MIMO in WiFi Systems

Rohit U. Nabar

Smart Antenna Workshop

Aug. 1, 2014

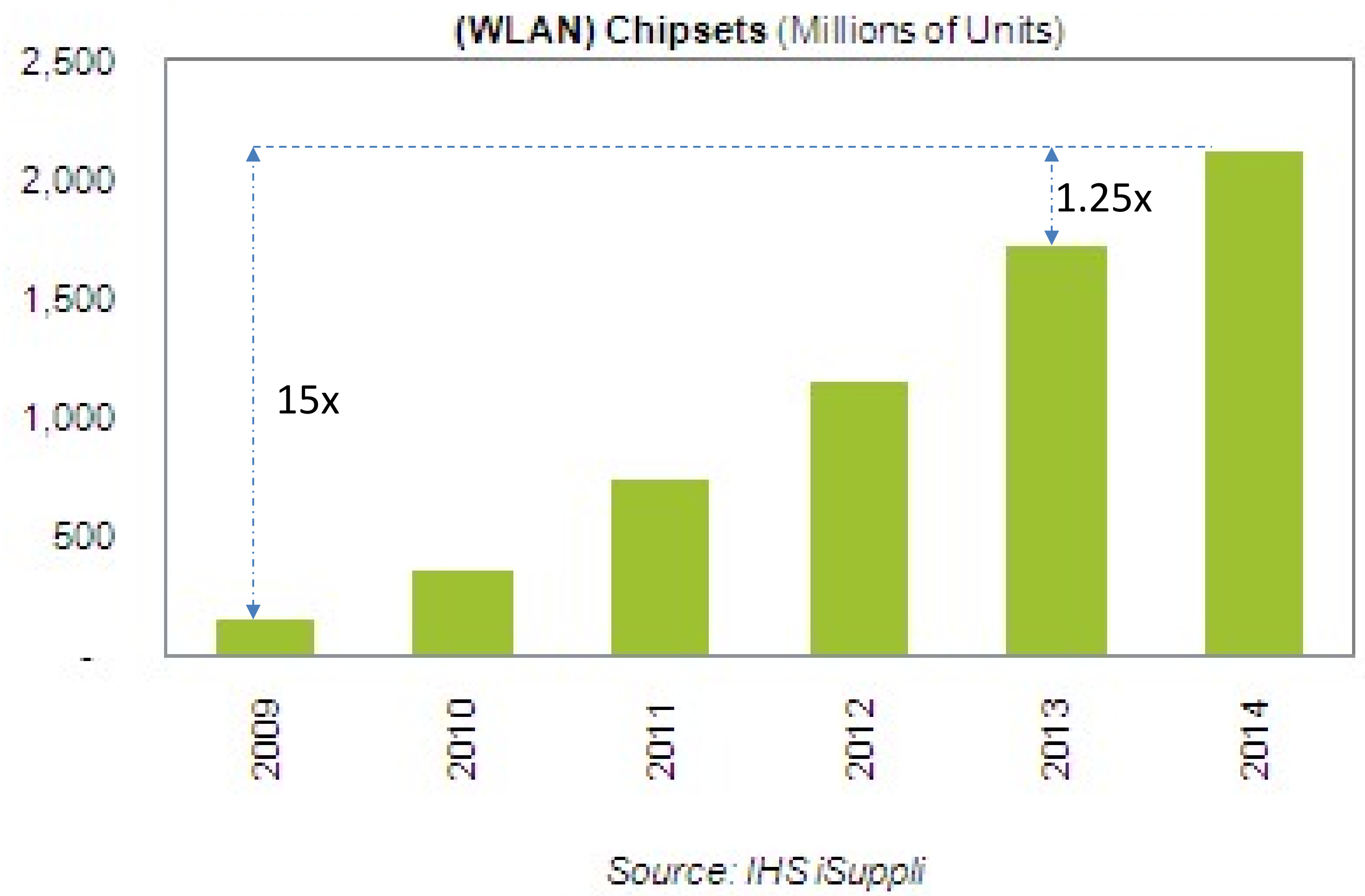
WiFi

- 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)

