Ultra-Wide (UWB) Communications: New Paradigms and Opportunities.

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Ultra-Wideband (UWB) Communications: New Paradigms and Opportunities

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February, 2004
The *UWB* communication problem

- Truly *Ultra-wide*: 3.1 GHz to 10.5 GHz (FCC approved in 2001)
- The usable bandwidth is 7.4 GHz (!!)

- Multipath components are resolvable
  - Could use a **RAKE receiver**

- However, at high information rates (in excess of 100 Mbps), inter-symbol interference (ISI) is present
  - An **equalizer** is needed

- This type of situation has never been studied before
  - **New channel model** needed
  - Cannot rely on CDMA/spread-spectrum experience
  - IEEE 802.15.3a study group (Intel, Time Domain and Mitsubishi)
UWB Emission Limit for Indoor Systems

![Graph showing UWB EIRP emission levels in dBm against frequency in GHz. The graph indicates the indoor limit and part 15 limit with specific frequency bands highlighted.]
UWB Spectrum and Narrowband Systems

-41 dBm/Mhz

Emitted Signal Power

GP
PCS
Bluetooth, 802.11b
Cordless Phones
Microwave Ovens

802.11a

"Part 15 Limit"

Frequency (Ghz)

1.6 1.9 2.4 3.1 5 10.6

UWB Spectrum

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## Channel Model from IEEE 802.15.3a group (Nov. 2003)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda ) [1/nsec] Cluster arrival rate</td>
<td>0.0233</td>
<td>0.4</td>
<td>0.0667</td>
<td>0.0667</td>
</tr>
<tr>
<td>( \lambda ) [1/nsec] Ray arrival rate</td>
<td>2.5</td>
<td>0.5</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>( \Gamma ) Cluster decay factor</td>
<td>7.1</td>
<td>5.5</td>
<td>14.0</td>
<td>24.0</td>
</tr>
<tr>
<td>( \gamma ) Ray decay factor</td>
<td>4.3</td>
<td>6.7</td>
<td>7.9</td>
<td>12.0</td>
</tr>
<tr>
<td>( \sigma_1 ) [dB] Cluster lognormal fading term</td>
<td>3.3941</td>
<td>3.3941</td>
<td>3.3941</td>
<td>3.3941</td>
</tr>
<tr>
<td>( \sigma_2 ) [dB] Ray lognormal fading term</td>
<td>3.3941</td>
<td>3.3941</td>
<td>3.3941</td>
<td>3.3941</td>
</tr>
<tr>
<td>( NP_{10dB} ) MERL, TR-2003-73</td>
<td>12.5</td>
<td>15.3</td>
<td>24.9</td>
<td>41.2</td>
</tr>
<tr>
<td>( NP_{10dB} (*) ) SJSU, 12/13/2004</td>
<td>14.57</td>
<td>15.0</td>
<td>23.5</td>
<td>32.2</td>
</tr>
</tbody>
</table>

(*) Average over 200 channel realizations with T. Becker's Matlab model.
Matlab model simulation results
(February 13, 2004)
The CM1 Channel: LOS, 0-4 m

100 Impulse Responses for the CM1 Channel
The CM2 Channel: NLOS, 0-4 m
The CM3 Channel: NLOS, 4-10 m

100 Impulse Responses for the CM3 Channel

Magnitude

Time (nsec)
The CM4 Channel: Strong Multipath

100 Impulse Responses for the CM4 Channel

Time (nsec)

Magnitude

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Some receiver design considerations

• FCC mandates the use of at least 500 MHz of UWB bandwidth

• This translates into a pulse duration of the order of 2 ns

• Data rates of the order of 100 Mbps translate into symbol periods of the order of 10 ns. The larger the data rate, the longer the symbol duration.

• This means that spectral peaks will appear in the spectrum, unless some form of “dithering” is used

• Even for line-of-sight (LOS) conditions, with high data rates, the maximum delay spread is greater than the symbol period
When to “RAKE” the received signal?

- Signal with very narrow pulses and relatively long symbol period
  - Pulse-based modulation: PPM, PAM

- Spread the symbols using pseudo-noise (PN) sequences with good autocorrelation properties
  - Spread-spectrum modulation (as in CDMA)
  - Chip duration short enough to resolve the multipath components

- [Proakis] Rake receiver improves reliability of the communication link provided that
  \[ T >> \tau_m, \]

  where \( T \) is the symbol period, and \( \tau_m \) is the maximum delay spread of the channel
Example 1: Pulse-based modulation and two-path channel

\[ y(t) = \alpha_0 x(t-\tau_0) + \alpha_1 x(t-\tau_1) \]

**Rake receiver:** Combines the two components in a constructive manner, to increase the signal energy, prior to the demodulation process.
Example 1 (cont.): Rake receiver

![Diagram of Rake receiver]

Maximum-likelihood channel gain estimator:

\[ \alpha_i' = \alpha_i^* + W_i, \quad \text{where } W_i \text{ is Gaussian distributed, } i=1,2 \]
Example 2:
Spread-spectrum modulation and two-path channel

Autocorrelation function of a PN sequence of length N:
Example 2 (cont.): Rake receiver

PN sequence correlators are used in order to resolve (i.e., estimate the delay and gain of) the paths
When to “equalize” the received signal?

- The maximum delay spread of the channel, $\tau_m$, exceeds the symbol period $T$
  \[ T \ll \tau_m, \]

- A Rake receiver is no longer able to resolve independent paths, no matter how many “fingers” it has.

- Paths span several symbol periods and therefore symbols interfere with each other: **Inter-symbol interference (ISI)**

- ISI in turn mean that the channel is no longer “flat” over the signal bandwidth

- An **equalizer** can be used to “flatten” the channel
  - Multi-carrier (OFDM) signalling with frequency-domain equalization is an option
To RAKE or to equalize?

• In conventional (narrowband) digital communication systems, multipath channels can be classified as either “flat” or “frequency-selective”

• A Rake receiver is applicable in “flat” (or mildly frequency-selective) channels. Example: Cellular systems.

• An equalizer can be used in frequency-selective multipath channels. Example: Wireless LANs.

• However, the UWB channel contains such large number of multipath components that the models and receivers designed for narrowband systems are (highly?) suboptimal.
The UWB paradigm and joint RAKE-equalization

• The solution lies between the energy-capture capabilities of a Rake receiver and the ISI-removal properties of an equalizer

• A new type of digital receiver will emerge to handle the promises of high-data rates in very-large-bandwidth UWB systems

• The biggest challenges at this point in time appear to be
  – Short-time accurate estimation of (correlated) channel paths
  – Low-complexity (low-power) solutions to the joint optimization of Rake and equalizer:
    • Number of Rake fingers
    • Number of equalizer taps
    • Linear or nonlinear structures?
    • Data-aided or decision-directed?