

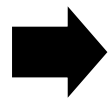
IEEE 802.11n: Throughput, Robustness, and Reliability Enhancements to WLANs

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Outline

- Introduction
- PHY
 - MIMO/SDM basics
 - 11n PHY design criteria
- MAC
 - Aggregation and Block Ack
 - Interoperability / Coexistence
 - Advanced Features
- Summary

Outline

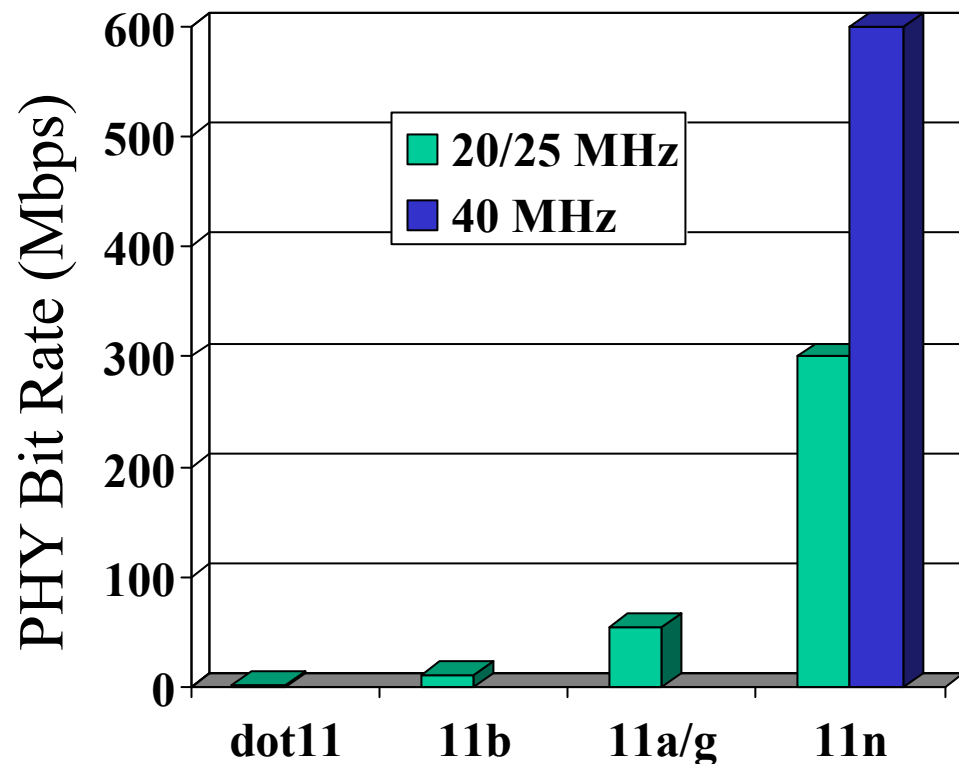


Introduction

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Requirements of the 11n Standard Amendment

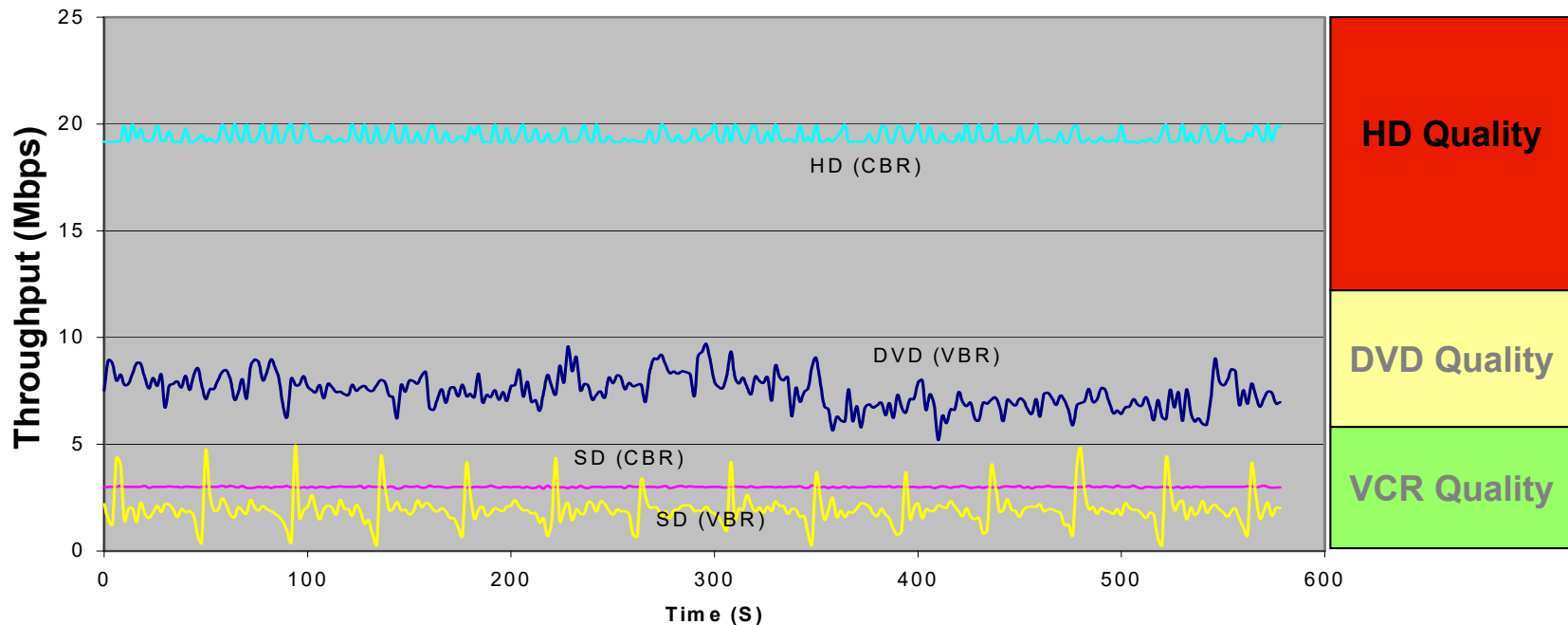
- High Throughput
 - Significant increase in throughput
 - Throughput is measured at the MAC, which requires increased efficiency in the MAC
- Spectral efficiency
- Robustness
 - High throughput with reasonable range
- Backward compatibility and coexistence with legacy devices



Environment & Applications

- 11n WLAN systems will be deployed in
 - Residential, home office / small office, medium & large sized enterprise, hotspots, industrial
- Expected applications include:
 - DV Audio/video, SDTV, HDTV, DVD
 - Internet Streaming video/audio
 - VoIP, Video phone, Video Conf
 - Content download (photo camera)
 - Internet File transfer (email, web, chat)
 - Local File transfer, printing
 - Interactive Gaming [Controller to Console, Console to Display, Console to Internet Access]

Video Throughput Requirements



Sample of MPEG2 streams measured in lab

- HD quality streaming exceeds WLAN capability in a typical home environment
- Even lower rate video will stress a WLAN system

11n History (1/2)

