
Peer reviewed version

Link to published version (if available):
[10.1109/MC-SS.2011.5910710](https://doi.org/10.1109/MC-SS.2011.5910710)

Link to publication record in Explore Bristol Research
PDF-document
Beamforming Performance Analysis for OFDM Based IEEE 802.11ad Millimeter-Wave WPANs

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

8\textsuperscript{th} International Workshop on Multi-Carrier Systems and Solutions
Outline

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Overview of Wireless Personal Area Network (WPAN)

60 GHz Frequency Band Allocation

- Large availability of 7 GHz unlicensed in worldwide
- Potentially small device components
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
## 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
Outline

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Operating Modes

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

### Table: OFDM Modulation and Coding Schemes

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Coded Bits/Symbol</th>
<th>Data Bits/Symbol</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>672</td>
<td>336</td>
<td>1386.00</td>
</tr>
<tr>
<td>QPSK</td>
<td>5/8</td>
<td>672</td>
<td>420</td>
<td>1732.50</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>672</td>
<td>504</td>
<td>2079.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>1344</td>
<td>672</td>
<td>2772.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>5/8</td>
<td>1344</td>
<td>840</td>
<td>3465.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>1344</td>
<td>1008</td>
<td>4158.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>13/16</td>
<td>1344</td>
<td>1092</td>
<td>4504.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/8</td>
<td>2016</td>
<td>1260</td>
<td>5197.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>2016</td>
<td>1512</td>
<td>6237.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>13/16</td>
<td>2016</td>
<td>1638</td>
<td>6756.75</td>
</tr>
</tbody>
</table>
Operating Modes

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

### Table: OFDM Modulation and Coding Schemes

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Coded Bits/Symbol</th>
<th>Data Bits/Symbol</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>672</td>
<td>336</td>
<td>1386.00</td>
</tr>
<tr>
<td>QPSK</td>
<td>5/8</td>
<td>672</td>
<td>420</td>
<td>1732.50</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>672</td>
<td>504</td>
<td>2079.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>1344</td>
<td>672</td>
<td>2772.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>5/8</td>
<td>1344</td>
<td>840</td>
<td>3465.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>1344</td>
<td>1008</td>
<td>4158.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>13/16</td>
<td>1344</td>
<td>1092</td>
<td>4504.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/8</td>
<td>2016</td>
<td>1260</td>
<td>5197.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>2016</td>
<td>1512</td>
<td>6237.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>13/16</td>
<td>2016</td>
<td>1638</td>
<td>6756.75</td>
</tr>
</tbody>
</table>
Outline

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
MIMO Communication System

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 after beamforming, which 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.
MIMO Communication System

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

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

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 after beamforming, which is given by:

$$\tilde{H}_m = c^H H_m w, \quad m = 1, ... N$$

$w$ 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.
MIMO Communication System

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 after beamforming, which 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.
# Outline

1. **Introduction**
   - Overview of Wireless Personal Area Network (WPAN)
   - IEEE 802.11ad Standard

2. **System Model**
   - Channel Frequency Response
   - Optimization Criteria

3. **OFDM Based Beamforming**
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. **Numerical Results**
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Choose the Optimal Weight Vectors

Optimization Criteria

- Max-codeword-distance
- Max-BER
- Max-mutual-information
- Max-effective-SNR

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

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

Optimization Criteria

- Max-codeword-distance
- Max-BER
- Max-mutual-information
- Max-effective-SNR

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

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

**Optimization Criteria**

- Max-codeword-distance
- Max-BER
- Max-mutual-information
- Max-effective-SNR

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

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 $c^H c = M_r$. 
Outline

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Maximize the Received SNR on Each Subcarrier

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

**Figure**: Block diagram of subcarrier-wise beamforming
Maximize the Received SNR on Each Subcarrier

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

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Symbol-wise

Each Subcarrier Applies the Same Weight Vector

**Pre-defined beam codebook**
- Full channel state information is not required
- Depends on the number of antenna elements and beams

**Figure:** Block diagram of symbol-wise beamforming
Each Subcarrier 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
Each Subcarrier Applies the Same Weight Vector

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

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
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
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
Compromise the complexity and performance

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

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

2. System Model
   - Channel Frequency Response
   - Optimization Criteria

3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Preliminaries

System assumptions

- $N=512$ OFDM subcarriers
- 1D half wavelength isotropic radiators
- $M = M_t = M_r$ antenna elements

Channel assumptions

- 60 GHz channel models
- Both LOS and NLOS
## Preliminaries

### System assumptions
- $N=512$ OFDM subcarriers
- 1D half wavelength isotropic radiators
- $M = M_t = M_r$ antenna elements

