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Beamforming Performance Analysis for OFDM Based IEEE 802.11ad Millimeter-Wave WPANs

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8th 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

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Operating Modes

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

Table: OFDM Modulation and Coding Schemes

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

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MIMO Communication System

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

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

where $\mathbf{x}_m$ is the transmitted data symbol, $\mathbf{n}_m$ is the Gaussian noise vector with zero mean and variance σ^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:

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

$\mathbf{w}$ and $\mathbf{c}$ are the transmitter and the receiver beam steering vector respectively, and $\mathbf{H}_m$ 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**

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

where γ_m is the symbol SNR experienced on the m th subcarrier, β is a parameter dependent on MCS.

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Choose the Optimal Weight Vectors

Optimization Criteria

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- **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 $c^H c = M_r$.

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Maximize the Received SNR on Each Subcarrier

Figure: Block diagram of subcarrier-wise beamforming

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

Subcarrier-wise

Maximize the Received SNR on Each Subcarrier

Figure: Block diagram of subcarrier-wise beamforming

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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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Symbol-wise

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

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Symbol-wise

Each Subcarrier Applies the Same Weight Vector

Figure: Block diagram of symbol-wise beamforming

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

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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

Figure: Block diagram of hybrid beamforming

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

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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

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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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NLOS Scenario

Evaluate beamforming performance

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

- 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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Bit Error Rate

Figure: BER for QPSK 1/2 with LOS

Figure: BER for QPSK 1/2 with NLOS

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

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Link Throughput in LOS

Link Adaptation Scheme

- The PHY mode with highest throughput will be selected:

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

Figure: Link throughput with LOS

- 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

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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

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

Figure: Operation range in LOS

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

Operation Range in LOS

Link Budget Model

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

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Figure: Operation range in LOS

Operation Range in NLOS

Link Budget Model

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

Figure: Operation range in NLOS

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

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

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For Further Reading I

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Thank you! and Questions?

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