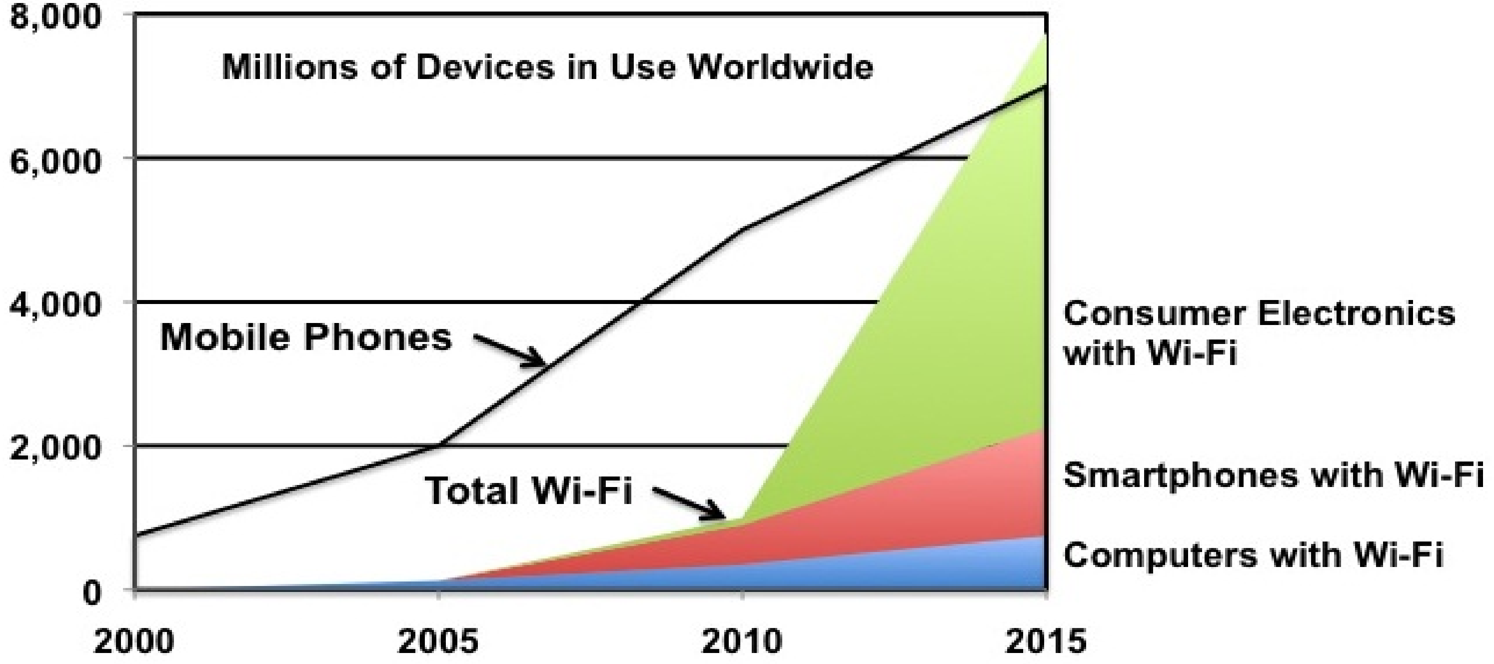
Advantages

- 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

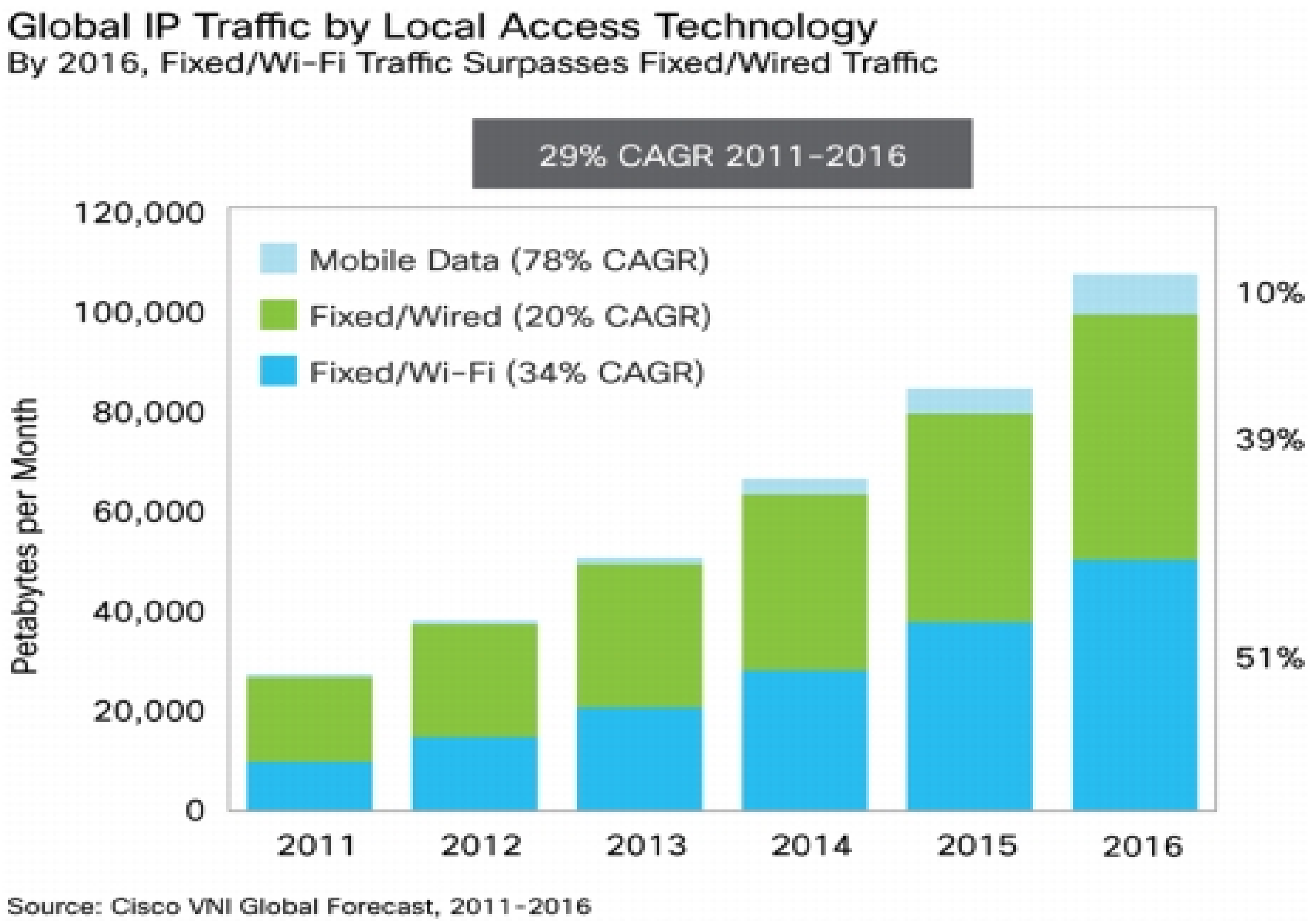


Cumulative WiFi Devices in Use



NORTH RIVER VENTURES

Data by Local Access



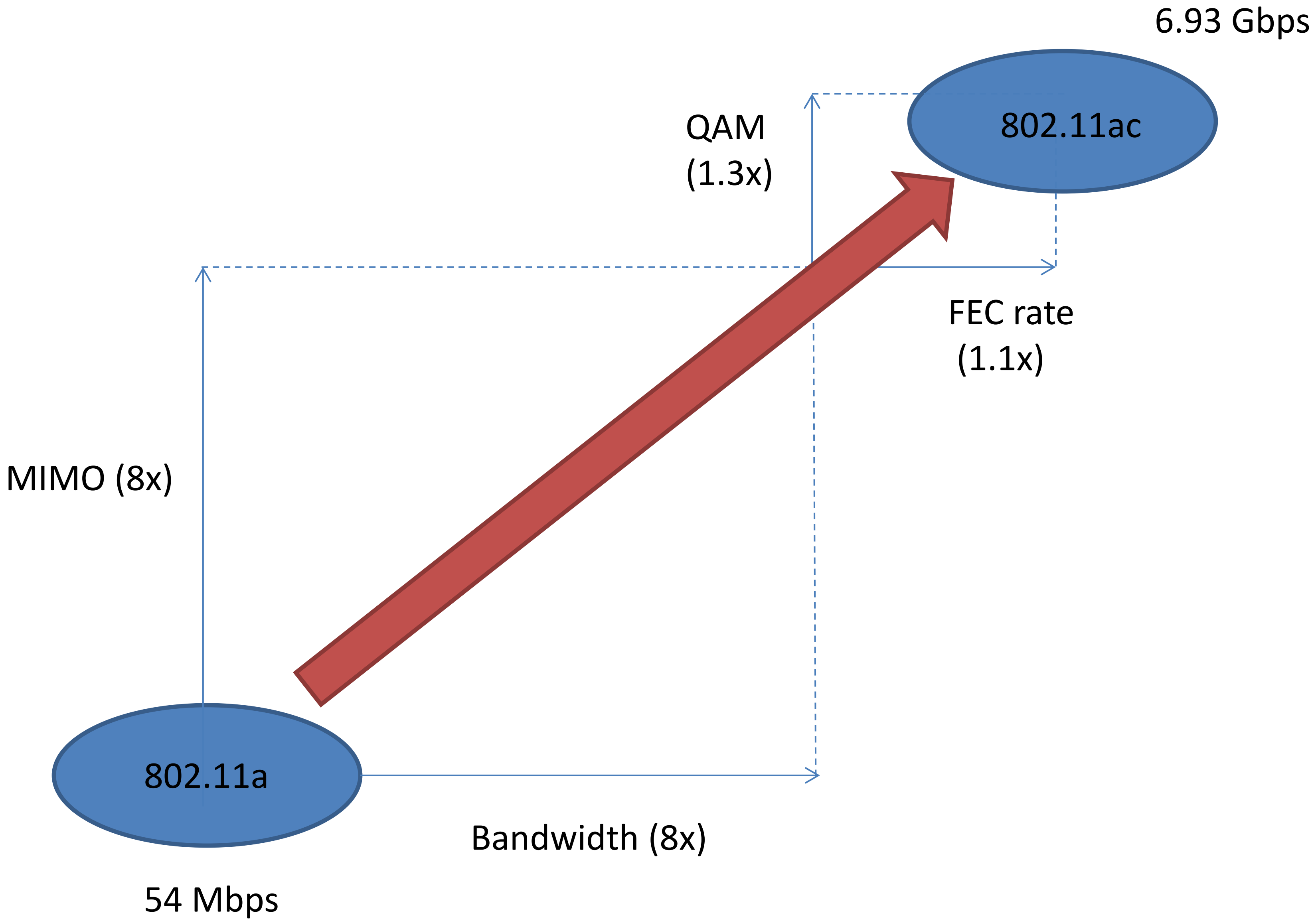
The IEEE 802.11 Standards Family

Standard	Year Ratified	Frequency Band	Modulation	Channel Bandwidth	Max. Data Rate
802.11b	1999	2.4 GHz	DSSS	22MHz	11 Mbps
802.11a	1999	5 GHz	OFDM	20 MHz	54 Mbps
802.11g	2003	2.4 GHz	OFDM	20 MHz	54 Mbps
802.11n	2009	2.4/5 GHz	MIMO-OFDM	20,40 MHz	600 Mbps