- High Throughput Study Group (HTSG) kicked off in the Monterey, Sept. 2002 IEEE802.11 meeting
 - Development of PAR, Channel model, Usage Models
- TGn formed with first meeting in Singapore, Sept. 2003
 - Started with development of Functional Requirements and Comparison Criteria documents
 - Functional Requirements must be addressed by any proposal claiming that it is a complete proposal in response to the IEEE 802.11 TGn call for proposals
 - Throughput
 - Backward compatibility
 - Spectral Efficiency
 - Comparison Criteria must be addressed by any proposal claiming that it is a complete proposal in response to the IEEE 802.11 TGn call for proposals
 - Marketability
 - Backward Compatibility and Coexistence with Legacy Devices
 - Performance Measurements at the MAC SAP
 - PHY performance simulations
 - Began call for proposals May 17 '04

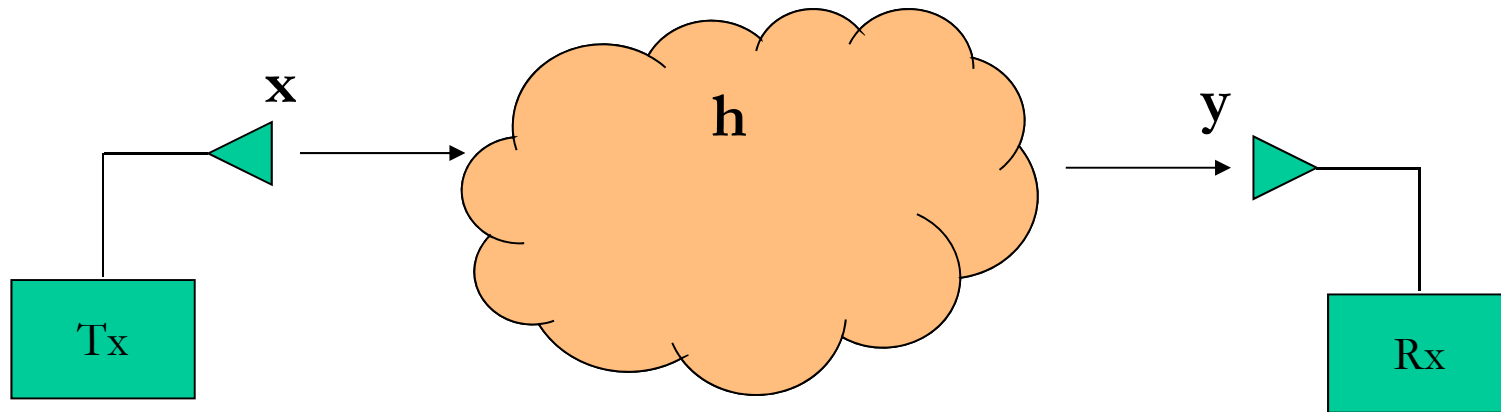
11n History (2/2)

- Intel, Cisco, Agere, Sony start TGn Sync proposal team
 - Cover broad range of markets: PC, enterprise, CE
- Broadcom, Conexant, TI start WWiSE proposal team
 - Simple upgrade to 11a
- First proposal presentations in Sept. 2004 (Berlin)
- A series of proposal down select votes and confirmation votes took place
- In May 2005 (Cairns) final confirmation of TGn Sync proposal failed
- Joint proposal effort began to merge proposals together
- Joint Proposal submitted for confirmation to TGn and unanimously passed in Jan. 2006
- The proposal was converted to Draft 1.0 and a letter ballot was issued March 2006
- The letter ballot failed, and comment resolution began in May 2006...
- Next steps include completing comment resolution, passing subsequent letter ballots and sponsor ballots
- Expected completion date of 11n standard is April 2008

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SISO (11a/g) Background

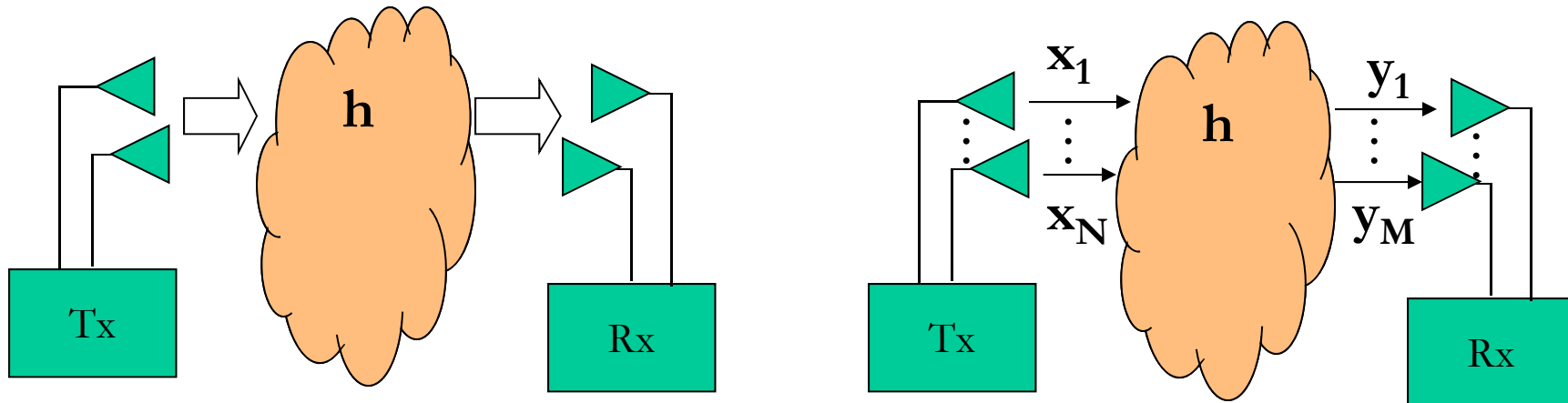


- The transmitter sends data x
- Which is received as $y = h * x + n$
 - h : *channel fading coefficient*
 - n : *AWGN*
- The receiver extracts the information by equalizing the received signal:

$$\hat{x} = h^{-1} y$$

$$= x + h^{-1} n$$

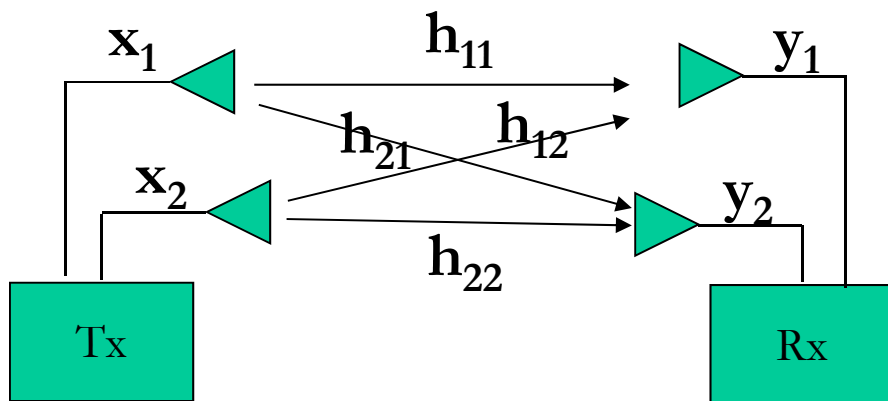
MIMO



- **MIMO: multiple input (to the environment), multiple output (from the environment)**
- MIMO means different things to different people
- A transmit beamforming antenna array and/or multiple receive diversity antennas qualifies as MIMO by some
- These systems improve robustness and increase the rate at a given range, but they do not increase the maximum data rate

- **Spatial division multiplexing (SDM): transmit independent data streams on different antennas**
- The maximum data rate increases as a function of the number of transmit antennas
- The number of receive antennas is least the number of data streams with a linear equalizer

