Radio (IR).

[Schematic of an UWB ultra-short-pulse transmitter (left) and measured output (right)]

The most currently adopted pulse shape is modelled as the first derivative or the second derivative of a Gaussian function.

- Such pulse shapes are easy to generate and have zero DC offset so that they can be radiated in an efficient way.
• The way by which the information data symbols modulate the pulses may vary
  – **Pulse Position Modulation** (PPM) and **Pulse Amplitude Modulation** (PAM) are commonly adopted modulation schemes
• In addition to modulation and in order to shape the spectrum of the generated signal, the data symbols are encoded using pseudorandom or pseudo noise (PN) codes.
The UWB radio signal

- The UWB definition released by the FCC as mentioned in the previous lecture, does not limit, however, the generation of UWB signals to IR.

- According to the FCC definition, the UWB concept can be extended to continuous-like transmission techniques, provided that the occupied bandwidth of the transmitted signal is greater than 500 MHz.

![Diagram of continuous-time, RF modulated digital signal with pulse rate \(1/T\)]

![Power density spectrum of the transmitted signal](frequency)

Example of continuous-time, RF modulated digital signal with pulse rate \(1/T\)
Transmission scheme for a PPM-TH-UWB signal

- Introduces redundancy
- Modulates and encodes the signal
- Shapes the spectrum
Generation of TH-UWB signals (2/8)

The Code Repetition Coder

- Given the binary sequence \( b \), generated at a rate of \( R_b = \frac{1}{T_b} \), a first system repeats each bit \( N_s \) times and generates a binary sequence \( a \) at a rate of \( R_{cb} = \frac{N_s}{T_b} = \frac{1}{T_s} \).

- This system introduces redundancy and is denoted as a \((N_s, 1)\) code repetition coder.

\[
\begin{align*}
R_b &= \frac{1}{T_b} \\
R_{cb} &= \frac{N_s}{T_b} = \frac{1}{T_s}
\end{align*}
\]

\( T_s \): frame time, or average pulse repetition period

Original binary sequence

\[001010\]

Code repeated binary sequence

\[000000111000111000\]
A second block called a transmission coder applies an integer-valued code $c$ to the binary sequence $a$ and generates a new sequence $d$.

- The generic element $j$ of the sequence $d$ is expressed as indicated in the figure, where $T_c$ and $\varepsilon$ are constant terms that satisfy the condition $c_j T_c + \varepsilon < T_s$ for all $c_j$. One also has, in general, $\varepsilon < T_c$.

- Code $c$ might be periodic, and in that case, its period is $N_p$. 

\[ d_j = c_j T_c + a_j \varepsilon \]
Generation of TH-UWB signals (4/8)

Original binary sequence
1 0

Code repeated binary sequence
1 1 1 0 0 0

Transmission Coder

Coded real valued sequence
\[ d_j = c_j T_c + a_j \varepsilon \]

\[ 0.2, 3.2, 1.2, 2.0, 0.0, 3.0 \]
values in nanoseconds

Time Hopping code \( c (N_p = 4) \)

0 3 1 2

chip time \( T_c = 1 \text{ ns} \)

PPM shift \( \varepsilon = 0.2 \text{ ns} \)
• The coded real-valued sequence $d$ enters a third system, the PPM modulator, which generates a sequence of unit pulses (Dirac pulses $\delta(t)$) at a rate of $R_p = N_s / T_b = 1 / T_s$.
  
  These pulses are located at times $jT_s + d_j$, and are therefore shifted in time from nominal positions $jT_s$ by $d_j$. Pulses occur at times $(jT_s + c_j T_c + a_j \varepsilon)$. 

The PPM modulator

\[
\begin{align*}
R_c &= \frac{N_s}{T_b} = \frac{1}{T_s} \\
R_p &= \frac{N_s}{T_b} = \frac{1}{T_s}
\end{align*}
\]
Generation of TH-UWB signals (6/8)

Original binary sequence

1 0

Code repeated binary sequence

1 1 1 0 0 0

Coded real valued sequence

0.2 , 3.2 , 1.2 , 2.0 , 0.0 , 3.0

values in nanoseconds

0.2 , 3.2 , 1.2 , 2.0 , 0.0 , 3.0
values in nanoseconds

Dirac pulses, with average pulse repetition period $T_S = 5$ ns

$$s(t) = \sum_{j=-\infty}^{+\infty} \delta(t - jT_S - c jT_C - a j\varepsilon)$$
Generation of TH-UWB signals (7/8)

• The last system is the pulse shaper filter with impulse response $p(t)$. The impulse response $p(t)$ must be such that the signal at the output of the pulse shaper filter is a sequence of strictly non-overlapping pulses.

$$s(t) = \sum_{j=-\infty}^{+\infty} p(t - jT_S - c jT_C - a j\epsilon)$$

Analytical expression for a PPM-TH-UWB signal
Generation of TH-UWB signals (8/8)

Signal at the input of the pulse shaper

Signal at the output of the pulse shaper
Generation of DS-UWB signals (1/6)

Transmission scheme for a PAM-DS-UWB signal

- Introduces redundancy
- Modulates and encodes the signal
- Shapes the spectrum
Generation of DS-UWB signals (2/6)

The Code Repetition Coder

• Given the binary sequence $b$ generated at a rate of $R_b = 1/T_b$, a first system repeats each bit $N_s$ times and generates a binary sequence $a^*$ at a rate of $R_{cb} = N_s/T_b = 1/T_s$ bits/s.