802.11ac	2013	5 GHz	MIMO-OFDM	20, 40, 80, 160 MHz	6.93 Gbps

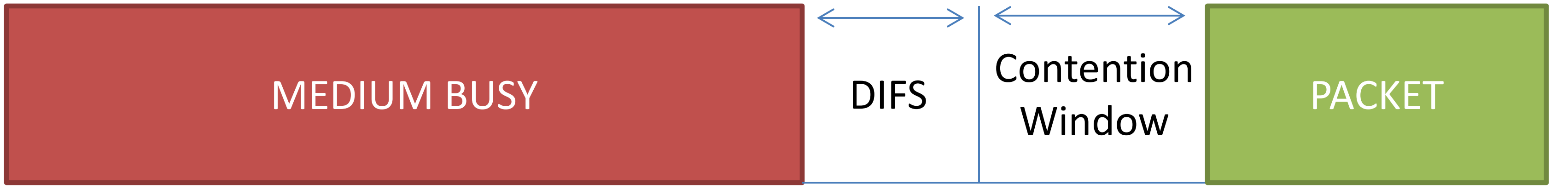
802.11a/ac PHY Comparison

	802.11a	802.11ac
Modulation	OFDM	MIMO-OFDM
Subcarrier spacing	312.5 KHz	312.5 KHz
Symbol Duration	4 us (800 ns guard interval)	3.6 us (400 ns guard interval)
FFT size	64	64(20 MHz)/512 (160 MHz)
FEC	BCC	BCC or LDPC
Coding rates	1/2, 2/3, 3/4	1/2, 2/3, 3/4, 5/6
QAM	BPSK, QPSK, 16-,64-QAM	BPSK, QPSK, 16-,64-,256-QAM

Factors Driving the Data Rate Increase



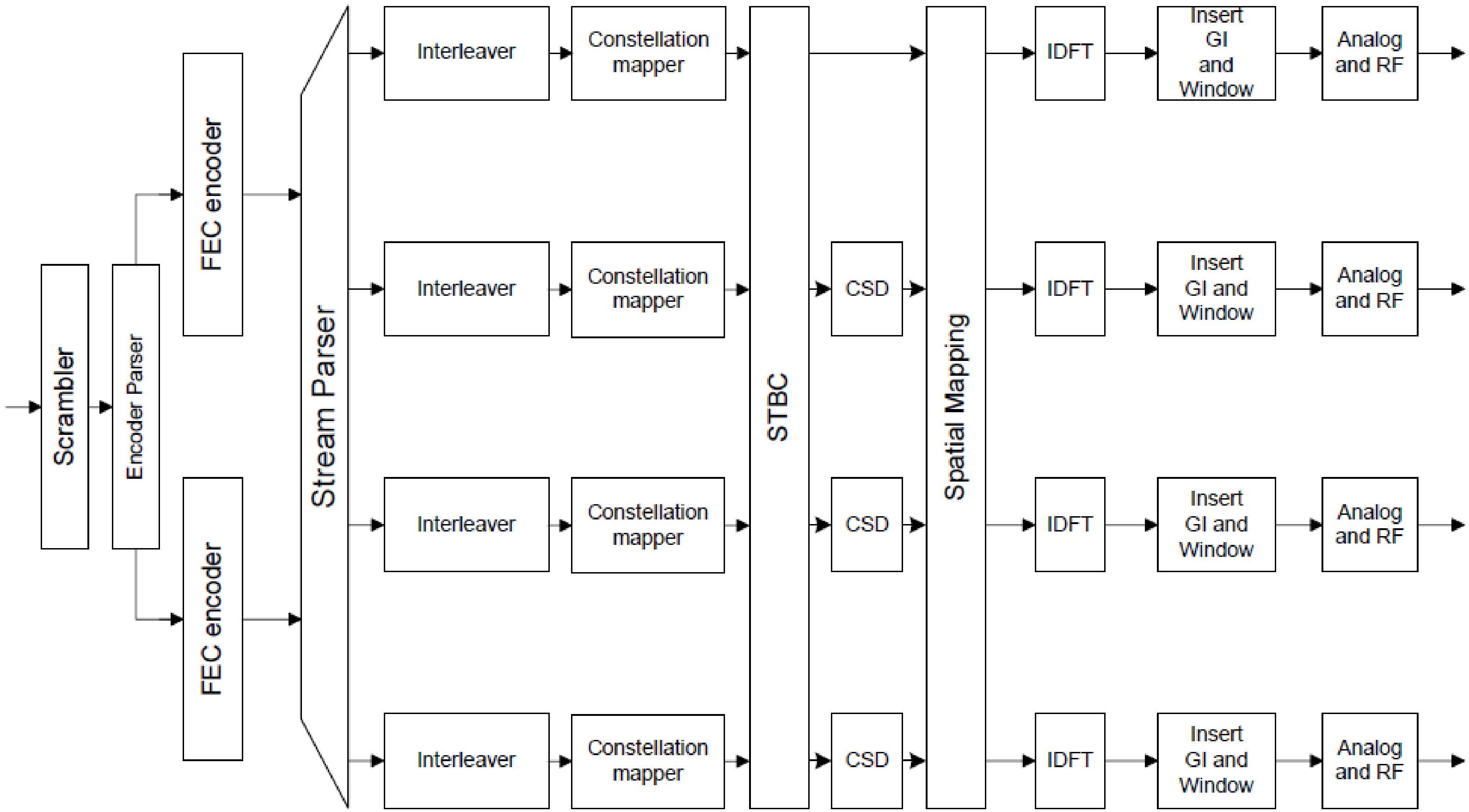
802.11 Medium Access Control (MAC)