MIMO Magic



$$y_1 = h_{11}x_1 + h_{12}x_2 + n_1$$

$$y_2 = h_{21}x_1 + h_{22}x_2 + n_2$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

- The MIMO/SDM system can be described in vector form with similar mathematical structure as a SISO system
- Conceptually, the equalizer can also be designed with a similar structure.

$$Y = HX + N$$

$$\hat{X} = H^{-1}Y$$

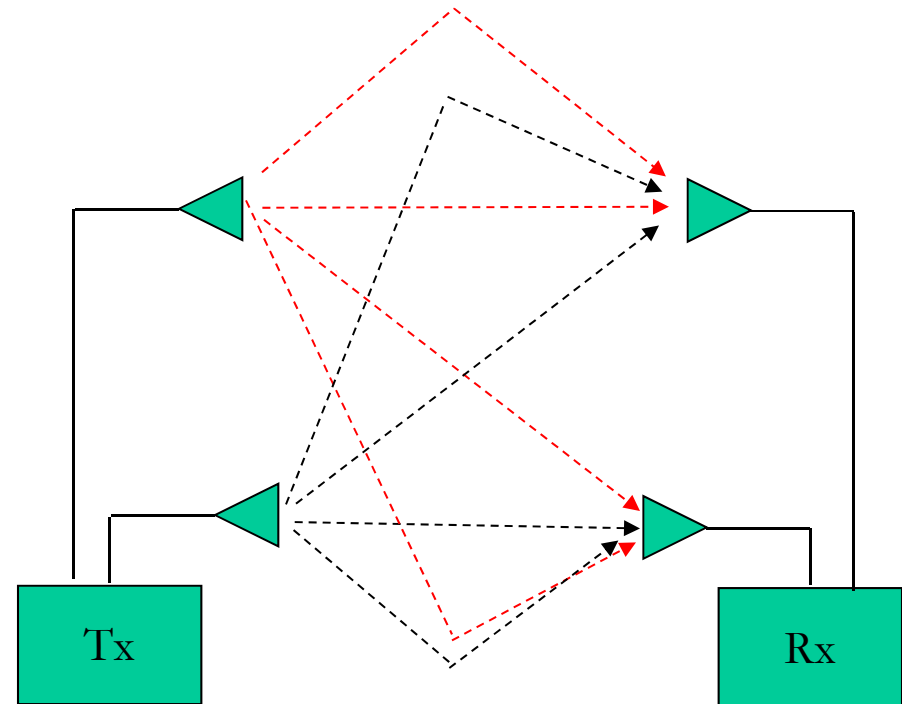
$$= X + H^{-1}N$$

What's the catch?

- Consider a benign LOS, non-fading environment with a SISO 11a/g system ($h = 1$)
 - The system works great. In fact this is a typical setup for conductive testing
- Consider the similar channel for a MIMO system
 - $H = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ It is not invertible
 - Receiver fails!
- The channel matrix must be invertible

MIMO Environment

- If the taps in the channel matrix are random distributed and uncorrelated with each other, statistically the channel matrix will be invertible a vast majority of the time
- Multipath fading creates such an environment
- A channel matrix exists for each tone with MIMO/OFDM
- How to ensure that the channel is uncorrelated enough?
 - Wide antenna spacing (at least a wavelength)
 - Low antenna coupling
 - NLOS conditions also help by not having a highly correlated direct path between transmit and receive devices (however this typically means reduce signal power at the receiver)
- PHY MIMO performance will vary with LOS/NLOS, delay spread, antenna correlation, doppler, path loss, and shadowing
- Hardware impairments that will degrade performance include power amplifier non-linearity, noise figure, clock stability, and phase noise



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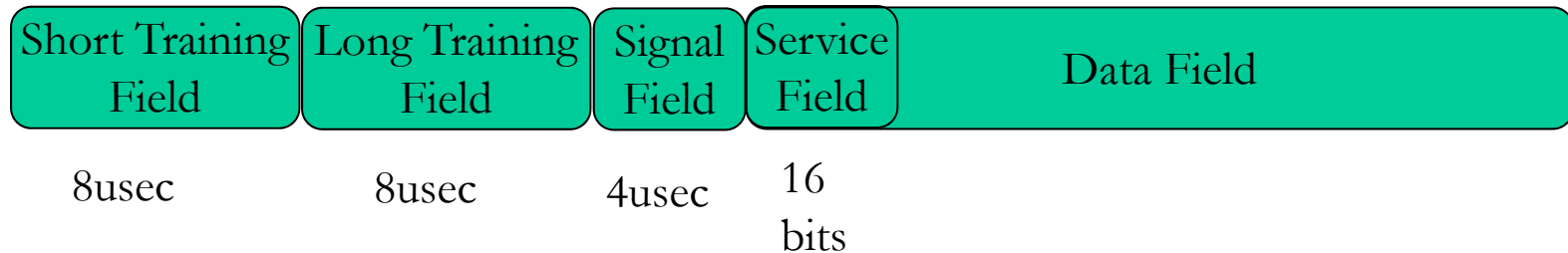
11n PHY design criteria

- Interoperable with 11a/g legacy OFDM devices
- High Throughput
- Robust performance

Interoperable with 11a/g legacy OFDM devices

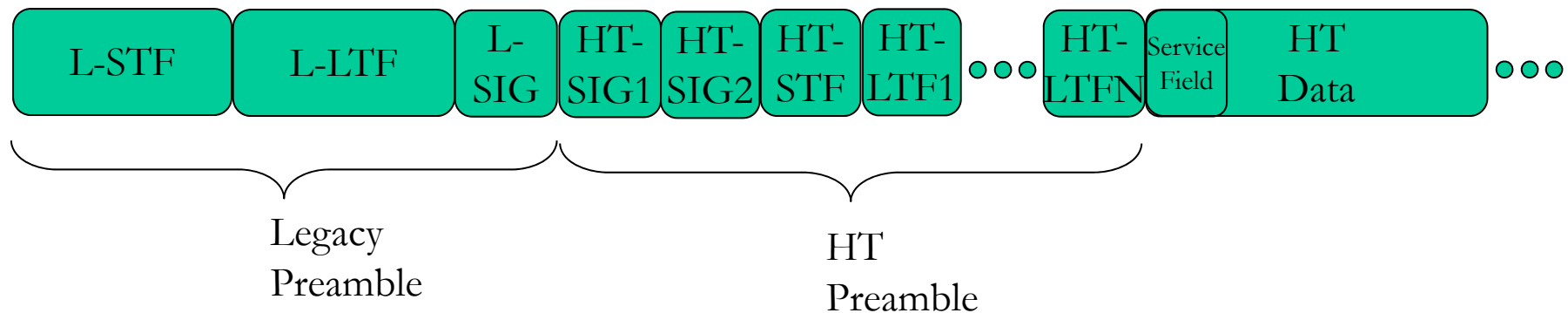
- Mixed mode preamble
- Auto-detection

11a PPDU Format Review



- Short training field (STF) used for start-of-packet detection, AGC setting, initial frequency offset estimation, initial time synchronization
- Long training field (LTF) used for accurate frequency offset estimation, time synchronization, and channel estimation
- Signal field (SIG) contains rate and length information
 - SIG has only one parity bit which leads to false detects
 - A reserve bit in the signal field has been used by some manufactures for more parity
- First 16 bits of the data field is the service field, containing reserve bits and scrambler initialization bits

