Line Spectrum Analysis of Impulse Radio UWB Systems
Using a Pulse Position Modulation

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Outline

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- Impulse PPM UWB Systems
- MA-Impulse PPM UWB Systems
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Motives

◊ Impulse radio (IR) ultra-wide bandwidth (UWB) Systems (Win and Scholtz ’98 ’00)

- IR systems for UWB communications
  - Baseband pulses of ultra short duration (<1ns), i.e. impulses
  - Extremely low power spectral density (PSD)
  - Time hopping (TH) binary pulse position modulation (PPM) for multiple access (MA)

- IR-UWB systems and conventional narrow bandwidth systems cannot help giving interferences to each other
  ⇒ Reduction and management of the accompanying line spectrums of IR-UWB signals are essential for the coexistence
Pseudo chaotic time hopping (PCTH) IR-UWB systems (Maggio et al. ’01)

- Reduce line spectrums by using nonperiodic TH sequence depending on information bit streams
- In reality, “non-binary PPM with impulses combined with a PCTH code and a Viterbi decoder”
  ⇒ If the PSD of IR-UWB systems using a PPM preserves the line spectrum property, we can replace the PCTH code with a better trellis code
PSD of IR-UWB Systems Using a PPM

◇ Preliminaries

- Transmitted signals using an $N$-ary PPM with uniform delay $\theta \in [0, T_f]

$$s_{tr}(t) = \sum_{i=-\infty}^{\infty} w_{tr}(t - iT_f - d_i T_s - \theta)$$ (1)

  - Slot time index is iid discrete uniform RV determined from successive $M$ data bits
    $$d_k = \sum_{i=0}^{M-1} b_{Mk+i}2^i$$ (2)

  - Gaussian monocycle
    $$w_{tr}(t) = 2\sqrt{eA\pi tf_c} \exp[-2(\pi tf_c)^2]$$ (3)
◊ PSD Analysis

• PSD of IR-UWB Systems Using a PPM

\[
\Phi_{s_{tr}}(f) = \mathcal{F}\{E[s_{tr}(t)s_{tr}(t + \tau)]\} = G(f) + G(f)E[\exp\{-jrT_s2\pi f\}] \left\{ \frac{1}{T_f} \sum_k \delta\left(f - \frac{k}{T_f}\right) - 1 \right\}
\]

\[- G(f) = \frac{1}{T_f} \frac{e}{2\pi f_c^2} A^2 f^2 \exp\left[-\left(\frac{f}{f_c}\right)^2\right]\]

\[- r: \text{discrete RV whose PDF is } p(r) = \frac{N-|r|}{N^2}\]

• Most of line spectrums \((f = \frac{k}{T_f} \text{ Hz})\) vanish

\[
E[\exp\{-jrT_s2\pi f\}] = \begin{cases} 
1 & \text{if } f = \frac{n.N}{T_f} = \frac{n}{T_s} \\
0 & \text{otherwise}
\end{cases}
\]
• Final form of the PSD

$$\Phi_{str}(f) = \begin{cases} \frac{1}{T_f} G(f) & \text{if } f = \frac{n}{T_s} \\ G(f) \left[ 1 - \left\{ \frac{1}{N} + \sum_{r=1}^{N-1} \frac{2(N-r)}{N^2} \cos(rT_s2\pi f) \right\} \right] & \text{otherwise} \end{cases}$$

(6)

⇒ Same line spectrum property as that of the PCTH IR-UWB system

• $N = 16$, $T_s = 1$ ns, $f_c = 2$ GHz, and $E_b = 1$ W/Hz.

⇒ The duration of line spectrums, 1 GHz, is so sparse that we may solve the coexistence problem
Impulse PPM UWB Systems

◊ System Description

- Line spectrum property is given in (6)
  - More reduced and manageable line spectrums compared with conventional IR-UWB systems
• Received signals

\[ r(t) = s_{re}(t) + n(t) \]  \hspace{1cm} (7)

\[ s_{re}(t) = \sum_{i=-\infty}^{\infty} w_{re}(t - iT_f - d_i T_s) \]

\[ w_{re}(t) = \frac{d}{dt} w_{tr}(t) \]

\[ n(t): \text{white Gaussian noise} \]

