Packet Acquisition and Band Tracking in Multi-antenna UWB MB-OFDM under RX Front-end Imperfections

Emil Dimitrov and Thomas Kaiser
Goals
- Analyze system performance for spatial multiplexing schemes
- Estimate impact of imperfections on packet detection probabilities

Contents
- Overview of MB-OFDM UWB PHY
- Proposed MIMO system
  - Transmitter
  - System Model
  - Receiver
- Packet detection and band tracking
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  - Carrier Frequency Offset
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Overview of MB-OFDM UWB PHY

- Based on proven OFDM technology, e.g. IEEE 802.11a/g, ADSL, DAB
- Data rates from 53 to 480 Mbps
- High robustness against NBI, spectral efficiency and flexibility

- Spectrum divided into 14 bands
- Band Group 1 ➔ 3.1 – 4.6 GHz, 3 sub-bands of 528 MHz
Overview of MB-OFDM UWB PHY

- Time-frequency hopping across 3 sub-bands defined by TFC
- During an OFDM symbol duration, all antennas transmit simultaneously and synchronously, and in the same frequency band
- 128-pt IFFT in 312.5 ns, 528 MHz DAC rate

<table>
<thead>
<tr>
<th>TFC</th>
<th>Mode 1: Length 6 TFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 2 3 1 2 3</td>
</tr>
<tr>
<td>2</td>
<td>1 3 2 1 3 2</td>
</tr>
<tr>
<td>3</td>
<td>1 1 2 2 3 3</td>
</tr>
<tr>
<td>4</td>
<td>1 1 3 3 2 2</td>
</tr>
</tbody>
</table>

$f (\text{MHz})$

$T_{\text{SYM}} = 312.5 \text{ ns}$
- **Transmitter Architecture**
- Independent data streams sent on each antenna pair
- Same LO for all branches controlled by TFI
MIMO MB-OFDM with Spatial Multiplexing

System Model

\[
\begin{align*}
\mathbf{r} &= (\mathbf{I}_{\text{Nr}} \otimes \mathbf{F}_N) \mathbf{y} = \sqrt{\frac{E_b}{N_T}} (\mathbf{I}_{\text{Nr}} \otimes \mathbf{F}_N) (\mathbf{H}_\text{cir} (\mathbf{I}_{\text{NT}} \otimes \mathbf{F}_N^{-1}) \mathbf{d} + \mathbf{\tilde{v}}) = \sqrt{\frac{E_b}{N_T}} \mathbf{H}_\text{eff} \mathbf{d} + \mathbf{n} \\
\mathbf{H}_\text{eff} &= \begin{pmatrix}
\text{diag}(\mathbf{F}_N \mathbf{h}_{11}) & \cdots & \text{diag}(\mathbf{F}_N \mathbf{h}_{1N_T}) \\
\vdots & \ddots & \vdots \\
\text{diag}(\mathbf{F}_N \mathbf{h}_{N_{\text{R}}1}) & \cdots & \text{diag}(\mathbf{F}_N \mathbf{h}_{N_{\text{R}}N_T})
\end{pmatrix}, \quad [\mathbf{F}_N]_{k,n} = \frac{1}{\sqrt{N}} e^{j2\pi kn/N} \\
\mathbf{h}_{qp}(t) &= \mathbf{X}_{qp} \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{qp}(k,l) \delta(t - T_{qp}(l) - \tau_{qp}(k,l)), \quad \mathbf{h}_{qp} = [h_{qp}[0], \ldots, h_{qp}[L-1]]^T
\end{align*}
\]

\(\mathbf{H}_\text{cir} = (\mathbf{I}_{\text{Nr}} \otimes \mathbf{P}_\text{rem}) \mathbf{H} (\mathbf{I}_{\text{NT}} \otimes \mathbf{P}_\text{add}),\)

\(\mathbf{H}_\text{cir}: \text{block circular channel matrix which can be diagonalized}\)
MIMO MB-OFDM with Spatial Multiplexing

**Receiver Architecture**

- **RF**
- **ADC**
- **PD**
- **Controller**
- **TFI**
- **CFO Tracking**

**Channel Estimation/Equalizer MIMO Detection**
- **Demapping**
- **Depunctur. Decoding**

**MUX**

(7)
MIMO MBO with Spatial Multiplexing

Packet Detection and Band Tracking

- Traditional PD-metric not applicable, since the receiver is fixed at a single band during detection; correlation between adjacent symbols not possible
  - Controlling the hopping of the RF circuit requires a feedback from the baseband
  - Larger HW complexity due to different TFCs and threefold CSI estimation

- Symbol Combiner (SC) – collects consecutive preamble symbols to increase noise immunity and effective SNR
  - Symbol Detector (SD) – applies correlation/power metric between output of SC and known preamble coefficients for each TFC

- Procedure Controller (PC) – judges on the presence of the signal by combining the metric output from each antenna branch by EGC
  - Frequency Hopping Controller (FHC) – controls the down-conversion circuit for
**Simulation Chain**