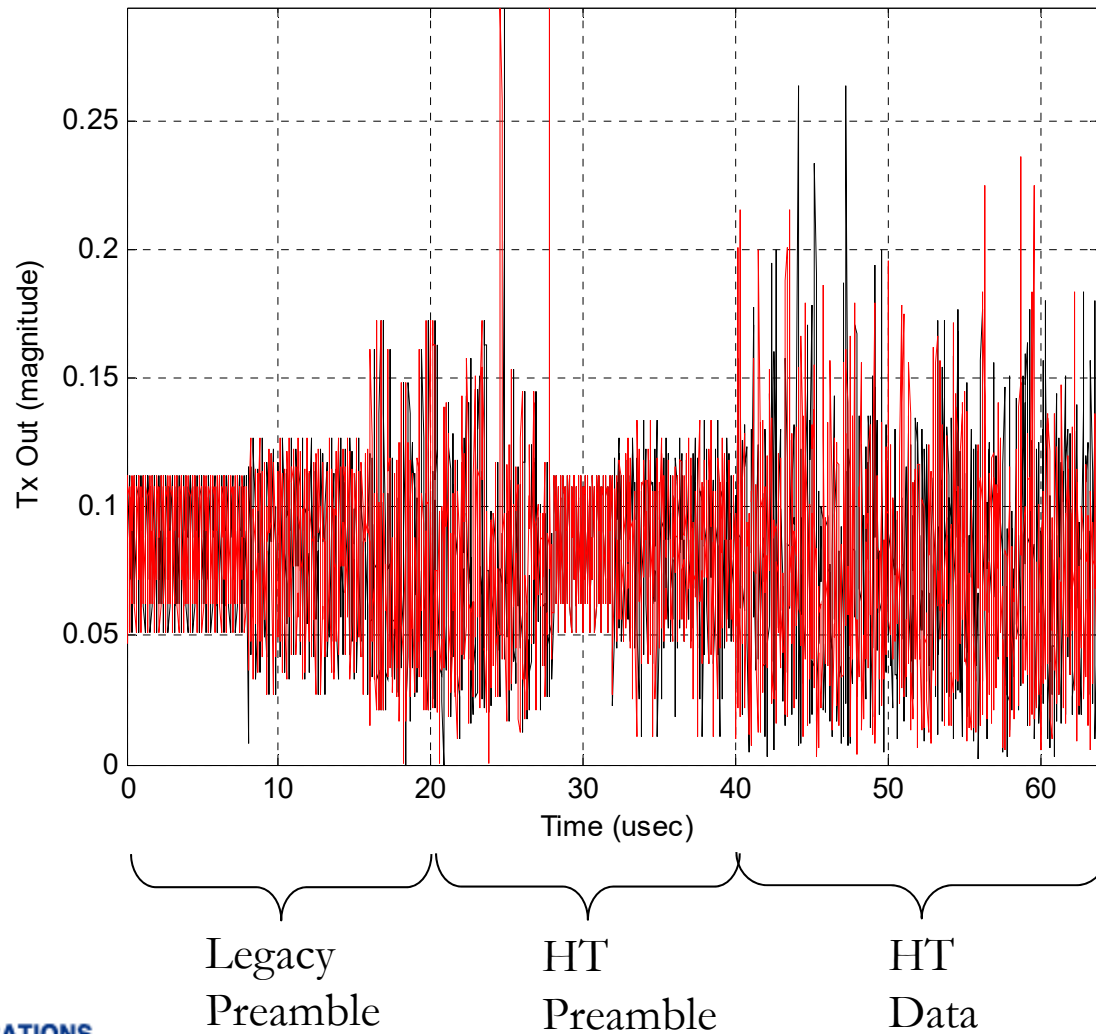
Mixed Mode High Throughput Preamble



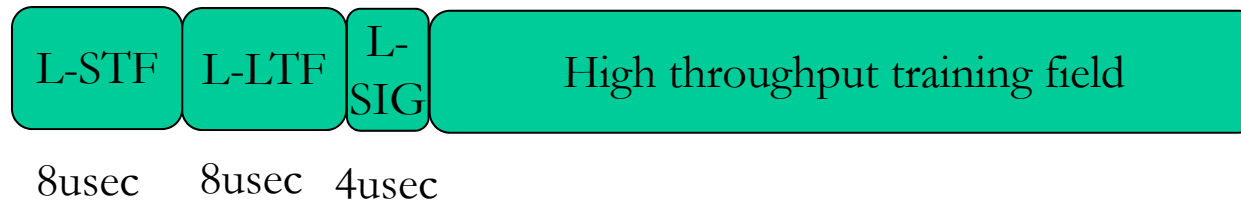
- Mixed mode (MM) high throughput preamble begins with the legacy 11a preamble
- This is followed by high throughput training fields