• A second system transforms the $a^*$ sequence into $a$, which is composed by binary antipodal symbols ($\pm 1$).

1 0
Original binary sequence

1 1 1 0 0 0
Code repeated binary sequence
The transmission coder applies a binary code \( c \) composed of \( \pm 1 \)'s and period \( N_p \) to the sequence \( a \) and generates a new sequence \( d = a \cdot c \) composed of elements \( d_j = a_jc_j \). \( N_p \) is commonly assumed to be a multiple of \( N_s \).

**Code repeated binary sequence**

+1 +1 +1 -1 -1 -1

**Direct Sequence code** \( c \) (\( N_p = 6 \))

-1 -1 +1 +1 -1 +1

**Coded binary sequence**

-1 -1 +1 +1 -1 +1
The PAM modulator

- Sequence \( d \) enters a third system, the PAM modulator, which generates a sequence of Dirac pulses \( \delta(t) \) at a rate of \( R_p = N_s/T_b = 1/T_s \).
- These pulses are located at times \( jT_s \).

\[
s(t) = \sum_{j=-\infty}^{+\infty} d_j \delta(t-jT_s)
\]

Coded binary sequence

-1 -1 +1 +1 -1 +1
The last system is the pulse shaper filter with impulse response $p(t)$. The impulse response $p(t)$ must be such that the signal at the output of the pulse shaper filter is a sequence of strictly non-overlapping pulses.

Analytical expression for a PAM-DS-UWB signal

$$s(t) = \sum_{j=-\infty}^{+\infty} d_j p(t-jT_s)$$
Generation of DS-UWB signals (6/6)

Signal at the input of the pulse shaper

Signal at the output of the pulse shaper
PPM vs. PAM

• Modulation efficiency of both PPM and PAM can be determined in terms of inter-symbol distance as a function of the energy per bit.

• The symbol constellations for PPM and PAM indicates that binary PAM leads to a greater inter-symbol distance than PPM, which results in a 3 dB advantage in efficiency: PPM requires twice as much energy as PAM to achieve the same bit error rate.

• On the other side, PPM requires only a single polarity for the generated pulses, so the transceiver structure may be simpler than that for PAM.
The Multi Band (MB) approach moves away from the Impulse Radio (IR) principle.

In particular, based on the UWB definition released by the FCC, the overall bandwidth is split into smaller frequency bands of at least 500 MHz each.

The transmission of data for a given user occurs on different sub-bands in subsequent periods of time.

Different types of modulation can be adopted for data modulation within each sub-band. The most popular criterion is based on the well-known Orthogonal Frequency Division Multiplexing (OFDM)
Generation of Multi Band UWB signals (2/4)

- An OFDM-modulated signal consists of the parallel transmission of several signals that are modulated at different carrier frequencies $f_m$. These carriers are equally spaced by $\Delta f$ in the frequency domain.

$$x(t) = g_T(t) \sum_{m=0}^{N-1} c_m e^{j2\pi f_m t}$$

Analytical expression of the complex envelope of a single OFDM symbol

- According to the MB-OFDM approach, different OFDM symbols may be transmitted by using different carriers, that is, by adopting a Frequency Hopping (FH) scheme.
Generation of Multi Band UWB signals (3/4)

\[ f_m = m\Delta f - \frac{N}{2} \quad g(t) = \frac{1}{\sqrt{T_G + T_0}} \quad \text{with } t \in [-T_G, T_0] \]

Reference architecture of an OFDM transmitter

Symbols:
- \( d_0, d_1, d_2, d_3 \) are groups of K bits
- \( c_0, c_1, c_2, c_3 \) are blocks of N symbols
- \( a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3 \) represent the complex points in the constellation

\[ c_m = a_m + jb_m \]

CP is for Tx/Rx synchronization

\[ T_0 = \frac{1}{\Delta f} \]

Symbol Time Transmission

Guard Time

OFDM symbol including cyclic prefix (CP)
Generation of Multi Band UWB signals (4/4)

original binary stream

… 1 0 0 1 1 0 1 0 1 1 …

groups of K bits

d_0 \ d_1 \ d_2 \ d_3 \ block of N symbols

c_0 \ c_1 \ c_2 \ c_3 \ block of N complex points in the constellation

IDFT

C_n = \sum_{m=0}^{N-1} c_m e^{j\frac{2\pi mn}{N}}

OFDM symbol ready for RF transmission

x_2 \ x_3 \ x_0 \ x_1 \ x_2 \ x_3

Cyclic prefix

\[ x_n = \sqrt{1/T} \left(-1\right)^n C_n \]