MIMO in WiFi Systems

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WiFi

• Local area wireless technology that allows communication with the internet using 2.4 GHz or 5 GHz radio waves per IEEE 802.11

• Proliferation in the number of devices that use WiFi today: smartphones, tablets, digital cameras, video-game consoles, TVs, etc

• Devices connect to the internet via wireless network access point (AP)
Advantages

• Allows convenient setup of local area networks without cabling – rapid network connection and expansion

• Deployed in unlicensed spectrum – no regulatory approval required for individual deployment

• Significant competition between vendors has driven costs lower

• WiFi governed by a set of global standards (IEEE 802.11) – hardware compatible across geographical regions
WiFi IC Shipment Growth

(WLAN) Chipsets (Millions of Units)

Source: IHS iSuppli
Cumulative WiFi Devices in Use
Data by Local Access

Global IP Traffic by Local Access Technology
By 2016, Fixed/Wi-Fi Traffic Surpasses Fixed/Wired Traffic

29% CAGR 2011-2016

Mobile Data (78% CAGR)
Fixed/Wired (20% CAGR)
Fixed/Wi-Fi (34% CAGR)

Petabytes per Month

Source: Cisco VNI Global Forecast, 2011-2016
# The IEEE 802.11 Standards Family

<table>
<thead>
<tr>
<th>Standard</th>
<th>Year Ratified</th>
<th>Frequency Band</th>
<th>Modulation</th>
<th>Channel Bandwidth</th>
<th>Max. Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>1999</td>
<td>2.4 GHz</td>
<td>DSSS</td>
<td>22MHz</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>802.11a</td>
<td>1999</td>
<td>5 GHz</td>
<td>OFDM</td>
<td>20 MHz</td>
<td>54 Mbps</td>
</tr>
<tr>
<td>802.11g</td>
<td>2003</td>
<td>2.4 GHz</td>
<td>OFDM</td>
<td>20 MHz</td>
<td>54 Mbps</td>
</tr>
<tr>
<td>802.11n</td>
<td>2009</td>
<td>2.4/5 GHz</td>
<td>MIMO-OFDM</td>
<td>20,40 MHz</td>
<td>600 Mbps</td>
</tr>
<tr>
<td>802.11ac</td>
<td>2013</td>
<td>5 GHz</td>
<td>MIMO-OFDM</td>
<td>20, 40, 80, 160 MHz</td>
<td>6.93 Gbps</td>
</tr>
</tbody>
</table>
# 802.11a/ac PHY Comparison

<table>
<thead>
<tr>
<th></th>
<th>802.11a</th>
<th>802.11ac</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulation</strong></td>
<td>OFDM</td>
<td>MIMO-OFDM</td>
</tr>
<tr>
<td><strong>Subcarrier spacing</strong></td>
<td>312.5 KHz</td>
<td>312.5 KHz</td>
</tr>
<tr>
<td><strong>Symbol Duration</strong></td>
<td>4 us (800 ns guard interval)</td>
<td>3.6 us (400 ns guard interval)</td>
</tr>
<tr>
<td><strong>FFT size</strong></td>
<td>64</td>
<td>64(20 MHz)/512 (160 MHz)</td>
</tr>
<tr>
<td><strong>FEC</strong></td>
<td>BCC</td>
<td>BCC or LDPC</td>
</tr>
<tr>
<td><strong>Coding rates</strong></td>
<td>1/2, 2/3, 3/4</td>
<td>1/2, 2/3, 3/4, 5/6</td>
</tr>
<tr>
<td><strong>QAM</strong></td>
<td>BPSK, QPSK, 16-,64-QAM</td>
<td>BPSK, QPSK, 16-,64-,256-QAM</td>
</tr>
</tbody>
</table>
Factors Driving the Data Rate Increase

- 802.11a: 54 Mbps
- MIMO (8x)
- QAM (1.3x)
- FEC rate (1.1x)
- 802.11ac: 6.93 Gbps
- Bandwidth (8x)
802.11 Medium Access Control (MAC)

- Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)