MM Waveform

802.11n 2-Spatial Streams, Full Packet

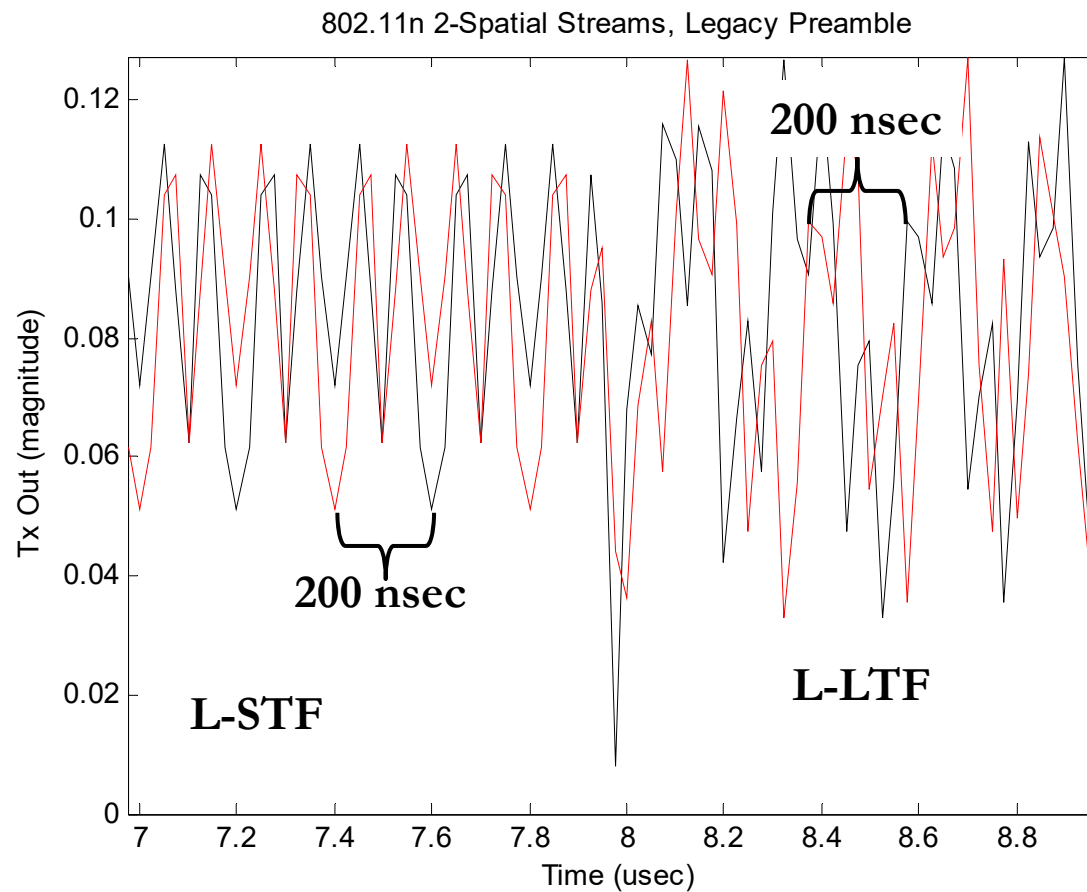


Interoperable PPDU Format with 11a/g Legacy OFDM Devices

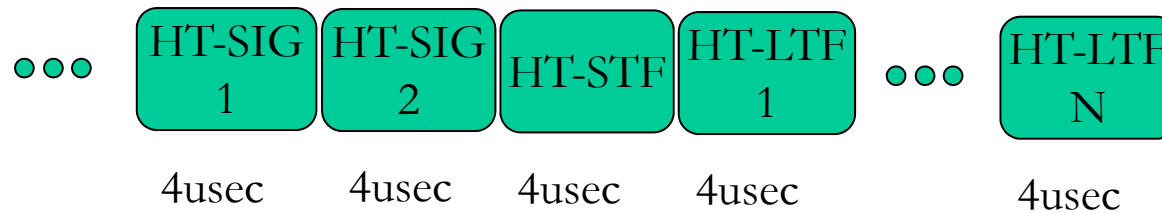


- A mixed mode (MM) preamble was created to provide PHY interoperability with legacy OFDM devices
- The first part of the MM preamble consists of legacy (L) training identical to 11a
 - Contains L-STF, L-LTF, and L-SIG field as 11a such that legacy devices can detect the preamble
- How do we transmit the single stream legacy part of the MM preamble with a multiple antenna device?
 - It is desirable to transmit the legacy training from all antennas for maximum power and range
 - However, this may cause unintentional and undesirable beamforming effects since we are transmitting the same signal from each antenna
- Cyclic shifts are applied to additional antennas to decorrelate transmission paths
 - Legacy devices with cross correlation receivers are sensitive to delay spread, which will be exacerbated by long cyclic shifts
 - Shorter shifts are used on the legacy training part of the MM preamble to conserve detection properties: maximum of 200nsec
 - Cyclic shifts are applied symbol by symbol basis

Legacy Part of the MM Preamble



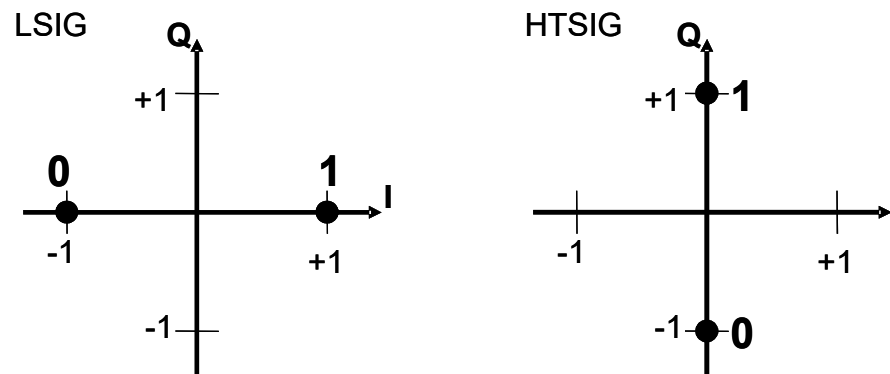
High Throughput Training



- Following L-SIG are:
- High throughput signal fields 1 & 2
 - New signaling information; auto-detection
- High throughput short training field
 - Redo AGC
- High throughput long training fields
 - MIMO channel estimation

High Throughput Signal Field

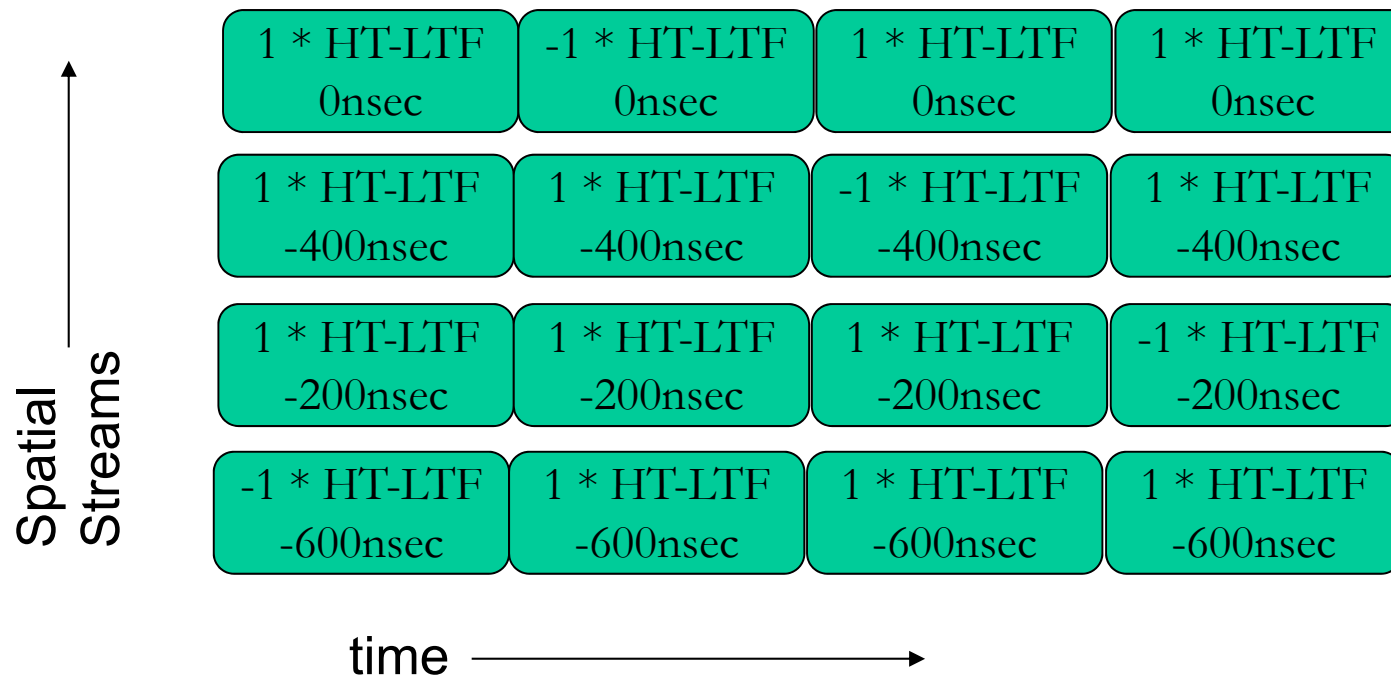
- HT-SIG fields are used for several purposes
- HT-SIG contains signaling information for new functions including modulation and coding (# of streams), length field, aggregation, sounding, LDPC coding, channel width etc.
- HT-SIG is also used for auto-detection between HT packet and legacy packet
 - HT-SIG is transmitted similarly to L-SIG (single stream, BPSK, $r=1/2$) but with BPSK rotated by 90° allowing for auto-detection between L-SIG and HT-SIG



