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Link to published version (if available):
10.1109/PIMRC.2011.6140109

Link to publication record in Explore Bristol Research
PDF-document
A Performance Evaluation of 60 GHz MIMO Systems for IEEE 802.11ad WPANs

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22\textsuperscript{nd} IEEE International Symposium
on Personal, Indoor and Mobile Radio Communications
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
   - Link Level Simulation
   - Throughput Performance
   - Operation Range
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
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IEEE 802.11ad Standard

System Model

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OFDM Based Beamforming

Subcarrier-wise
Symbol-wise
Hybrid

Numerical Results

Link Level Simulation
Throughput Performance
Operation Range
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>
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   - Symbol-wise
   - Hybrid

4. Numerical Results
   - Link Level Simulation
   - Throughput Performance
   - Operation Range
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.
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Choose the Optimal Weight Vectors

Optimization Criteria

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

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

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

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

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Choose the Optimal Weight Vectors

Optimization Criteria

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

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 \( c^H c = M_r \).
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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

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

Each Subcarrier Applies the Same Weight Vector

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

**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

Each Subcarrier Applies the Same Weight Vector

\[
\gamma_{\text{eff, symbol}} = \max_{c, w \in C} \left( -\beta \right) \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]
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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

\[ \gamma_{\text{eff, hybrid}} = \max_{w \in C} (-\beta) \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( -\frac{|c^H H_m w_{opt}|^2}{\beta M_t M_r \sigma^2} \right) \right] \]
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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
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Channel assumptions
- 60 GHz channel models
- Both LOS and NLOS
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
LOS Scenario

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Figure: Beamforming gain with LOS
NLOS Scenario

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
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A 2-by-2 antenna system is assumed
The simulated BER performance verified the numerical results
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System Model

OFDM Based Beamforming

Numerical Results

Summary

Operation Range

Link Throughput in 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 LOS

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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
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 device are close
- Adaptively switch to the lower speed when a device moves further away

Figure: Operation range in LOS
Operation Range in LOS

Link Budget Model

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

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- Adaptively switch to the lower speed when a device moves further away

Figure: Operation range in LOS
### 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 MIMO schemes over the OFDM based 60 GHz WPAN are studied;
- STBC produces the best performance due to its robustness in all conditions;
- SM doubles the error-free data rate and increase the reliability for lower MCS modes;
- Beamforming increase the performance significantly. In NLOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity.
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For Further Reading I

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

IEEE 802.11 Task Group AD
*IEEE 802.11-10/0433r2.*
May 2010.

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>