UWB with Frequency Domain Signal Processing

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Outline

- UWB
  - DS-UWB
- Background
  - UWB with TDSP
  - SC-FDE
- DS-UWB with FDSP
- Simulation Results
- Conclusions
Ultra Wideband (UWB)

**Definition**
- Frequency bandwidth $\geq 500$ MHz
- $-10$ dB fractional bandwidth: 
  
  \[
  \frac{\text{Frequency bandwidth}}{\text{Center frequency}} \geq 20\%
  \]

**Characteristics**
- Low output power below noise level
- Bit rate up to a few Gb/s
- Precise location and tracking

UWB Systems

- Impulse Radio (IR) schemes
  - Time Hopping UWB (TH-UWB)
  - DS-UWB

- Multicarrier scheme
  - Multiband OFDM
DS-UWB

- Use extremely short pulses with nanosecond duration
- Transmit after multiplying input bits by spreading code and pulse modulation of each element
- Spreading Code: Ternary code (code length : $N_c$)
- Modulation: BPSK

![Diagram of DS-UWB signal processing]

Background: DS-UWB with Time Domain Signal Processing

- DS-UWB
  - Use extreme short pulses and have high path resolution
  - Large path diversity gain with RAKE receiver
  - Multipath spreads over a lot of symbols at very high speed transmission
  - RAKE receiver needs a lot of fingers and thus becomes very complex
Background: SC-FDE

• Single Carrier (SC) Transmission with Frequency Domain Equalization (FDE)
  – Large frequency diversity gain even in highly frequency selective channel
  – Low peak-to-average power ratio (PAPR)
  – Effects of FDE on UWB in UWB multipath channels?

Readings

Purpose

• Performance evaluation of DS-UWB with Frequency Domain Signal Processing
  – Frequency Domain Equalization (FDE)
  – Frequency Domain Channel Estimation (FDCE)

Some of Our Achievements on UWB-FDE:


• S. Yoshida, T. Ohtsuki, and T. Kaneko, "Improvement of Bandwidth Efficiency of UWB-IR and DS-UWB with Frequency-Domain Equalization (FDE) based on Cyclic Prefix (CP) Reconstruction," IEEE VTC2005-Fall

Some of Our Achievements on UWB-FDE: 2


- Y. Ishiyama and T. Ohtsuki, ``Performance Evaluation of UWB-IR and DS-UWB with MMSE-Frequency Domain Equalization (FDE),'' IEEE GLOBECOM'2004

DS-UWB-FDE: Tx

- Data symbol sequence is first spread using the spreading code
- This sequence is divided into every $M$ symbols
- Last $C$ symbols of the block are copied and inserted to the front of the block as Cyclic Prefix (CP)
- Data block composed of $M+C$ symbols is transmitted after pulse modulation
DS-UWB-FDE: CP

Cyclic Prefix  \[ C \text{ symbols} \]

\[ \text{C symbol} \quad M \text{ symbols} \]

\[ M + C \text{ symbols} \]

DS-UWB-FDE: Rx

- Receiver first samples the received data block at a chip rate
- After removing the samples for the CP from the received samples, **FFT is applied to the rest samples**
- Estimate channel in frequency domain
- **FDE using the channel estimates**
- Decision variable is determined by a despreading procedure after IFFT
Frequency Domain Channel Estimation

- Channel in FD can be derived by removing the frequency components of the pilot symbols from the received pilot symbols

\[
\hat{H}(k) = \frac{\hat{R}(k)}{\hat{S}(k)}, \quad (k = 0, \ldots, MN_c - 1)
\]

- \( k \): \( k \)-th frequency component
- \( \hat{R}(k) \): frequency component of received pilot symbols
- \( \hat{S}(k) \): frequency component of pilot symbols
- \( M \): number of symbols in one block
- \( N_c \): spreading code length

Time Domain Channel Estimation

- Estimate channel by cross-correlating the received pilot symbols with the pilot symbols and averaging the cross-correlation value over all the pilot symbols

\[
\hat{h} = \frac{1}{P} \sum_{k=0}^{P-1} b_k^l y_k^l
\]