High Throughput Short Training Field

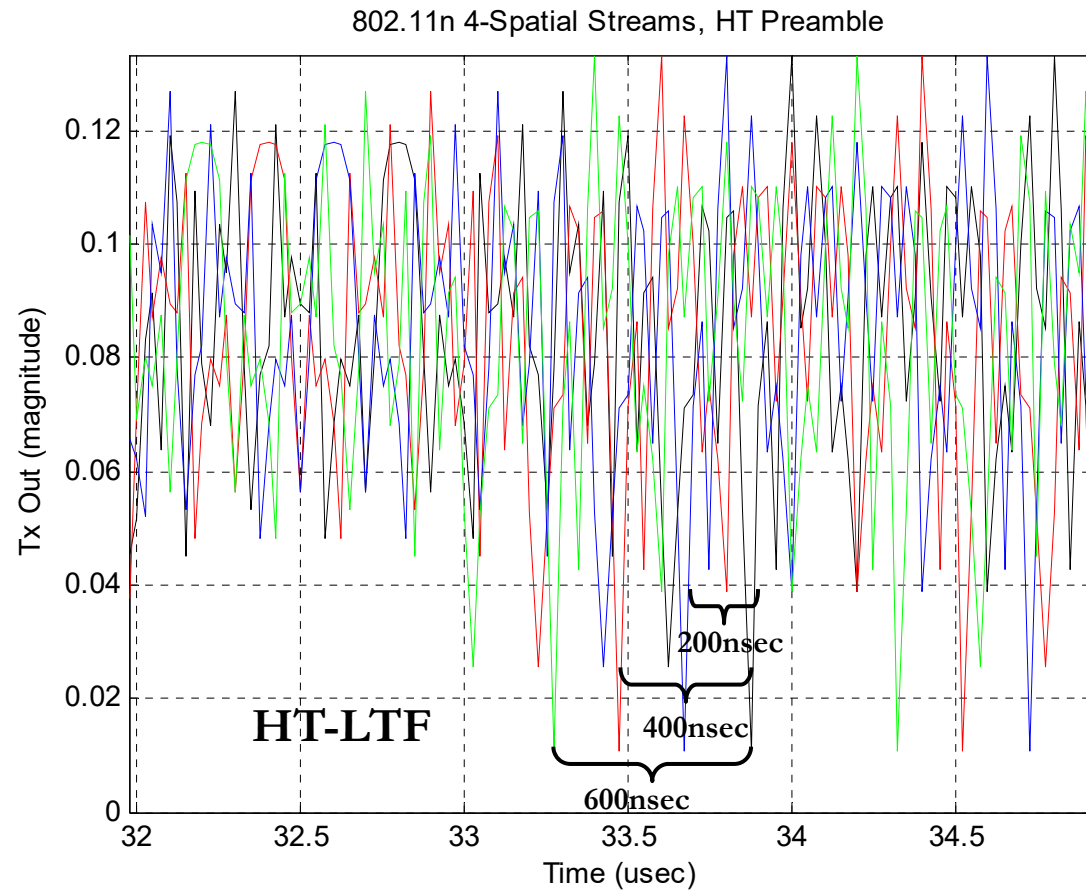
- MIMO requires accurate power estimates from transmit antennas to receive antennas
- A 2nd STF with longer cyclic shifts provides power estimates much better matched to HT data field
- More accurate AGC setting reduces the dynamic range requirement on the ADC

High Throughput Long Training



- The HT-LTF is used for MIMO channel estimation
- A HT long training symbol is transmitted for each data stream
- An orthogonal mapping matrix is used to generate the HT-LTF
- The same cyclic shifts used on HT-STF are applied to HT long training symbols to accurately match power variation to HT-Data

HT Preamble Waveform



Channel Estimation for Legacy

- Equalization in slides 10 & 12 assume knowledge of the channel which requires channel estimation
- SISO / legacy 11a review:
 - Receiver extracts the two long training symbols from the LTF
 - FFT is performed on the symbols and training tones are extracted
 - Tones from symbol one are averaged together with symbol two
 - Known training symbol information (either +1 or -1) is divided out of the signal leaving the channel estimate

$$y_{t1} = h \cdot LTS + n_{t1}$$

$$y_{t2} = h \cdot LTS + n_{t2}$$

$$\hat{h} = (y_{t1} + y_{t2}) / (2 \cdot LTS)$$

Channel Estimation for HT

- Same cyclic shift is applied to data streams as HT-LTF, so it can be treated as part of the channel and ignored
- The orthogonal mapping matrix allows for separation of the long training symbols on different streams
- Processing steps:
 - Receiver extracts the long training symbols from each of the HT-LTF's
 - FFT is performed on the symbols and training tones are extracted
 - Tones from symbol one and symbol two from antenna one are combined to generate estimates of h_{11} and h_{12}
 - Tones from symbol one and symbol two from antenna two are combined to generate estimates of h_{21} and h_{22}
 - Known train symbol information (either +1 or -1) is divided out of the signal leaving the channel estimate
- Similar processing is used to generate channel estimates with more spatial streams and receive antennas

$$y_{t_1, A_1} = h_{11} \cdot LTS + h_{12} \cdot LTS + n_{t_1, A_1}$$

$$y_{t_1, A_2} = h_{21} \cdot LTS + h_{22} \cdot LTS + n_{t_1, A_2}$$

$$y_{t_2, A_1} = h_{11} \cdot -1 \cdot LTS + h_{12} \cdot LTS + n_{t_2, A_1}$$

$$y_{t_2, A_2} = h_{21} \cdot -1 \cdot LTS + h_{22} \cdot LTS + n_{t_2, A_2}$$

$$\hat{h}_{11} = (y_{t_1, A_1} - y_{t_2, A_1}) / (2 \cdot LTS)$$

$$\hat{h}_{12} = (y_{t_1, A_1} + y_{t_2, A_1}) / (2 \cdot LTS)$$

$$\hat{h}_{21} = (y_{t_1, A_2} - y_{t_2, A_2}) / (2 \cdot LTS)$$

$$\hat{h}_{22} = (y_{t_1, A_2} + y_{t_2, A_2}) / (2 \cdot LTS)$$

High Throughput

- 20 & 40 MHz channelization
- 1 to 4 spatial streams
- $\frac{1}{2}$ GI
- 56 tones (in 20MHz)
- 5/6 coding
- GF preamble

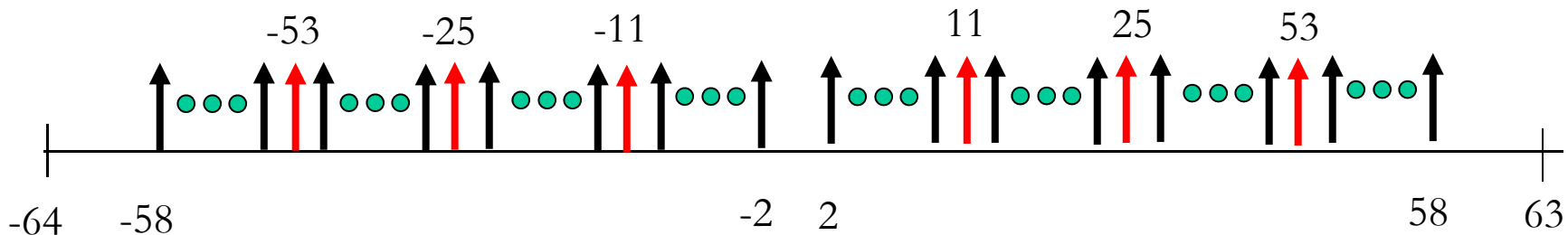
40 MHz Channels

- Unlicensed band, so spectrum is free
- Negligible increase in cost between 40MHz radio and 20MHz radio
- Issues:
 - Co-channel interference due to increased frequency reuse
 - Coexistence and interoperability between 20MHz and 40MHz devices