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

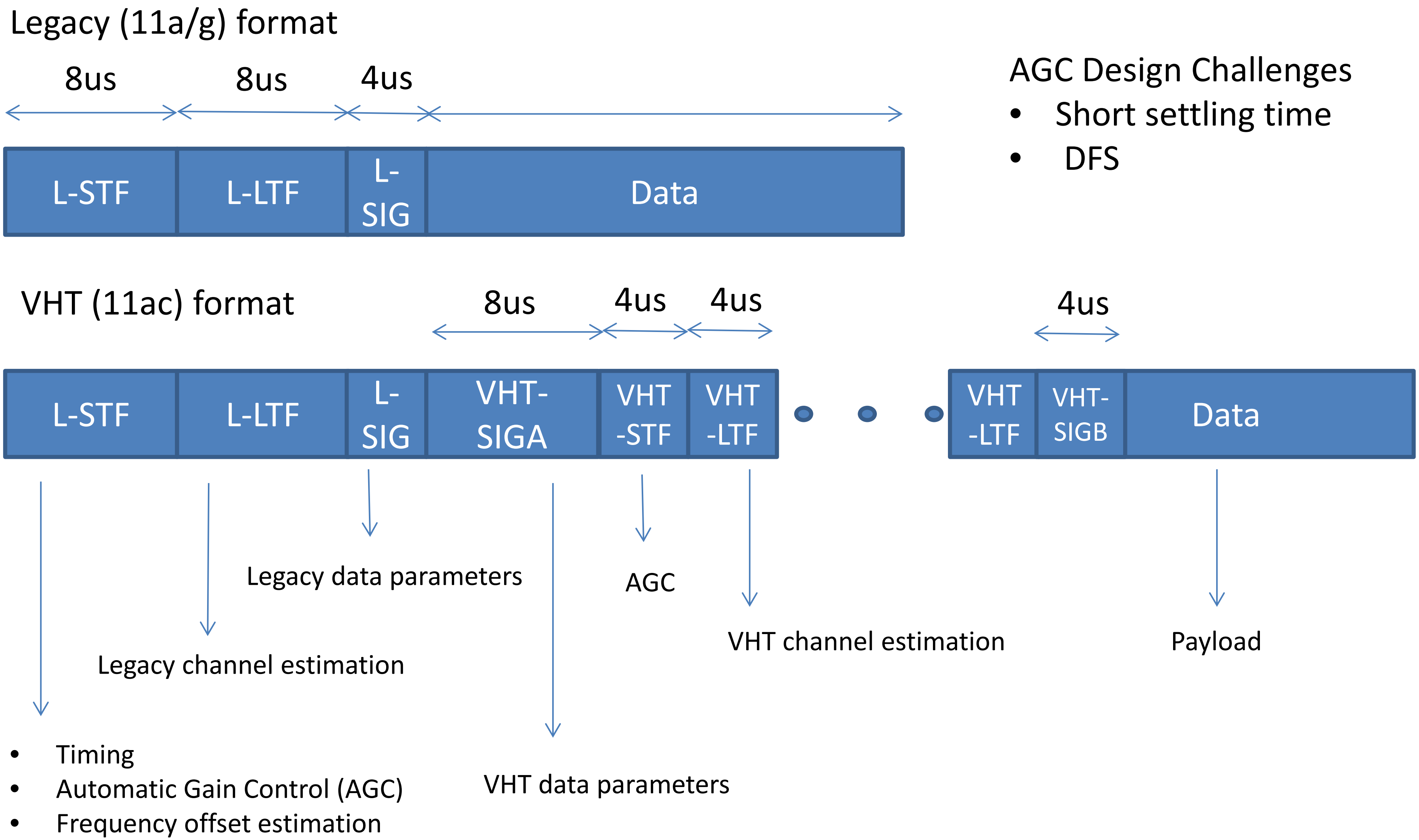
- A wireless node that wants to transmit performs the following sequence
  1. Listen on the desired channel
  2. If channel is idle transmit packet
  3. If channel is busy wait until transmission stops and further a contention period
  4. If channel idle at end of contention period transmit packet else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

802.11 Transmitter (PHY)



802.11 Frame Format

AGC Design Challenges
- Short settling time
- DFS



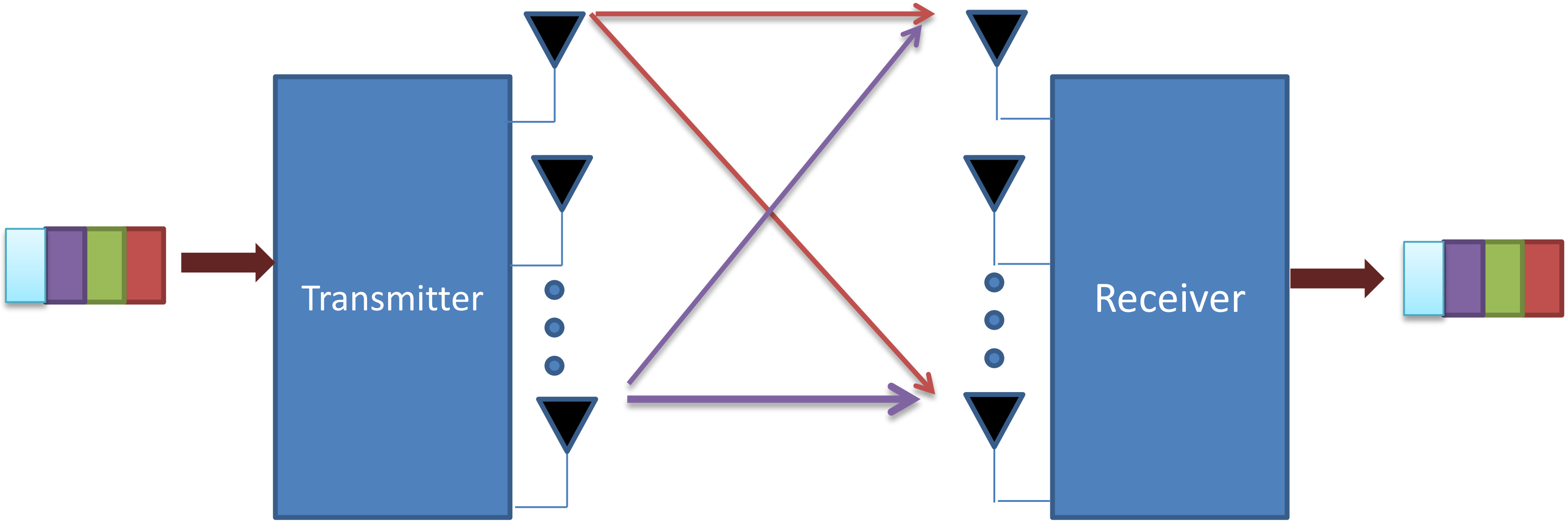
MIMO Signaling

- 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

MIMO Technique	Div/Mux	802.11n	802.11ac	Commercialization
Spatial multiplexing	Mux	✓	✓	High
Space-time Coding	Div	✓	✓	Moderate
Transmit Beamforming	Div/Mux	✓	✓	Emerging
MU-MIMO	Mux		✓	Emerging
Antenna Selection	Div	✓		Low