- A wireless node that wants to transmit performs the following sequence
  1. Listen on the desired channel
  2. If channel is idle transmit packet
  3. If channel is busy wait until transmission stops and further a contention period
  4. If channel idle at end of contention period transmit packet else return to step 3
802.11 Transmitter (PHY)
802.11 Frame Format

Legacy (11a/g) format
- L-STF
- L-LTF
- L-SIG
- Data

VHT (11ac) format
- L-STF
- L-LTF
- L-SIG
- VHT-SIGA
- VHT-STF
- VHT-LTF
- Data

AGC Design Challenges
- Short settling time
- DFS

Legacy data parameters
- Legacy channel estimation
- Timing
- Automatic Gain Control (AGC)
- Frequency offset estimation

VHT data parameters
- VHT channel estimation
- Payload
MIMO Signaling

- MIMO signaling may be used to increase spectral efficiency or link reliability

- Spatial multiplexing: Transmit independent data streams simultaneously

- Spatial diversity: Improve link reliability

- Fundamental tradeoff between multiplexing and diversity [Zheng and Tse, ‘03]

- 802.11n/ac support multiplexing, diversity and hybrid modes
# MIMO Techniques in 802.11n/ac

<table>
<thead>
<tr>
<th>MIMO Technique</th>
<th>Div/Mux</th>
<th>802.11n</th>
<th>802.11ac</th>
<th>Commercialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial multiplexing</td>
<td>Mux</td>
<td>✅</td>
<td>✅</td>
<td>High</td>
</tr>
<tr>
<td>Space-time Coding</td>
<td>Div</td>
<td>✅</td>
<td>✅</td>
<td>Moderate</td>
</tr>
<tr>
<td>Transmit Beamforming</td>
<td>Div/Mux</td>
<td>✅</td>
<td>✅</td>
<td>Emerging</td>
</tr>
<tr>
<td>MU-MIMO</td>
<td>Mux</td>
<td></td>
<td>✅</td>
<td>Emerging</td>
</tr>
<tr>
<td>Antenna Selection</td>
<td>Div</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
</tbody>
</table>
Spatial Multiplexing in 802.11n/ac

- Indoor channels have been found to support spatial multiplexing reliably
- 802.11n supports up to 4 streams
- 802.11ac supports up to 8 streams
SM Implementation Challenges

- Receiver complexity/die-size
  - 8 stream equalizer
  - 2 stream maximum-likelihood (ML) equalization with linear complexity
  - Sub-optimal hybrid ML techniques or linear equalizer for 2+ streams

- Noise statistics estimation
  - Contribution from phase-noise/IQ-imbalance/ICI is colored
  - Limited training in 802.11 preamble

- Use of receive diversity (#Rx > #Streams) for improved performance and lower-complexity equalization
  - Cost penalty in terms of die-size to accommodate additional receive chains
Space-time Coding in 802.11n/ac

- Alamouti code

- FEC + bit interleaving realizes significant frequency diversity gain
  - Additional diversity gain from STBC yields incremental improvement
Transmit Beamforming in 802.11

- Technique to ensure that transmitted signal couples into wireless channel with maximum gain
  - Realizes array gain + diversity gain

- Channel knowledge required at transmitter

- Support for both explicit and implicit beamforming
802.11 Explicit Beamforming

- Beamforming based on explicit knowledge of the forward channel
  - Channel is sounded via Null Data Packet (NDP)

- Steering matrix feedback compressed via Given’s rotation
Implementation – Sounding Frequency

- Feedback can incur significant overhead
- Tradeoff between sounding frequency and beamforming gain
  - Indoor channel environment is benign
Implementation – Computation Complexity

- Immediate feedback of steering matrix from beamformer minimizes degradation due to Doppler

- Eg. 8 Tx Bfmer, 4 Rx Bfmee, 160 MHz BW
  - 468 4 x 8 SVD computations over 16us
  - Additional matrix compression (Given’s rotation) operations for feedback

- Area efficient (possible sub-optimal) approaches that minimize loss in beamforming gain
Implementation – Phase Ambiguity

- Transmit power is QAM dependent
  - Eg. 64-QAM packet may be transmitted at 12 dBm while QPSK packet may be transmitted at 18 dBm
  - Transmit power determined by combination of analog and digital gain settings