Simulation with 100 IEEE UWB Channel Model CM1-4 realizations randomly chosen for each transmit-receive antenna pair, AWGN

!: multiple data streams
Performance Analysis

- **Detection Probabilities (w/o Imperfections)**

  $$P_{\text{Loss}} = P(U_0|G_1), \quad P_{\text{FA}} = P(U_1|G_0)$$

  $$P_{\text{Normal}} = P(U_1|G_1)P(G_1) + P(U_0|G_0)P(G_0)$$

- **Events**

  - $G_0$: no packet has been sent
  - $G_1$: packet has been sent
  - $U_0$: PD detects packet
  - $U_1$: PD misses packet

- **IEEE 803.15.3a UWB Channel**

<table>
<thead>
<tr>
<th>Channel</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS delay (ns)</td>
<td>5.3</td>
<td>8</td>
<td>14.3</td>
<td>25</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>0-4</td>
<td>0-4</td>
<td>4-10</td>
<td>10</td>
</tr>
<tr>
<td>Scenario</td>
<td>LOS</td>
<td>NLOS</td>
<td>NLOS</td>
<td>NLOS</td>
</tr>
</tbody>
</table>

  SNR = -6 dB
**Performance Analysis**

**I/Q Imbalance and CFO**

\[ z_{LO}(t) = \cos(2\pi f_{CT} + c(t)) - jg_R \sin(2\pi f_{CT} + c(t) + \varphi_R) \]

\[ = K_1 e^{-j(2\pi f_{CT} + c(t))} + K_2 e^{j(2\pi f_{CT} + c(t))} \]

\[ c(t) = c_0 + 2\pi (f_{LO} - f_C) t \]

\[ K_1 = \frac{1 + g_R e^{-j\varphi_R}}{2} \]

\[ K_2 = \frac{1 - g_R e^{j\varphi_R}}{2} \]

\[ z(t) = LP \{ r(t) z_{LO}(t) \} = K_1 y(t) e^{-j c(t)} + K_2 y^*(t) e^{j c(t)} \]
Simulation Results for 2x2 MBO in CM1-4

Detection Probabilities for IQ Imbalance with CFO in CM1

Detection Probabilities for IQ Imbalance with CFO in CM2

Detection Probabilities for IQ Imbalance with CFO in CM3

Detection Probabilities for IQ Imbalance with CFO in CM4
Conclusions

- **Doubling of data rate** with 2x2 SM MIMO feasible
- **Additionally**, demanding HW requirements are significantly relaxed with MIMO

Outlook

- Evaluate impact of real antennas on UWB MIMO channels
- Discuss further non-idealities and their possible compensation
- Trade-offs between system gains and complexity
- Interference and interoperability issues, MU scenarios
Thank you for your attention!
Packet Detection Algorithm

\[ M_q[m] = \frac{|A_q[m]|^2}{B_q^2[m]} \]

\[ A_q[m] = \sum_{n=0}^{N-m-1} p^n[n] z_q[n + m], \]

\[ B_q[m] = \sum_{n=0}^{N-1} |z_q[n + m]|^2 \]
- The SD based on Correlation/Power Meter metric
- Preamble carefully designed for good correlation properties to facilitate packet detection
- orthogonal and shift-orthogonal for at least the channel length to uniquely identify the separate links
- For MIMO-MBO, at least one preamble symbol per subband should be transmitted, i.e. 3 symbols per antenna
Channel Estimation and Equalization

\[ r = \sqrt{\frac{E_S}{N_T}} \mathbf{H}_{\text{eff}} \mathbf{d} + \mathbf{n} \]

\[ \tilde{\mathbf{d}} = \mathbf{W}_r = \mathbf{W} \left( \sqrt{\frac{E_S}{N_t}} \mathbf{H}_{\text{eff}} \mathbf{d} + \mathbf{n} \right) \]

- The estimated channel matrix \( \hat{\mathbf{H}} \) found by training sequence for each SB

\[ \mathbf{W}_{ZF} = \sqrt{\frac{N_T}{E_S}} \left( \hat{\mathbf{H}}^H \hat{\mathbf{H}} \right)^{-1} \hat{\mathbf{H}}^H = \sqrt{\frac{N_T}{E_S}} \hat{\mathbf{H}}^\dagger \]

\[ \mathbf{W}_{\text{MMSE}} = \sqrt{\frac{N_T}{E_S}} \left( \hat{\mathbf{H}}^H \hat{\mathbf{H}} + \sigma_n^2 \mathbf{I}_{N_T N} \right)^{-1} \hat{\mathbf{H}}^H, \]
March 22, 2007 at Leibniz University of Hannover
Technically co-sponsored by IEEE VTS
Will be published on IEEE Xplore
One focus is UWB
Special PULSERS session
Submission deadline has been extended until Dec 10, 2006
Call for paper and former proceedings at www.wpnc.net