• Correlator output for the \( u \)-th time slot in the \( k \)-th frame time

\[ m_{k,u} = \int_{kT_f + (u-1/2)T_s}^{kT_f + (u+1/2)T_s} s_{re}(t) \cdot w_{re}(t - kT_f - uT_s) \, dt \]  \hspace{1cm} (8)

\[ \Rightarrow \text{Use as the soft branch metric of the branch whose output of decimal form is} \ u \]

\[ \Rightarrow \text{Plays a major role for the good BER performance of the system} \]
◊ BER Performance

- \( N = 16, \ M = 4, \ T_s = 1 \text{ ns}, \) and \( f_c = 2 \text{ GHz} \)
Multiple Access Impulse PPM UWB systems

System Description

Impulse PPM UWB Systems

MA-Impulse PPM UWB Systems

User Signature Sequence of the $i$-th user

$T_s = N_c \cdot T_c$

$T_f = N \cdot T_s$
• \( l \)-th user’s own sequence of impulses

\[
v_{tr}^{(l)}(t) = \sum_{i=0}^{N_c-1} a_i^{(l)} w_{tr}(t - iT_c)
\]  

(9)

\( a_i^{(l)} \in \{-1, 1\} \): user signature sequence of the \( l \)-th user
• Transmitted signals

\[ s_{tr}^{(l)}(t) = \sum_{i=-\infty}^{\infty} v_{tr}^{(l)}(t - iT_f - d_i^{(l)}T_s - \theta) \quad (10) \]

• Received signals (assuming \(N_u\) users)

\[ r(t) = s_{re}^{(l)}(t) + \sum_{i=0}^{N_u-1} s_{re}^{(i)}(t - \tau^{(i)}) + n(t) \quad (11) \]

\[ - s_{re}^{(k)}(t) = \sum_{i=-\infty}^{\infty} v_{re}^{(k)}(t - iT_f - d_i^{(k)}T_s) \]

\[ - v_{re}^{(k)}(t) = \sum_{i=0}^{N_c-1} a_i^{(k)} w_{re}(t - iT_c) \]

\[ - \tau^{(i)}: \text{delay of an } i\text{-th user's signals} \]

• Correlator output for the \(u\)-th time slot in the \(k\)-th frame time

\[ m_{k,u}^{(l)} = \int_{kT_f+(u-\frac{1}{2})T_s}^{kT_f+(u+\frac{1}{2})T_s} r(t) \cdot v_{re}^{(l)}(t - kT_f - uT_s) \, dt \quad (12) \]
\textbf{PSD Analysis}

- PSD of the \( l \)-th user’s transmitted signals

\[
\Phi_{s_{tr}}^{(l)}(f) = \begin{cases} 
\frac{1}{T_f} G'(f) \\
G'(f) \left[ 1 - \left\{ \frac{1}{N} + \sum_{r=1}^{N-1} \frac{2(N-r)}{N^2} \cos(rT_s 2\pi f) \right\} \right]
\end{cases}
\]

\[\text{if } f = \frac{n}{T_s} \]

\[\text{otherwise} \quad (13)\]

\[- G'(f) = \frac{1}{T_f} \frac{e}{2\pi f_c^4} f^2 \exp \left[ - \left( \frac{f}{f_c} \right)^2 \right] |C^{(l)}(f)|^2 \]

\[- C^{(l)}(f) = \sum_{i=0}^{N_c-1} a_i^{(l)} \exp[-j2\pi f iT_c] \]

: dependent on the “user signature sequence” of the \( l \)-th user, \( a_i^{(l)} \)

\[\Rightarrow\] Same line spectrum property as that of the “impulse PPM UWB system”

\[\Rightarrow\] Includes that of the MA-PCTH IR-UWB system (Laney et al. ’02) whose line spectrum property is not given
User Signature Sequence

- Considering the MA-interferences, the BER performance mainly depends on the crosscorrelation property of “user signature sequences”

- When the slot time is synchronized (the case of a forward link)
  - Hadamard sequences are good candidates
  - Same BER performance as that of the “impulse PPM UWB system”

- When the slot time is not synchronized (the case of a reverse link)
  - “User signature sequences” with optimal aperiodic crosscorrelation property are necessary
**Concluding Remarks**

- We derive the general PSD of IR-UWB systems using a PPM and verify that the line spectrum property of the system is the same as that of the PCTH IR-UWB system.

- We propose a new IR-UWB system with a preferable line spectrum property whose BER performance exceeds that of the PCTH IR-UWB system.

- We propose a new MA-system for IR-UWB communications with its line spectrum property which includes that of the MA-PCTH IR-UWB system.