- Change in analog gain distribution may cause phase difference between sounding packet and steered packet
  - Needs to be countered by careful design or compensation mechanisms
Implementation – Transmit Power Normalization

- Rows of steering matrix may not have equal norm
- Back off total power to maintain steering matrix structure reduces beamforming gain
- Need for appropriate power normalization strategies that sacrifice minimal beamforming gain

\[
\begin{align*}
E|v_{11}x_1 + v_{12}x_2|^2 &\propto P(Tx1) \\
E|v_{21}x_1 + v_{22}x_2|^2 &\propto P(Tx2) \\
E|v_{31}x_1 + v_{32}x_2|^2 &\propto P(Tx3) \\
E|v_{41}x_1 + v_{42}x_2|^2 &\propto P(Tx4)
\end{align*}
\]
Implementation – AGC Design

VHT (11ac) format

- L-STF
- L-LTF
- L-SIG
- VHT-SIGA
- VHT-STF
- VHT-LTF
- Data

- 8us
- 4us
- 4us
- 4us

Rx power

~ upto 10 dB increase in signal power

- No prior knowledge if packet is beamformed
- AGC needs to re-settle in 4 us
802.11 Implicit Beamforming

- Forward channel inferred from reverse channel
  - Physical channel is reciprocal, RF chain response is not

- No steering matrix feedback overhead
Transparent Implicit Beamforming

- Beamform to any 802.11 device
- Drawback: Insufficient sounding (inability to estimate full dimensionality of MIMO channel)
- RF Calibration
Implementation -- Implicit Beamforming

• Implementation challenges are similar to explicit beamforming

• Added complexity of maintaining calibrated RF response across temperature
  – RF gain/phase response may change with temperature in the forward and/or reverse directions
  – Operating temperature can vary between -40 to 85 degrees celsius
Beamforming Gains

TCP Tput (Mbps)

15 ft  30 ft  100 ft  130 ft

Source: Marvell

11n 4 Tx Bfmer
11n 2Rx Bfmer

Source: Marvell

TxBF ON
TxBF OFF
Multi-User MIMO in 802.11ac

- Downlink multi-user MIMO introduced in 802.11ac
- Support for up to 8 simultaneous streams across 4 users with up to 4 streams per client
Implementation – Multi-user MIMO

- Challenges similar to TxBF

- Additional challenges
  - User-grouping and scheduling

- Margin for error due to steering inaccuracy smaller compared to TxBF
  - All streams in (single user) TxBF intended for the same user
  - High inter-stream/user interference in MU-MIMO can severely limit performance gains
  - Multi-user detection (MUD) may reduce potential gains from MU-MIMO
System imperfections result in steering inaccuracy: channel Doppler, channel estimation error, transmit power normalization
## Supporting The Highest Rate

### 20 MHz

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<th>Value</th>
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<td>Tx EVM</td>
<td>-35</td>
</tr>
<tr>
<td>Front end components</td>
<td>-40</td>
</tr>
<tr>
<td>11 bit ADC 2x oversampled 13 dB backoff</td>
<td>-58</td>
</tr>
<tr>
<td>Rx IQ imbalance</td>
<td>-45</td>
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<tr>
<td>Rx Phase Noise</td>
<td>-45</td>
</tr>
<tr>
<td>Residual ICI</td>
<td>-45</td>
</tr>
<tr>
<td>Loss due to channel estimation error</td>
<td>3</td>
</tr>
<tr>
<td><strong>Net SNR</strong></td>
<td>29.90153</td>
</tr>
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### 160 MHz

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<td><strong>Net SNR</strong></td>
<td>26.8145</td>
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</table>

- SNR to support MCS 9 (256 QAM, code rate 5/6) ~ 28 dB
- Techniques such as beamforming critical to ensure sufficient fading margin
- **Challenges**
  - Achieving the right performance/die-size tradeoff
  - Production costs (calibration)
  - Temperature variation
  - Volume production
Future WiFi Challenges

• Device level
  – Pushing the highest data rates
  – Multi-function radios: LTE/WiFi/Bluetooth coexistence

• Network level (high density deployment)
  – Interference management
  – Network MIMO and coordination

• New task group formed by the IEEE – 802.11ax