Spatial Multiplexing in 802.11n/ac

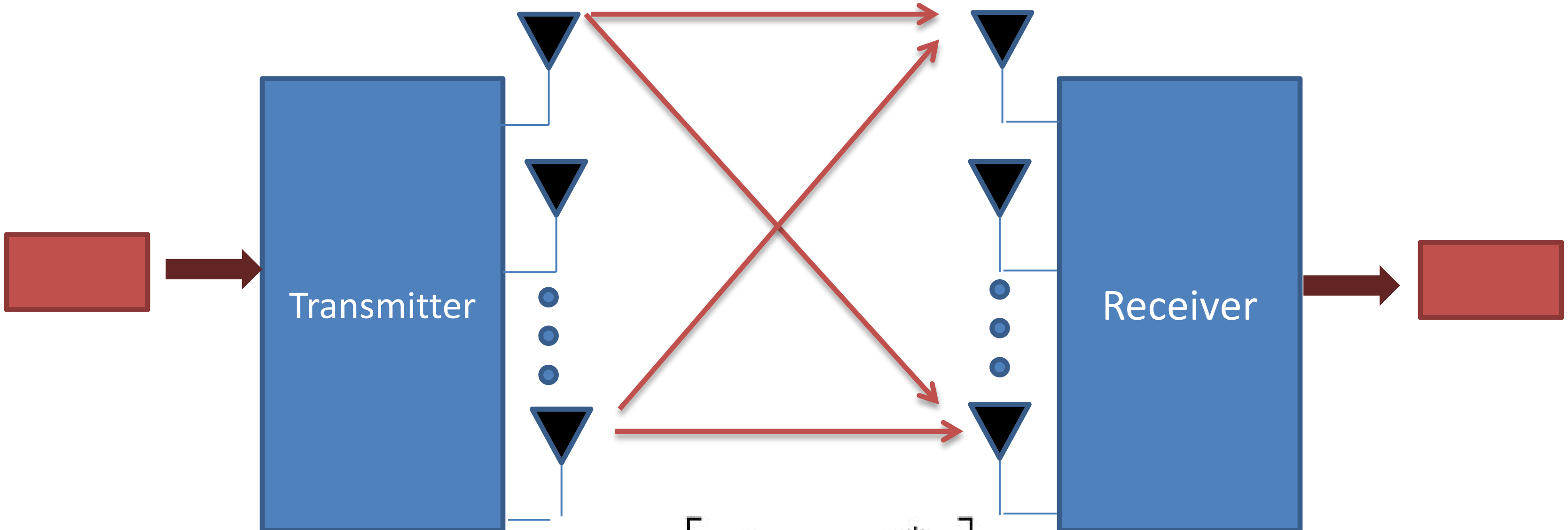


- Indoor channels have been found to support spatial multiplexing reliably
- 802.11n supports up to 4 streams
- 802.11ac supports up to 8 streams

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

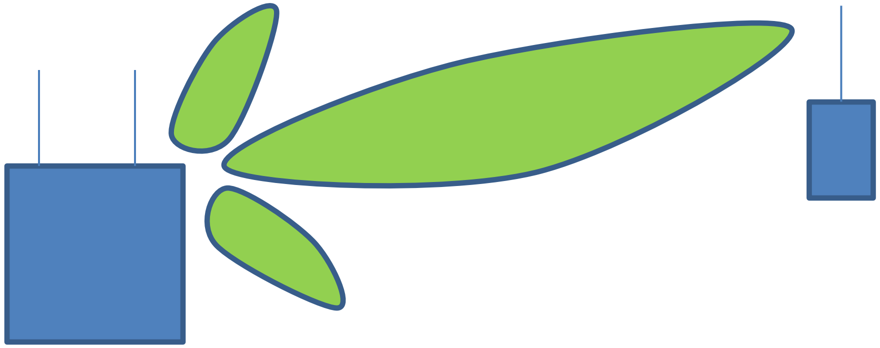


$$X = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$

- Alamouti code

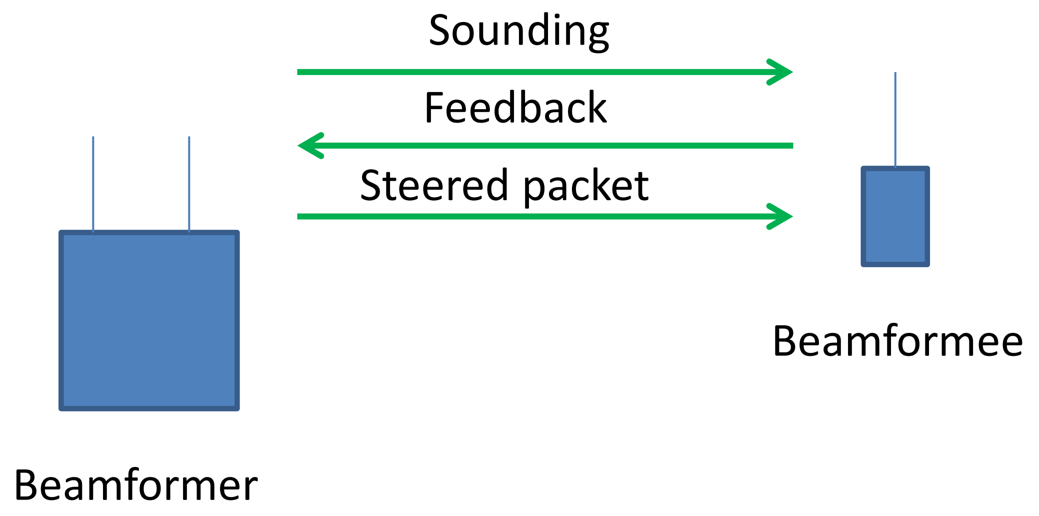
- FEC + bit interleaving realizes significant frequency diversity gain
  - Additional diversity gain from STBC yields incremental improvement

Transmit Beamforming in 802.11



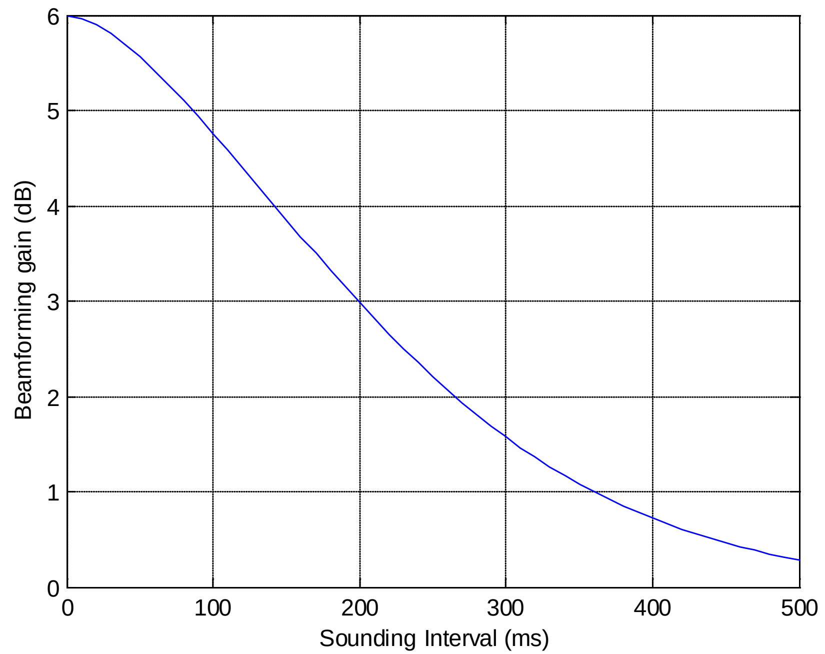
- Technique to ensure that transmitted signal couples into wireless channel with maximum gain
  - Realizes array gain + diversity gain
- Channel knowledge required at transmitter
- Support for both explicit and implicit beamforming

