Channel Estimation, Diversity and Preamble Requirements for Broadband Wireless Using OFDM

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Channel Estimation, Diversity and Preamble Requirements for Broadband Wireless Using OFDM

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September 11, 2001
Outline

- Optimum Channel Estimation
- Time Synchronization
  - Preamble correlation vs. cyclic prefix correlation
- Cyclic prefix issue
- Alamouti and related MIMO techniques
Optimum Channel Estimation

**Frequency Domain**

Minimizing MSE = \( \left\langle \left| R_\ell - \hat{H}_\ell X_\ell \right|^2 \right\rangle \)

\( \langle \cdot \rangle : \) average over training blocks

\[
\hat{H}_\ell = \frac{\left\langle R_\ell X_\ell^* \right\rangle}{\left\langle \left| X_\ell \right|^2 \right\rangle} = \frac{\left\langle R_\ell \right\rangle}{\left\langle X_\ell \right\rangle}
\]

\( \left| X_\ell \right|^2 : \) constant
Optimum Channel Estimation

**Mixed Domain** (Li, Seshadri, Ariyavisitakul, IEEE JSAC, Mar. 1999)

Minimizing MSE:

\[
\left\langle \sum_{n=0}^{M-1} \left| r_n - \sum_k \hat{h}_k x_{n-k} \right|^2 \right\rangle = \left\langle \frac{1}{M} \sum_{\ell=0}^{M-1} \left|R_\ell - \left( \sum_{n=0}^K \hat{h}_n e^{-\frac{j2\pi n\ell}{M}} \right) X_\ell \right|^2 \right\rangle
\]

\(\langle \cdot \rangle\): average over training blocks

\[
\hat{H}_\ell = \text{FFT}(\hat{h}_k)
\]

\[
\begin{pmatrix}
\hat{h}_0 \\
\vdots \\
\hat{h}_K
\end{pmatrix} = \left\langle |X_\ell|^2 \right\rangle R^{-1} \begin{pmatrix}
\tilde{h}_0 \\
\vdots \\
\tilde{h}_K
\end{pmatrix}
\]

\(\tilde{h}_k : \text{IFFT}(\langle R_\ell / X_\ell \rangle)\)

\[
R = \begin{pmatrix}
\rho_0 & \rho_{-1} & \cdots & \rho_{-K} \\
\rho_1 & \rho_0 & \cdots & \cdots \\
\vdots & \vdots & \ddots & \vdots \\
\rho_K & \cdots & \cdots & \rho_0
\end{pmatrix}
\]

\[
\rho_n = \left\langle \sum_{m=0}^{M-1} x_m x^*_{m-n} \right\rangle = \left\langle \frac{1}{M} |X_\ell|^2 \sum_{\ell=a}^{M-1-a} e^{-\frac{j2\pi n\ell}{M}} \right\rangle
\]

\(a : \text{number of guard tones}\)

assuming \(|X_\ell|^2 : \text{constant}\)
Optimum Channel Estimation

**Mixed Domain** (continued)

if $a = 0$, then $R = I \langle |X_{\ell}|^2 \rangle \iff \begin{bmatrix} \hat{h}_0 \\ \vdots \\ \hat{h}_k \end{bmatrix} = \text{IFFT}(\langle R_{\ell} / X_{\ell} \rangle)$

if $a \neq 0$, $R^{-1}$ needs to be pre-computed for optimum performance

**Frequency-Domain Interpolation and Averaging**

$\iff$ **Time-Domain Truncation and Decimation**
Desirable Preamble for Channel Estimation

- Has a flat spectrum and low PAR
- Includes multiple sub-blocks, each with length no more than $K = \text{maximum channel dispersion}$
Simulation Assumptions

