
Peer reviewed version

Link to published version (if available): 10.1109/ICCE.2012.6161865

Link to publication record in Explore Bristol Research
PDF-document

University of Bristol - Explore Bristol Research
General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available: http://www.bristol.ac.uk/pure/about/ebr-terms
A Performance Enhancement for 60 GHz Wireless Indoor Applications

Xiaoyi Zhu\textsuperscript{1}  Angela Doufexi\textsuperscript{1}  Taskin Kocak\textsuperscript{2}

\textsuperscript{1}Department of Electrical and Electronic Engineering
University of Bristol, UK

\textsuperscript{2}Department of Computer Engineering
Bahcesehir University, Turkey

30\textsuperscript{th} INTERNATIONAL CONFERENCE ON CONSUMER ELECTRONICS 2012
Outline

1. Introduction
   - Overview of Wireless Personal Area Network
   - IEEE 802.11ad Standard

2. OFDM Based MIMO Models
   - Space-Time Block Coding
   - Spatial Multiplexing
   - Beamforming

3. MAC Enhancement
   - ACK Operations

4. Numerical Results
   - Link Level Simulation
   - Throughput Performance
   - MAC Performance
   - Operation Range

5. Summary
Overview of 60 GHz WPAN

Standards over 60 GHz WPAN
- IEEE 802.15.3c
- WirelessHD
- WiGig
- ECMA-387
- IEEE 802.11ad

Characteristics of 60 GHz millimeter-wave WPANs
- In-door (<10m)
- Uncompressed HDTV and high rate data transfer
- At least 1 Gbps throughput, 3-4 Gbps preferable
Operating Modes

- Single Carrier: Low complexity and control information
- OFDM: High performance applications

**Table:** Parameters for OFDM Systems in IEEE 802.11ad

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency (MHz)</td>
<td>2640</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>512</td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>336</td>
</tr>
<tr>
<td>Number of pilot subcarriers</td>
<td>16</td>
</tr>
<tr>
<td>Subcarrier frequency spacing (MHz)</td>
<td>5.156</td>
</tr>
<tr>
<td>Sample duration (ns)</td>
<td>0.38</td>
</tr>
<tr>
<td>IFFT and FFT period (ns)</td>
<td>194</td>
</tr>
<tr>
<td>OFDM symbol duration (ns)</td>
<td>242</td>
</tr>
</tbody>
</table>
MIMO-OFDM Communication Model

Let $y_m$ be the received decision baseband signal for the $m$th subcarrier

$$y_m = \tilde{H}_m x_m + n_m, \quad m = 1, \ldots, N$$

where $x_m$ is the transmitted data symbol, $n_m$ is the Gaussian noise vector with zero mean and variance $\sigma^2$, $N$ is the number of subcarriers, and $\tilde{H}_m$ represents the frequency response of the equivalent channel matrix for the $m$th subcarrier.
Space-Time Block Coding

Maximizing Spatial Diversity

Figure: Block diagram of MIMO-OFDM Transmitter

- Enables linear decoding at the receiver
- Transmission matrix \([x_1, -x_2^*, x_2, x_1^*]\) for a \(2 \times 2\) architecture
Increasing Spectral Efficiency

Figure: Block diagram of MIMO-OFDM Transmitter

- **Spatial Multiplexing**
  - Doubles the peak data rate for a $2 \times 2$ architecture
  - Increase the reliability and throughput for lower modes
  - Both STBC and SM need an FFT/IFFT per antenna
Recall

\[ y_m = \tilde{H}_m x_m + n_m, \quad m = 1, \ldots, N \]

Here the frequency response of the equivalent channel matrix for the \( m \)th subcarrier after beamforming \( \tilde{H}_m \) can be is given by:

\[ \tilde{H}_m = c^H H_m w, \quad m = 1, \ldots, N \]

\( w \) and \( c \) are the transmitter and the receiver beam steering vector respectively, and \( H_m \) is the response of the MIMO channel for the \( m \)th subcarrier.
Optimization Criteria

Maximize Effective SNR

\[ \gamma_{\text{eff}} = -\beta \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( -\frac{\gamma_m}{\beta} \right) \right] \]

where \( \gamma_m \) is the symbol SNR experienced on the \( m \)th subcarrier, \( \beta \) is a parameter dependent on MCS.