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

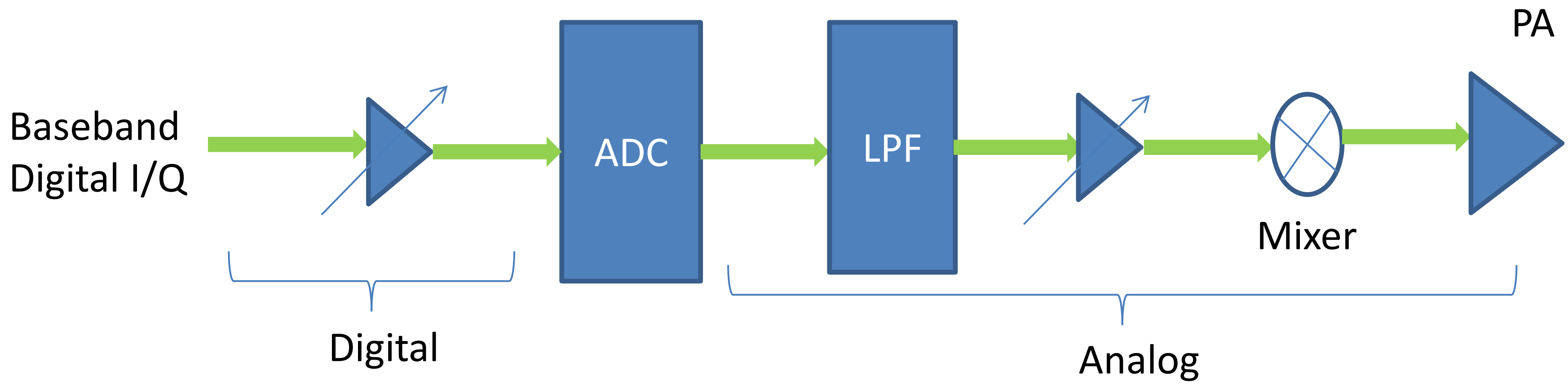
Implementation – Computation Complexity

- Immediate feedback of steering matrix from beamformee 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

x_1, x_2 → $\begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \\ v_{31} & v_{32} \\ v_{41} & v_{42} \end{bmatrix}$ →

$E|v_{11}x_1 + v_{12}x_2|^2 \propto$ 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)

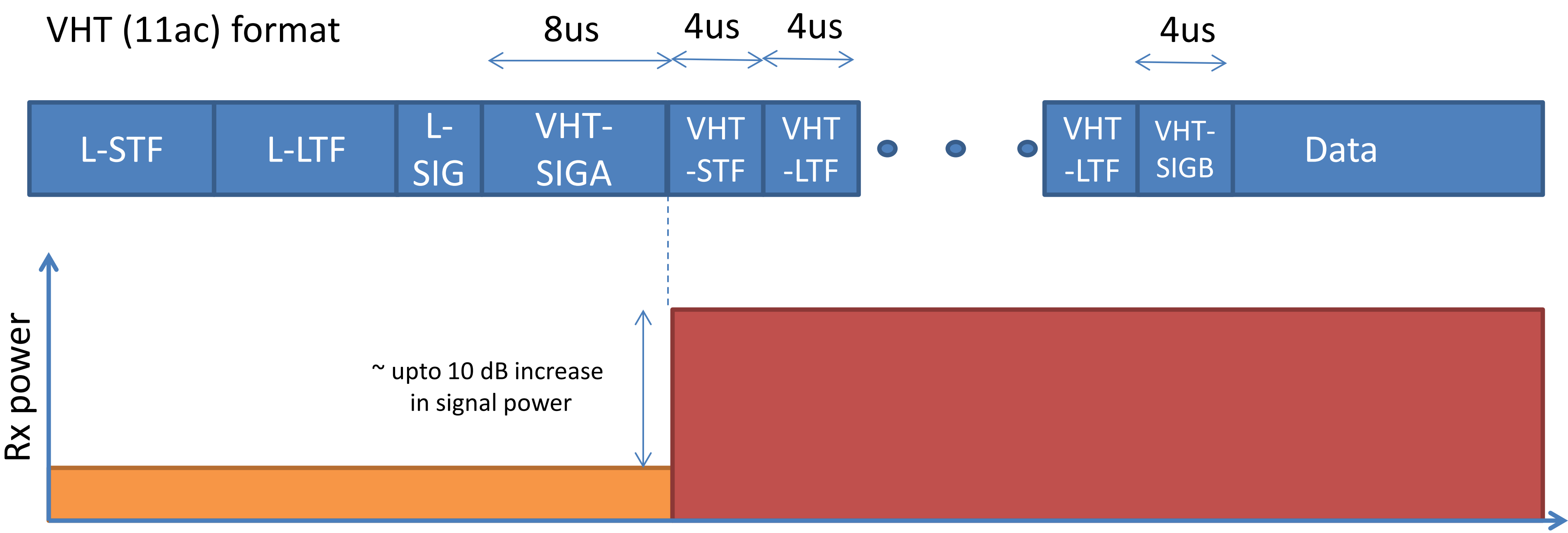
$E|v_{41}x_1 + v_{42}x_2|^2 \propto$ P(Tx4)