- Monte-Carlo simulation with 20,000 channel samples
- **256-FFT** (only middle 200 tones used), **3.5 MHz OFDM** (cf. 802.16.23)
  - Sampling frequency = 4.0832 MHz
- Channel models: **SUI4** and **SUI6** with omni antennas (latest versions)
  - Block fading is assumed
- Modulation: **16QAM**
- Coding: **BICM** using rate 1/2 conv. codes with k=7 and Gray mapping
  - Each FFT block contains 192 QAM symbols
- Interleaver: as specified in the standard draft—PRBS bit interleaving within each block of 96 QAM symbols, followed by symbol interleaving using a row-column interleaver, each row consisting of 96 QAM symbols
- **Cyclic prefix** length: 64 (128) samples (maximum specified for 256 FFT)
- Preamble consists of multiple repeated training sequences generated by 256-FFT with nulled tones
  - Nonzero tones have constant amplitude and pseudo-random phases
- Time synchronization based on preamble correlation
- Performance measure: ABER
  - $10^{-3}$ ABER $\approx 1\%$ ABLE
  - $10^{-4}$ ABER $\approx 0.1\%$ ABLE
  - (1 block in ABLE = 192 QAM symbols)
Performance with Different Numbers of Training Seq.

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI4 (omni), 3.5 MHz, FFT size = 256, 1 Tx-1 Rx ant.
Increasing training sequence length gives same performance as interpolation.
Outline

• Optimum Channel Estimation
• Time Synchronization
  – Preamble correlation vs. cyclic prefix correlation
• Cyclic prefix issue
• Alamouti and related MIMO techniques
OFDM is insensitive to small timing offset/jitter, however...
Timing Based on Cyclic Prefix Correlation

Timing based on CP correlation

CP

OFDM symbol

FFT window

delayed replica due to multipath

CP

OFDM symbol

interference from next symbol
Performance of Cyclic Prefix Correlation over SUI4

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI4 (omni), 3.5 MHz, FFT size = 256, training 2 x 64

Average BER vs. Average SNR
Performance of Cyclic Prefix Correlation over SUI5&6

Maximum delay spread $K = 41$ for SUI5, and $K = 82$ for SUI6

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI5 and 6 (omni), 3.5 MHz, FFT size = 256, 2 x 256 training

cyclic prefix = 128 samples

Cyclic prefix correlation is inadequate for highly dispersive channels
Outline

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Effect of Insufficient Cyclic Prefix Length

“Channel SNR-based” means perfect channel knowledge and no FFT boundary effects taken into account

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI6 (omni), 3.5 MHz, FFT size = 256, cyclic prefix = 64

Average SNR

Average BER

channelSNR

perf. ch. est.

training 2 x 64
Effect of Insufficient Cyclic Prefix Length

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI6 (omni), 3.5 MHz, FFT size = 256, cyclic prefix = 128

Average BER vs. Average SNR

Cyclic prefix length MUST BE greater than maximum delay spread
# Current Specifications of Maximum Cyclic Prefix Length

**256-FFT**

<table>
<thead>
<tr>
<th>Band</th>
<th>Maximum Cyclic Prefix Length (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETSI 1.75 MHz</td>
<td>31.35 µs</td>
</tr>
<tr>
<td>ETSI 3.5 MHz</td>
<td>15.67 µs</td>
</tr>
<tr>
<td>ETSI 7 MHz</td>
<td>7.84 µs</td>
</tr>
<tr>
<td>ETSI 14 MHz</td>
<td>3.92 µs</td>
</tr>
<tr>
<td>ETSI 20 MHz</td>
<td>1.96 µs</td>
</tr>
<tr>
<td>PCS 2.5 MHz</td>
<td>21.94 µs</td>
</tr>
<tr>
<td>PCS 5 MHz</td>
<td>10.97 µs</td>
</tr>
<tr>
<td>PCS 10 MHz</td>
<td>5.49 µs</td>
</tr>
<tr>
<td>PCS 15 MHz</td>
<td>3.66 µs</td>
</tr>
<tr>
<td>ETSI 15 MHz</td>
<td>5.61 µs</td>
</tr>
<tr>
<td>UNII 15 MHz</td>
<td>5.61 µs</td>
</tr>
<tr>
<td>UNII 10 MHz</td>
<td>5.61 µs</td>
</tr>
<tr>
<td>UNII 20 MHz</td>
<td>2.81 µs</td>
</tr>
</tbody>
</table>

Highlighted: < 20 µs

Need to *either* correct the specs *or* classify operating environment (e.g., antenna heights) and corresponding channel model subset for each system.
Outline

• Optimum Channel Estimation

• Time Synchronization
  – Preamble correlation vs. cyclic prefix correlation

• Cyclic prefix issue

• Alamouti and related MIMO techniques
Alamouti + BICM is an “overall” good transmit diversity and MIMO technique for

- 2 and 4 (combined with delay diversity) Tx antennas
- 1 and 2 Rx antennas
- Up to 4 bps/Hz throughput rate
Comparison of Different Tx Diversity Techniques

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
flat fading, 2 Tx-1 Rx ant.

