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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary

A Performance Enhancement for 60 GHz Wireless Indoor Applications

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Outline				



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





Introduction ●○	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Overview of Wirele	ss Personal Area Network			
Overvie	w of 60 GHz WI	PAN		

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)</p>
- Uncompressed HDTV and high rate data transfer
- At least 1 Gbps throughput, 3-4 Gbps preferable

Introduction o	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
IEEE 802.11ad S	Standard			
Operat	ina Modes			

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

Table: Parameters for OFDM Systems in IEEE 802.11ad

Parameter	Value
Sampling frequency (MHz)	2640
Number of subcarriers	512
Number of data subcarriers	336
Number of pilot subcarriers	16
Subcarrier frequency spacing (MHz)	5.156
Sample duration (ns)	0.38
IFFT and FFT period (ns)	194
OFDM symbol duration (ns)	242

MIMO-OFDM Communication Model

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

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

where \mathbf{x}_m is the transmitted data symbol, \mathbf{n}_m is the Gaussian noise vector with zero mean and variance σ^2 , \mathbf{N} is the number of subcarriers, and \widetilde{H}_m represents the frequency response of the equivalent channel matrix for the *m*th subcarrier.

Introduction	OFDM Based MIMO Models ●○○○○○○○○	MAC Enhancement	Numerical Results	Summary
Space-Time Bloc	k Coding			
Maximi	zing Spatial Dive	ersity		



Figure: Block diagram of MIMO-OFDM Transmitter

Space-Time Block Coding

- Enables linear decoding at the receiver
- Transmission matrix [x₁, -x₂^{*}; x₂, x₁^{*}] for a 2 × 2 architecture

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Introduction	OFDM Based MIMO Models ○●○○○○○○○○	MAC Enhancement	Numerical Results	Summary
Spatial Multiplexing	ng			
Increas	ing Spectral Effi	ciency		



Figure: Block diagram of MIMO-OFDM Transmitter

Spatial Multiplexing

- Doubles the peak data rate for a 2×2 architecture
- Increase the reliability and throughput for lower modes
- Both STBC and SM need an FFT/IFFT per antenna

Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Beamforming				
Optimiz	vation Criteria			

Recall

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

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

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

w and **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.

Introduction	OFDM Based MIMO Models ○○○●○○○○○○	MAC Enhancement	Numerical Results	Summary
Beamforming				
Optimiz	ation Criteria			

Maximize Effective SNR

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

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

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

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 $c_{\mu}^H c_{\mu} = M_{\mu}$

Introduction	OFDM Based MIMO Models ○○○●○○○○○○	MAC Enhancement	Numerical Results	Summary
Beamforming				
Optimiz	ation Criteria			

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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 $c^H_{-}c = M_{r_r}$.



Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
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Subcarrier-wise: Maximize SNR on Each Subcarrier



Figure: Block diagram of subcarrier-wise beamforming

Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
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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

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summa
	0000000000			

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

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summa
	0000000000			

Symbol-wise: Applies the Same Weight Vector



Figure: Block diagram of symbol-wise beamforming

Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
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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

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
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Hybrid: Compromise the Complexity and Performance



Figure: Block diagram of hybrid beamforming

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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

Introduction	OFDM Based MIMO Models	MAC Enhancement ●○	Numerical Results	Summary
ACK Operations				

Immediate ACK and Delayed ACK

Frame n-1	SIFS	Imm-ACK	DIFS	Frame n	SIFS	Imm-ACK
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Figure: Imm-ACK



Figure: Dly-ACK

Introduction	OFDM Based MIMO Models	MAC Enhancement ○●	Numerical Results	Summary
ACK Operations				

Block ACK and Block NAK



Figure: Blk-ACK



Figure: Blk-NAKs



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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Link Level Simulation	ı			
Prelimina	aries			

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

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Link Level Sim	ulation			
Prelim	inaries			
Sim	ulation Setup			
• P	acket Size: 1KB	Chan	nel Coding: LDF	°C
• P	ER target: 1%	Cyclic	c Prefix: 128	

Table: OFDM Modulation and Coding Schemes

Modulation	Coding	Coded	Data	Data Rate	SM Data Rate	-
	Rate	Bits/Symbol	Bits/Symbol	(Mbps)	(Mbps)	
QPSK	1/2	672	336	1386.00	2772.00	-
QPSK	5/8	672	420	1732.50	3465.00	
QPSK	3/4	672	504	2079.00	4158.00	
16-QAM	1/2	1344	672	2772.00	5544.00	
16-QAM	5/8	1344	840	3465.00	6930.00	
16-QAM	3/4	1344	1008	4158.00	8316.00	
16-QAM	13/16	1344	1092	4504.50	9009.00	CC
64-QAM	5/8	2016	1260	5197.50	10395.00	centre fo communicat
64-QAM	3/4	2016	1512	6237.00	12474.00	research
64-QAM	13/16	2016	1638	6756.75	13513.50	*) (

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Introd	luction

MAC Enhancement

Numerical Results

Summary

Link Level Simulation

LOS Scenario



Figure: PER comparison with LOS

- STBC gives about 7 dB gain over SISO system
- All beamforming schemes offer about 5 dB gain

 Spatial Multiplexing is almost unusable

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Link Level Simula	ation			
NLOS S	Scenario			



Figure: PER comparison with NLOS

- 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



Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Throughput Perfo	ormance			
Link Th	roughput in LOS	5		

Link Adaptation Scheme

• The PHY mode with highest throughput will be selected:

Throughput = R(1 - PER)



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

Figure: Link throughput with LOS

Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Throughput Perfe	ormance			
l ink Th	proughput in NLC)S		

Link Adaptation Scheme

The PHY mode with highest throughput will be selected:

Throughput =
$$R(1 - PER)$$



- 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 CCC dB, SM is the best

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MAC Enhancement

MAC Performance

Throughput vs BER



Figure: MAC throughput for different BERs with QPSK 1/2

- 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

Introd	uction

MAC Enhancement

27

Numerical Results

Summary

MAC Performance

Max Throughput Achieved for Each Mode



Figure: Max Throughput for Each Mode

- Imm-ACK does not depend on the mode
- While Blk-ACK varies depening on PHY mode
- Imm-ACK efficiency is 6.9%-26%, and Blk-ACK improves by 3-8 times

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MAC Enhancement

Summary

Operation Range

Operation Range in LOS

Path Loss Model



Figure: Operation range in LOS

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

MAC Enhancement

Operation Range

Operation Range in LOS

Link Budget Model



Figure: Operation range in LOS

- $P_T PL \ge kTB + NF + ReceiverSNR$
 - 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

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MAC Enhancement

Numerical Results

Summary

Operation Range

Operation Range in NLOS

Link Budget Model



Figure: Operation range in NLOS

$P_T - PL \ge kTB + NF + ReceiverSNR$

- 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

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Introduction	OFDM Based MIMO Models	MAC Enhancement	Numerical Results	Summary
Summa	ary			

- 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



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Thank you! and Questions?

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