New Spectrum Allocation in US

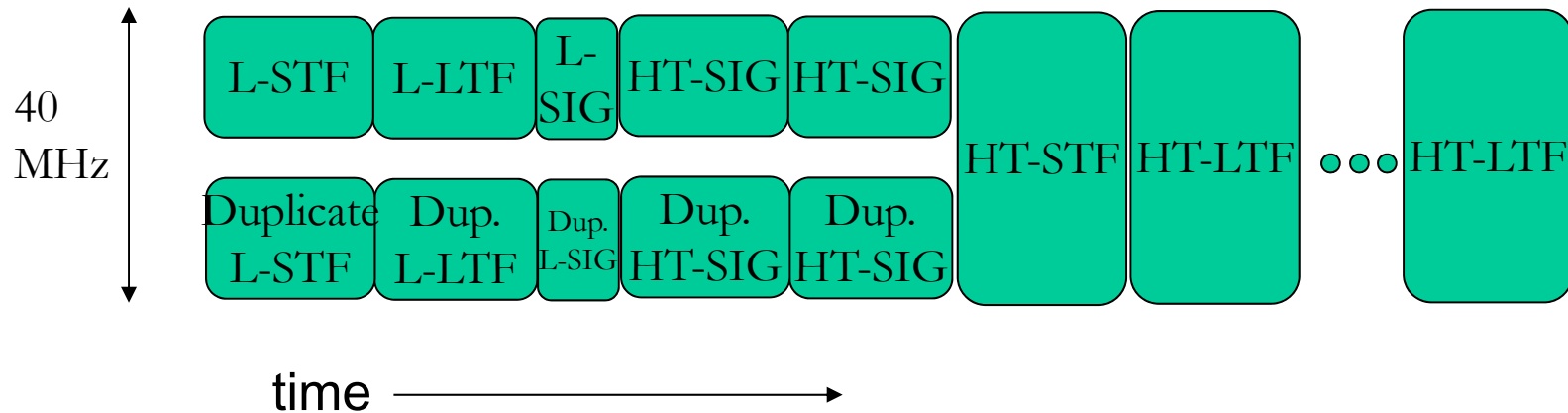
- Existing
 - UNII lower
 - Four 20MHz channels
 - 5.15-5.25 GHz
 - UNII middle
 - Four 20MHz channels
 - 5.25-5.35 GHz
- ETSI bands
 - Ten 20MHz channels
 - 5.5-5.7GHz

40MHz Tone Design



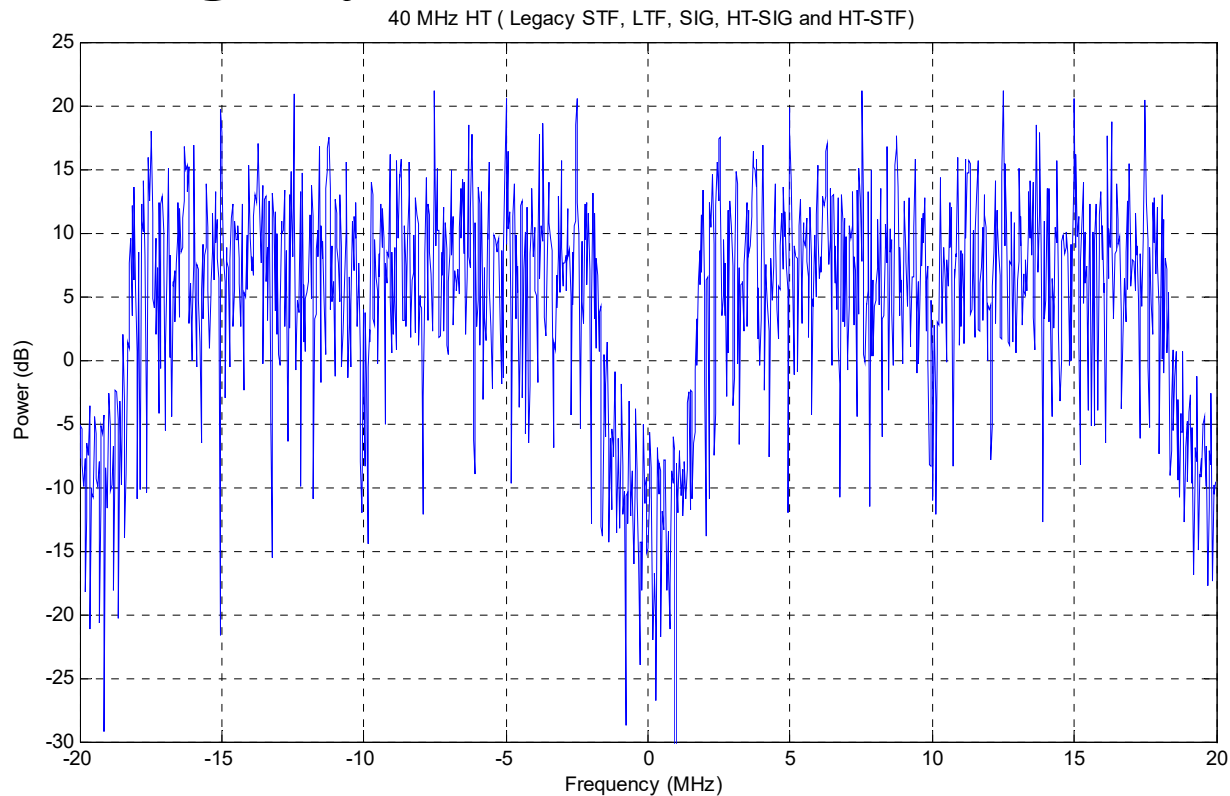
- 14 Null tones: $\{-64, \dots -59, -1, 0, 1, 59, \dots 63\}$
- 114 Populated tones: $\{-58, \dots -2, 2, \dots 58\}$
 - 6 Pilot tones: $\{-53, -25, -11, 11, 25, 53\}$
 - 108 Data tones: $\{\text{Populated tones}\} - \{\text{Pilot tones}\}$