Spatial streams

Steering matrix

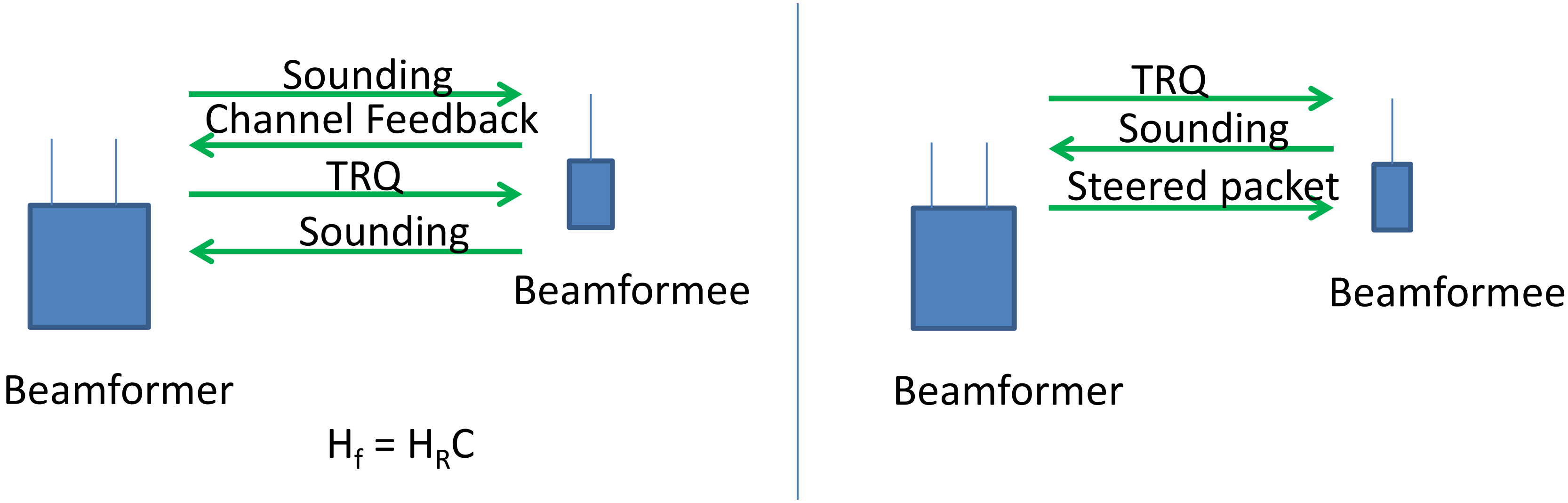
- Rows of steering matrix may not have equal norm
- Back off total power to maintain steering matrix structure reduces beamforming gain
- Need for appropriate power normalization strategies that sacrifice minimal beamforming gain

Implementation – AGC Design



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

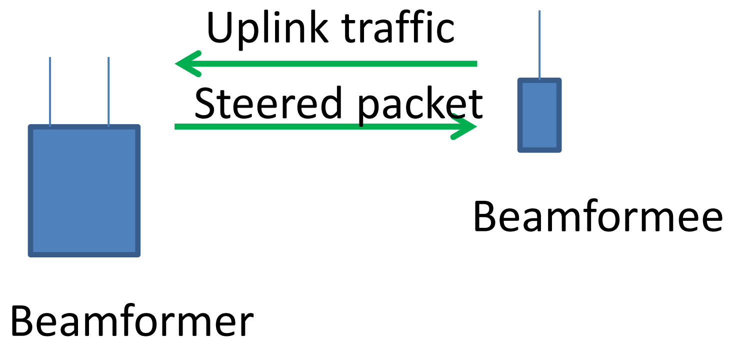
802.11 Implicit Beamforming



$H_f = H_R C$

- Forward channel inferred from reverse channel
  - Physical channel is reciprocal, RF chain response is not
- No steering matrix feedback overhead

Transparent Implicit Beamforming

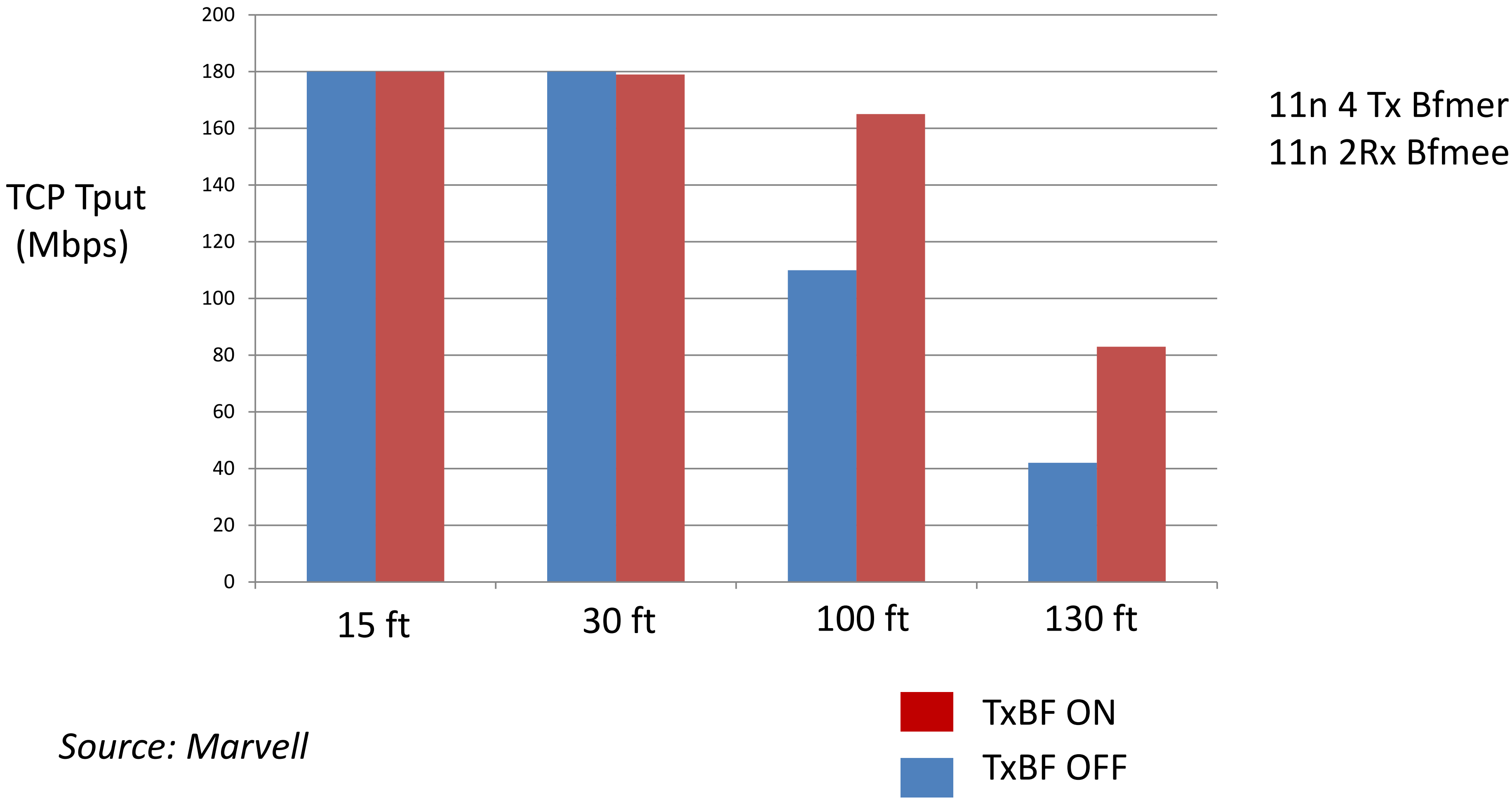


- Beamform to any 802.11 device
- Drawback: Insufficient sounding (inability to estimate full dimensionality of MIMO channel)
- RF Calibration