5 MHz, 512-FFT, channel SNR-based for this and the next 5 slides
Comparison of Different Tx Diversity Techniques

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI2 (omni), 2 Tx-1 Rx ant.
Comparison of Different Tx Diversity Techniques

OFDM, 16QAM with rate 3/4 bit-interleaved conv. code
SUI2 (omni), 2 Tx-1 Rx ant.

Alamouti is relatively insensitive to code rate and channel conditions
Comparison of Different Tx Diversity Techniques

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI2 (omni), 4 Tx-1 Rx ant.

St block code
Delay diversity
Switched
Alamouti + delay
1 Tx ant.
Alamouti + BICM vs. Capacity

“Outage capacity” is the probability that the channel does not support 2 bps/Hz
Alamouti + BICM vs. Capacity vs. ST Conv. Code

MIMO performance comparison
flat fading, 2 Tx-2 Rx ant., 2 bps/Hz, 800 bits/block

Block Error Rate vs. Average SNR

- Alamouti + rate 1/2 coded 16QAM
- 16-state ST conv. coded QPSK
- capacity
Proposed Preamble Structure

• Basic structure

\[
\begin{array}{c|c}
CP & \text{Training Seq.} \\
\hline
CP & \text{Training Seq.} & \text{Training Seq.}
\end{array}
\]

1×128

2×128

• 2 Tx antennas

\[
\begin{array}{c|c}
CP & \{x\} \\
\hline
CP & \{x\}
\end{array}
\]

\[
\begin{array}{c|c}
CP & \{x\} \\
\hline
CP & -\{x\}
\end{array}
\]

1×128

also extendable to > 2 Tx antennas
Proposed Preamble Structure (Cont.)

• Received signal during each preamble block

\[ R_{a,\ell} = H_{1,\ell} X_\ell + H_{2,\ell} X_\ell + N_{a,\ell} \]

\[ R_{b,\ell} = H_{1,\ell} X_\ell - H_{2,\ell} X_\ell + N_{b,\ell} \]

\[ \hat{H}_{1,\ell} = \frac{1}{2} \left( \langle \frac{R_{a,\ell}}{X_\ell} \rangle + \langle \frac{R_{b,\ell}}{X_\ell} \rangle \right) \]

\[ \hat{H}_{2,\ell} = \frac{1}{2} \left( \langle \frac{R_{a,\ell}}{X_\ell} \rangle - \langle \frac{R_{b,\ell}}{X_\ell} \rangle \right) \]

• Advantages compared to disjoint preamble
  – Lower power amplifier rating requirement by 3 dB
  – Does not require accurate \( \frac{1}{\sqrt{2}} \) scaling
Training Performance for SUI4

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI4 (omni), 3.5 MHz, FFT size = 256, 1 Rx ant.

with frequency averaging

Average BER

Average SNR
Training Performance for SUI6

OFDM, 16QAM with rate 1/2 bit-interleaved conv. code
SUI6 (omni), 3.5 MHz, FFT size = 256, 1 Rx ant.
with frequency averaging

![Graph](image-url)
Summary

- Short training sequences not only reduce overhead and processing delay, but also give good performance through frequency-domain interpolation and averaging
- Cyclic prefix correlation is inadequate for highly dispersive channels
- Cyclic prefix length MUST BE greater than maximum delay spread
- Alamouti + BICM is a viable transmit diversity and MIMO technique for small numbers of Tx and Rx antennas
- Proposed preamble structure performs to within
  - 1.5 dB for 1x128
  - 0.5 dB for 2x128
  compared to ideal performance with perfect channel knowledge