- \( b_k^l \): \( k \)-th pilot symbol
- \( P \): number of pilot symbols
- \( y_k^l \): received training sample
- \( L_{est} \): number of estimation paths

\[
\hat{h} = [\hat{h}_0, \hat{h}_1, \ldots, \hat{h}_{L_{est}-1}]^T
\]

\[
y_k^l = [y_k^0, y_k^1, \ldots, y_k^{L_{est}-1}]^T
\]
Simulation Parameters

<table>
<thead>
<tr>
<th>System</th>
<th>DS-UWB (FD)</th>
<th>DS-UWB (TD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Length</td>
<td>16 Blocks (1 pilot, 15 data)</td>
<td></td>
</tr>
<tr>
<td># of pilot symbols/packet</td>
<td>$P = 32, 64, 128$</td>
<td></td>
</tr>
<tr>
<td># of data symbols/block</td>
<td>$M = 32, 64, 128$</td>
<td></td>
</tr>
<tr>
<td>Spreading code</td>
<td>Ternary code with length $N_c=32$</td>
<td></td>
</tr>
<tr>
<td>Frame Length</td>
<td>$T_f = 5.344 \text{ ns}$</td>
<td></td>
</tr>
<tr>
<td>Chip Width</td>
<td>$T_c = 0.167 \text{ ns}$</td>
<td></td>
</tr>
<tr>
<td>Guard Block</td>
<td>Cyclic Prefix</td>
<td>Guard Interval</td>
</tr>
<tr>
<td></td>
<td>CP Length = GI Length</td>
<td></td>
</tr>
<tr>
<td>Equalization</td>
<td>Maximum Ratio Combining</td>
<td></td>
</tr>
<tr>
<td>Channel Model</td>
<td>IEEE 802.15.3a Multipath Channel Model : CM3</td>
<td></td>
</tr>
</tbody>
</table>

IEEE UWB Multipath Channel Model

<table>
<thead>
<tr>
<th>Channel</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean excess delay (ns)</td>
<td>5.0</td>
<td>9.94</td>
<td>15.9</td>
<td>30.1</td>
</tr>
<tr>
<td>RMS delay (ns)</td>
<td>5</td>
<td>8</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Model</td>
<td>LOS (0-4 m)</td>
<td>NLOS (0-4 m)</td>
<td>NLOS (4-10 m)</td>
<td>Extreme NLOS</td>
</tr>
</tbody>
</table>
• Consider only # of multiplications in channel estimation and one block data detection
• # of fingers: $L_p = 10$
• Lest: # of estimated paths

• FDSP (FDCE+FDE) has lower computational complexity
  → Cross-correlation operation in TDCE has a large computational complexity
MSE of Each Channel Estimation

- **Low $E_b/N_0$:** $FDCE < TDCE$
  - TDCE can reduce the effect of noise by averaging the number of pilot symbols
  - FDCE is affected largely by power penalty by CP

- **High $E_b/N_0$:** $FDCE > TDCE$
  - FDCE can obtain large frequency diversity
  - Effect of frequency diversity becomes apparent in high $E_b/N_0$

Computational Complexity:
- $FDCE << TDCE$

BER vs. $E_b/N_0$: ideal ch. Estimation

- FDE achieves better BER
  - Larger diversity gain
- FDE: over one block ($M$ symbols)
- RAKE: over one symbol
BER vs. $E_b/N_0$: $L_{est} = 1024$

**High $E_b/N_0$:** FDE > RAKE

- Effect of frequency diversity in FDE becomes apparent
- Effect of Frequency diversity in FDE is small owing to low MSE

**Low $E_b/N_0$:** FDE < RAKE

- Effect of signal capturing in RAKE is large
- Noise power is small

Computational Complexity: FDE << RAKE

BER vs. $E_b/N_0$: $L_{est} = 128$

To reduce computational complexity in TDCE ⇒ $L_{est} = 128$

- Effect of signal capturing in RAKE is reduced
- BER of RAKE is degraded

Computational Complexity: FDE < RAKE

FDE can achieve the better BER with low computational complexity than RAKE
BER vs. SNR: 2-BOK, CM4

- $M = 64$
- Optimum CP length exists
- Large CP:
  - Large reduction of ISI
  - Large power penalty
- Small CP:
  - Small reduction of ISI
  - Small power penalty

Conclusions

- We present performance of UWB with Frequency Domain Signal Processing
  - Frequency Domain Channel Estimation (FDCE)
  - Frequency Domain Equalization (FDE)

- DS-UWB with FDE and FDCE has significantly the less computational complexity and achieves the better performance than DS-UWB with RAKE and TDCE in high $Eb/N0$

- Frequency Domain Signal Processing is attractive for UWB