Implementation -- Implicit Beamforming

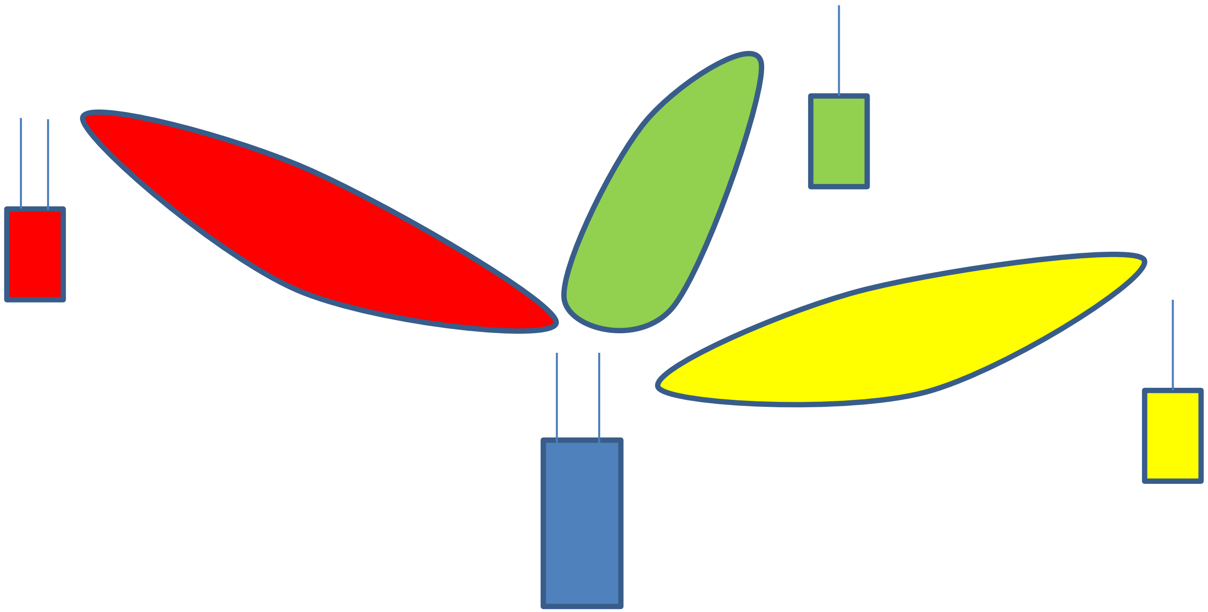
- Implementation challenges are similar to explicit beamforming
- Added complexity of maintaining calibrated RF response across temperature
  - RF gain/phase response may change with temperature in the forward and/or reverse directions
  - Operating temperature can vary between -40 to 85 degrees celsius

Beamforming Gains



Source: Marvell

Multi-User MIMO in 802.11ac

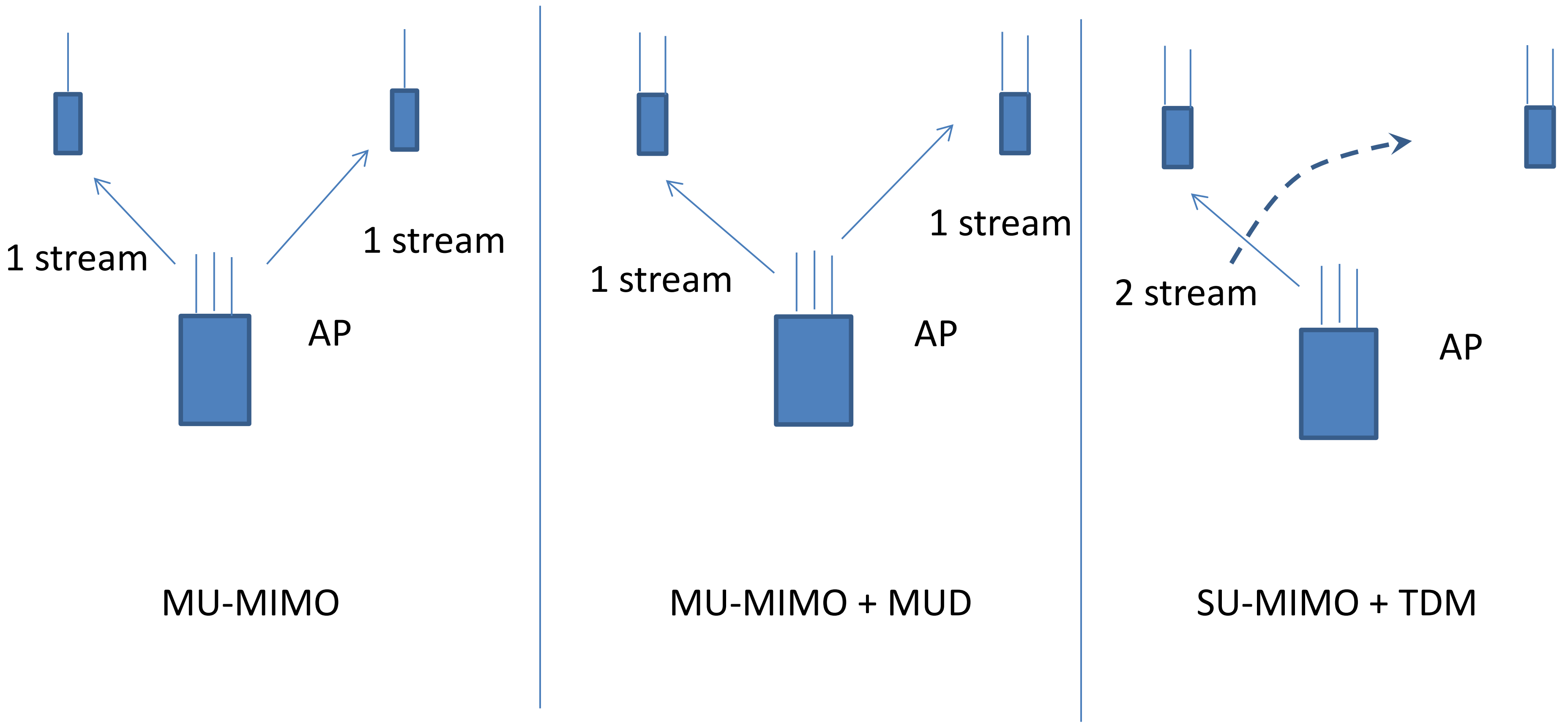


- Downlink multi-user MIMO introduced in 802.11ac
- Support for up to 8 simultaneous streams across 4 users with up to 4 streams per client

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

MU-MIMO/MUD



System imperfections result in steering inaccuracy: channel Doppler, channel estimation error, transmit power normalization

Supporting The Highest Rate

20 MHz

Tx EVM	-35
Front end components	-40
11 bit ADC 2x oversampled 13 dB backoff	-58
Rx IQ imbalance	-45
Rx Phase Noise	-45
Residual ICI	-45
Loss due to channel estimation error	3
Net SNR	29.90153

160 MHz

Tx EVM	-35
Front end components	-32
11 bit ADC 2x oversampled 13 dB backoff	-58
Rx IQ imbalance	-45
Rx Phase Noise	-45
Residual ICI	-45
Loss due to channel estimation error	3
Net SNR	26.8145

- 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