### Channel assumptions
- 60 GHz channel models
- Both LOS and NLOS
Beamforming Gain

LOS Scenario

Evaluate beamforming performance

\[ G = \frac{\gamma_{\text{eff, beamforming}}}{\gamma_{\text{eff, SISO}}} \]

- Beamforming gain has a bound when single path exists
- The performance difference is not noticeable, because the LOS component exists

Figure: Beamforming gain with LOS
Beamforming Gain

LOS Scenario

Evaluate beamforming performance

\[ G = \frac{\gamma_{\text{eff, beamforming}}}{\gamma_{\text{eff, SISO}}} \]

- Beamforming gain has a bound when single path exists
- The performance difference is not noticeable, because the LOS component exists

Figure: Beamforming gain with LOS
Evaluate beamforming performance

\[ G = \frac{\gamma_{\text{eff, beamforming}}}{\gamma_{\text{eff, SISO}}} \]

- Subcarrier-wise is the best, hybrid is the next and symbol-wise is the worst.
- The more antenna elements, the higher improvement can be achieved by hybrid beamforming.

Figure: Beamforming gain with NLOS.
### Outline

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
</tr>
<tr>
<td></td>
<td>Overview of Wireless Personal Area Network (WPAN)</td>
</tr>
<tr>
<td></td>
<td>IEEE 802.11ad Standard</td>
</tr>
<tr>
<td>2</td>
<td>System Model</td>
</tr>
<tr>
<td></td>
<td>Channel Frequency Response</td>
</tr>
<tr>
<td></td>
<td>Optimization Criteria</td>
</tr>
<tr>
<td>3</td>
<td>OFDM Based Beamforming</td>
</tr>
<tr>
<td></td>
<td>Subcarrier-wise</td>
</tr>
<tr>
<td></td>
<td>Symbol-wise</td>
</tr>
<tr>
<td></td>
<td>Hybrid</td>
</tr>
<tr>
<td>4</td>
<td>Numerical Results</td>
</tr>
<tr>
<td></td>
<td>Beamforming Gain</td>
</tr>
<tr>
<td></td>
<td>BER Performance</td>
</tr>
<tr>
<td></td>
<td>Link Throughput and Ranges</td>
</tr>
</tbody>
</table>
A 2-by-2 antenna system is assumed

The simulated BER performance verified the numerical results
Outline

1 Introduction
   - Overview of Wireless Personal Area Network (WPAN)
   - IEEE 802.11ad Standard

2 System Model
   - Channel Frequency Response
   - Optimization Criteria

3 OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid

4 Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges
Link Adaptation Scheme

The PHY mode with highest throughput will be selected:

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

- The throughput envelop is the ideal adaptive MCS based on the optimum switching point.
- At a certain SNR, beamforming systems offer higher throughput than SISO.

Figure: Link throughput with LOS
Link Adaptation Scheme

- The PHY mode with highest throughput will be selected:

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

- The throughput envelop is the ideal adaptive MCS based on the optimum switching point.

- At a certain SNR, beamforming systems offer higher throughput than SISO.

Figure: Link throughput with LOS
Link Throughput in NLOS

**Link Adaptation Scheme**

- The PHY mode with highest throughput will be selected:

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

- Beamforming schemes do not improve the peak error-free throughput
- More gain can be achieved for very high throughput (>4500 Mbps)

**Figure:** Link throughput with NLOS
Path Loss Model

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

- The system operates at its maximum throughput when the device are close.
- Adaptively switch to the lower speed when a device moves further away.

Figure: Operation range in LOS
Link Budget Model

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

- The system operates at its maximum throughput when the device are close.
- Adaptively switch to the lower speed when a device moves further away.

**Figure**: Operation range in LOS
Introduction

System Model

OFDM Based Beamforming

Numerical Results

Summary

Link Throughput and Ranges

Operation Range in NLOS

Link Budget Model

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

- The SISO system could not provide service beyond 1m
- Subcarrier-wise and hybrid beamforming extend the achievable range significantly

Figure: Operation range in NLOS
Summary

- A performance evaluation of three types of beamforming schemes over the OFDM based 60 GHz WPAN are studied;
- Beamforming schemes increase the system performance significantly;
- In NLOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity.
Summary

- A performance evaluation of three types of beamforming schemes over the OFDM based 60 GHz WPAN are studied;
- Beamforming schemes increase the system performance significantly;
- In NLOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity
A performance evaluation of three types of beamforming schemes over the OFDM based 60 GHz WPAN are studied;

Beamforming schemes increase the system performance significantly;

In NLOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity
For Further Reading I

S. Yoon, et.al
Hybrid beam-forming and beam-switch for OFDM based WPAN

IEEE 802.15 Working Goup
*IEEE 802.15-08-0355-00-003c.*
May 2008.

A. Maltsev, et.al
*Channel models for 60 GHz WLAN systems.*
May 2010.
Thank you! and Questions?

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