\[ \gamma_m = \frac{\mathbb{E} \left[ |c^H H_m w_x|^2 \right]}{\mathbb{E} \left[ |n_m|^2 \right]} = \frac{\left| c^H H_m w_x \right|^2}{M_t M_r \sigma^2} \]

where \( M_t \) and \( M_r \) are the number of antenna elements at the transmitter and the receiver respectively. When normalized, \( w^H w = M_t \) and \( c^H c = M_r \).
Optimization Criteria

Maximize Effective SNR

\[
\gamma_{\text{eff}} = -\beta \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( -\frac{\gamma_m}{\beta} \right) \right]
\]

where \( \gamma_m \) is the symbol SNR experienced on the \( m \)th subcarrier, \( \beta \) is a parameter dependent on MCS.

\[
\gamma_m = \frac{E \left[ |c^H H_m w x_m|^2 \right]}{E \left[ |n_m|^2 \right]} = \frac{|c^H H_m w x_m|^2}{M_t M_r \sigma^2}
\]

where \( M_t \) and \( M_r \) are the number of antenna elements at the transmitter and the receiver respectively. When normalized, \( w^H w = M_t \) and \( c^H c = M_r \).
**Beamforming**

**Subcarrier-wise: Maximize SNR on Each Subcarrier**

![Block diagram of subcarrier-wise beamforming](image)

\[ \gamma_{\text{eff, subcarrier}} = -\beta \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( -\frac{\max_{c, w} |c^H H_m w|^2}{\beta M_t M_r \sigma^2} \right) \right] \]
Subcarrier-wise: Maximize SNR on Each Subcarrier

**Figure:** Block diagram of subcarrier-wise beamforming

**Optimal but not practical**

- Need full channel state information
- Requires one FFT/IFFT processor per antenna
Symbol-wise: Applies the Same Weight Vector

Figure: Block diagram of symbol-wise beamforming

Pre-defined beam codebook
- Full channel state information is not required
- Depends on the number of antenna elements and beams
Symbol-wise: Applies the Same Weight Vector

\[ \gamma_{\text{eff, symbol}} = \max_{c,w \in C} (-\beta) \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( - \frac{|c^H H_m w|^2}{\beta M_t M_r \sigma^2} \right) \right] \]
Hybrid: Compromise the Complexity and Performance

**Figure:** Block diagram of hybrid beamforming

**Symbol-wise at Tx, and subcarrier-wise at Rx**

- Optimal each receiver steering vector
- Also use pre-defined codebook
Beamforming

Hybrid: Compromise the Complexity and Performance

Figure: Block diagram of hybrid beamforming

$$\gamma_{\text{eff, hybrid}} = \max_{w \in C} (-\beta) \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( - \frac{\left| c_{opt}^H H_m w \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$
Medium Access Control Layer

Hybrid Access
- CSMA/CA: Lower average latency (web browsing)
- TDMA: Better QoS (video transmission)

Sources of Overhead
- Preamble
- Header
- Gap Time
- Acknowledgment Frames
Immediate ACK and Delayed ACK

**Figure: Imm-ACK**

**Figure: Dly-ACK**
ACK Operations

Block ACK and Block NAK

Figure: Blk-ACK

Figure: Blk-NAKs
Preliminaries

System Assumptions

- 1D uniform linear array
- \( M_t = M_r = 2 \) antenna elements
- Half wavelength isotropic radiators

Channel Assumptions

- Statistic channel from measurements and ray-tracing
- Channel correlation 0.1 (low), 0.5 (medium) and 0.9 (high)
- Both LOS and NLOS
Introduction

OFDM Based MIMO Models

MAC Enhancement

Numerical Results

Summary

Link Level Simulation

Preliminaries

Simulation Setup

- Packet Size: 1KB
- PER target: 1%

- Channel Coding: LDPC
- Cyclic Prefix: 128

Table: OFDM Modulation and Coding Schemes

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Coded Bits/Symbol</th>
<th>Data Rate (Mbps)</th>
<th>SM Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>672</td>
<td>1386.00</td>
<td>2772.00</td>
</tr>
<tr>
<td>QPSK</td>
<td>5/8</td>
<td>672</td>
<td>1732.50</td>
<td>3465.00</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>672</td>
<td>2079.00</td>
<td>4158.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>1344</td>
<td>2772.00</td>
<td>5544.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>5/8</td>
<td>1344</td>
<td>3465.00</td>
<td>6930.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>1344</td>
<td>4158.00</td>
<td>8316.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>13/16</td>
<td>1344</td>
<td>4504.50</td>
<td>9009.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/8</td>
<td>2016</td>
<td>5197.50</td>
<td>10395.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>2016</td>
<td>6237.00</td>
<td>12474.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>13/16</td>
<td>2016</td>
<td>6756.75</td>
<td>13513.50</td>
</tr>
</tbody>
</table>
LOS Scenario

- STBC gives about 7 dB gain over SISO system
- All beamforming schemes offer about 5 dB gain
- Spatial Multiplexing is almost unusable

Figure: PER comparison with LOS
STBC and SM performance varies depending on the correlation factors.

- STBC offers a PER gain of 7-8.5 dB.
- SM requires higher SNR than SISO but doubles the data rate.
- Hybrid beamforming achieves 4 dB gain.

Figure: PER comparison with NLOS
Link Adaptation Scheme

The PHY mode with highest throughput will be selected:

\[
\text{Throughput} = R(1 - \text{PER})
\]

- The throughput envelope is the ideal adaptive MCS based on the optimum switching point
- At a certain SNR, MIMO systems outperform SISO system
Link Throughput in NLOS

**Throughput Performance**

**Link Adaptation Scheme**

- The PHY mode with highest throughput will be selected:

\[
\text{Throughput} = R(1 - \text{PER})
\]

- STBC and hybrid beamforming provide 2-6 dB gain
- More gain can be achieved for very high throughput (>4500 Mbps)
- After the switching point at 21 dB, SM is the best

**Figure:** Link throughput with NLOS
MAC Performance

Throughput vs BER

- Blk-ACK/Blk-NAK increases the MAC efficiency
- BER target should be better than $10^{-3}$
- Throughput reaches to the peak when BER better than $10^{-6}$

Figure: MAC throughput for different BERs with QPSK 1/2
Imm-ACK does not depend on the mode

While Blk-ACK varies depending on PHY mode

Imm-ACK efficiency is 6.9%-26%, and Blk-ACK improves by 3-8 times

Figure: Max Throughput for Each Mode
**Operation Range in LOS**

**Path Loss Model**

\[ PL(dB) = A + 20 \log_{10}(f) + 10n \log_{10}(D) \]

- The system operates at its maximum throughput when the devices are close.
- Adaptively switch to the lower speed when a device moves further away.
- Beamforming increase 50% of the tolerance distance, while STBC doubles.

**Figure:** Operation range in LOS
**Operation Range**

**Operation Range in LOS**

**Link Budget Model**

\[ P_T - PL \geq kTB + NF + \text{ReceiverSNR} \]

- The system operates at its maximum throughput when the devices are close.
- Adaptively switch to the lower speed when a device moves further away.
- Beamforming increase 50% of the tolerance distance, while STBC doubles.

**Figure:** Operation range in LOS
The SISO system could not provide service beyond 1m.

Hybrid beamforming extend the achievable range to 3.5m, and STBC is possible to provide service up to 10m.
Summary

- STBC produces the best performance due to its robustness in all conditions; While SM doubles the error-free data rate and increase the reliability for lower MCS modes;

- Beamforming increases the performance significantly. In NLOS, hybrid beamforming provides considerable improvements while maintaining reasonable hardware complexity.

- Frame aggregation and Blk-ACK increase the MAC throughput 3-8 times compared to Imm-ACK
Summary

- STBC produces the best performance due to its robustness in all conditions; While SM doubles the error-free data rate and increase the reliability for lower MCS modes;

- Beamforming increases the performance significantly. In NLOS, hybrid beamforming provides considerable improvements while maintaining reasonable hardware complexity.

- Frame aggregation and Blk-ACK increase the MAC throughput 3-8 times compared to Imm-ACK.
Summary

- STBC produces the best performance due to its robustness in all conditions; While SM doubles the error-free data rate and increase the reliability for lower MCS modes;
- Beamforming increases the performance significantly. In NLOS, hybrid beamforming provides considerable improvements while maintaining reasonable hardware complexity.
- Frame aggregation and Blk-ACK increase the MAC throughput 3-8 times compared to Imm-ACK
Thank you! and Questions?

please Email to <x.zhu@Bristol.ac.uk>