40MHz Preamble



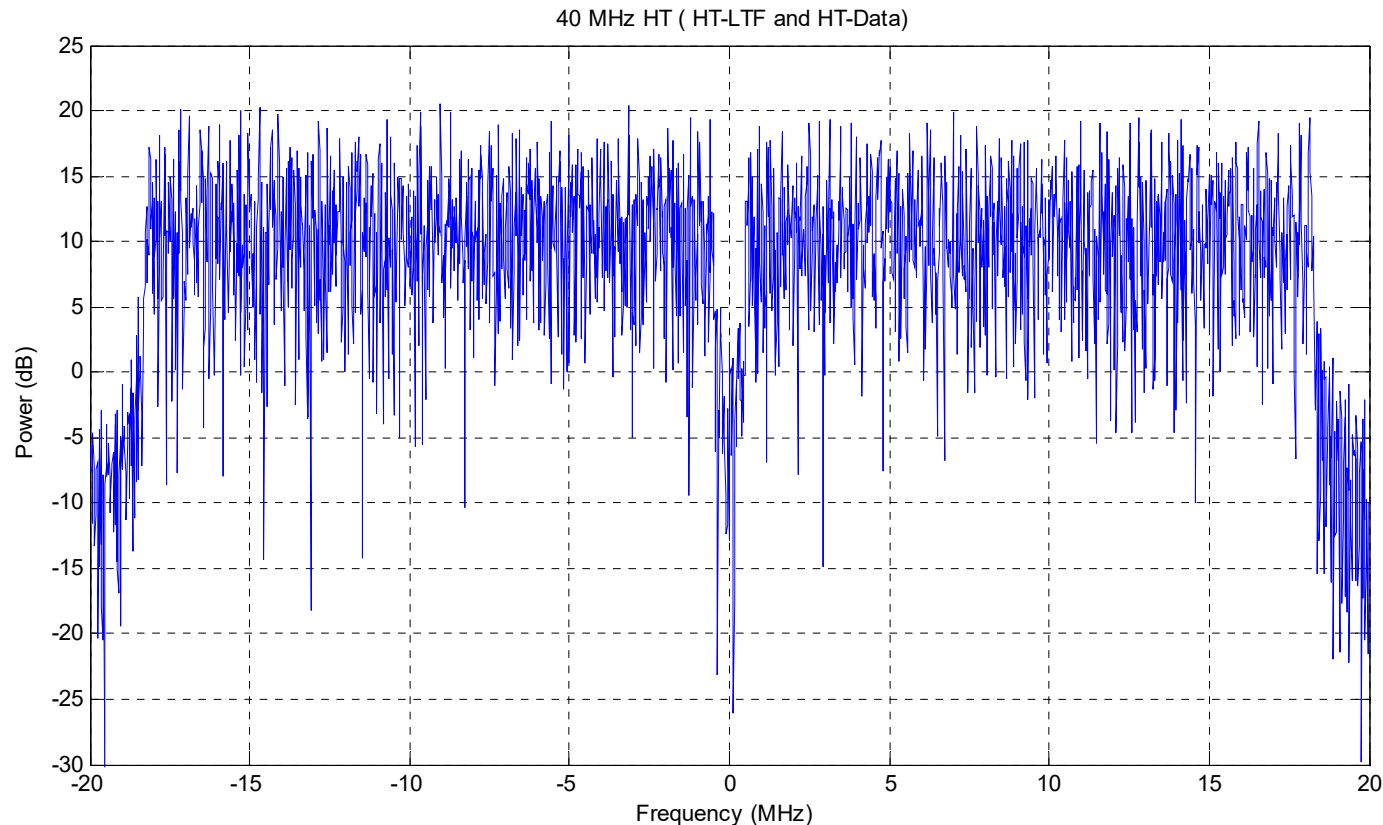
- The legacy fields are duplicated in the extension 20MHz channel.
- The extension channel is rotated by 90° to reduce power variation
- Duplication of the legacy fields enables a 20MHz receiver to decode the legacy fields and HT-SIG transmitted by a 40MHz device for interoperability between 20 and 40MHz devices
- A bit in HT-SIG indicates whether the signal is a 20MHz or 40MHz transmission

40MHz Spectral Plot – Legacy Portion of Preamble



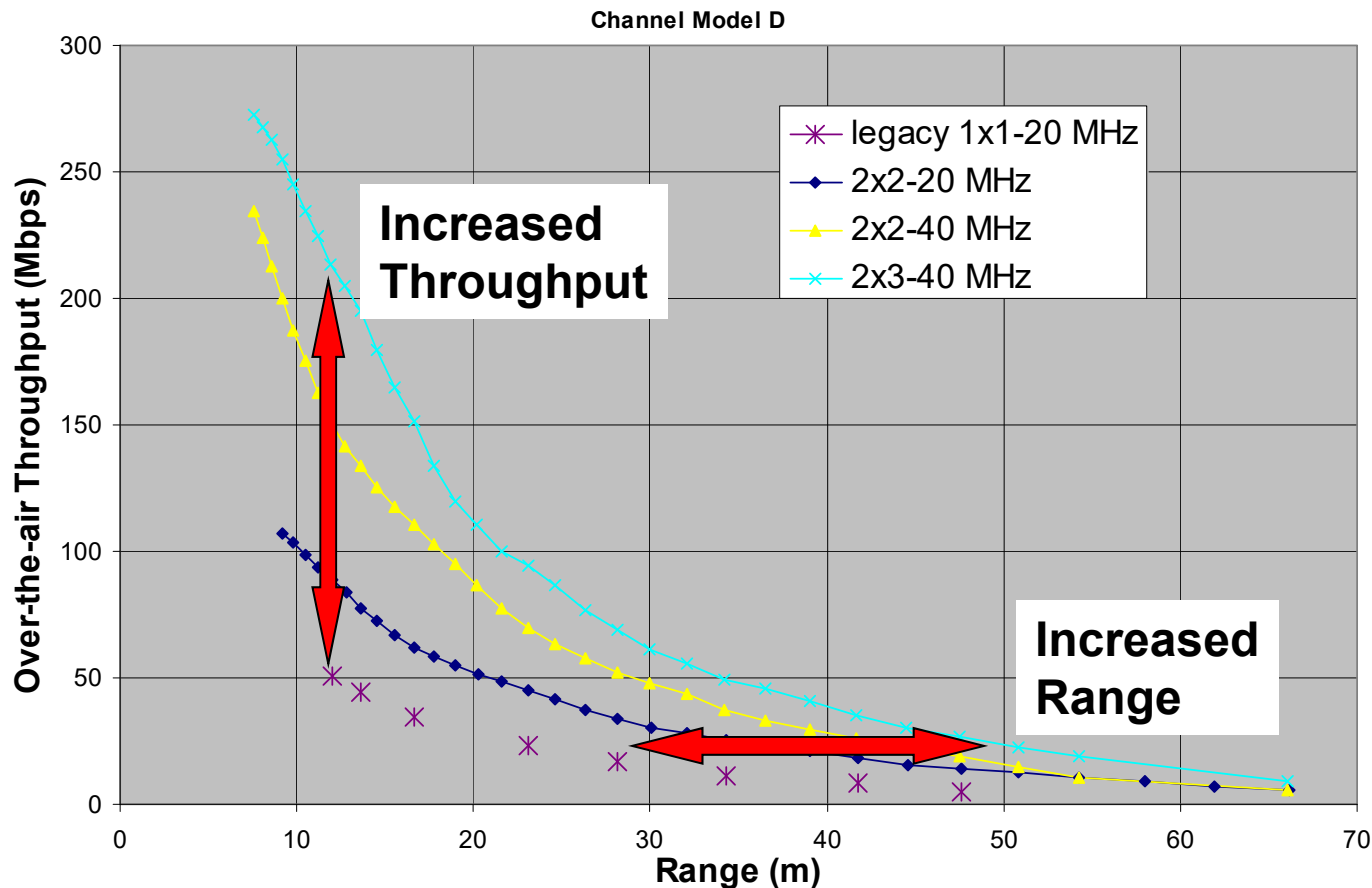
Legacy portion of preamble contains many null tones in DC area

40MHz Spectral Plot – HT Portion of Preamble



In HT portion of preamble and data most of the null tones in DC area are filled in with data tones

Performance Improvement with 40MHz

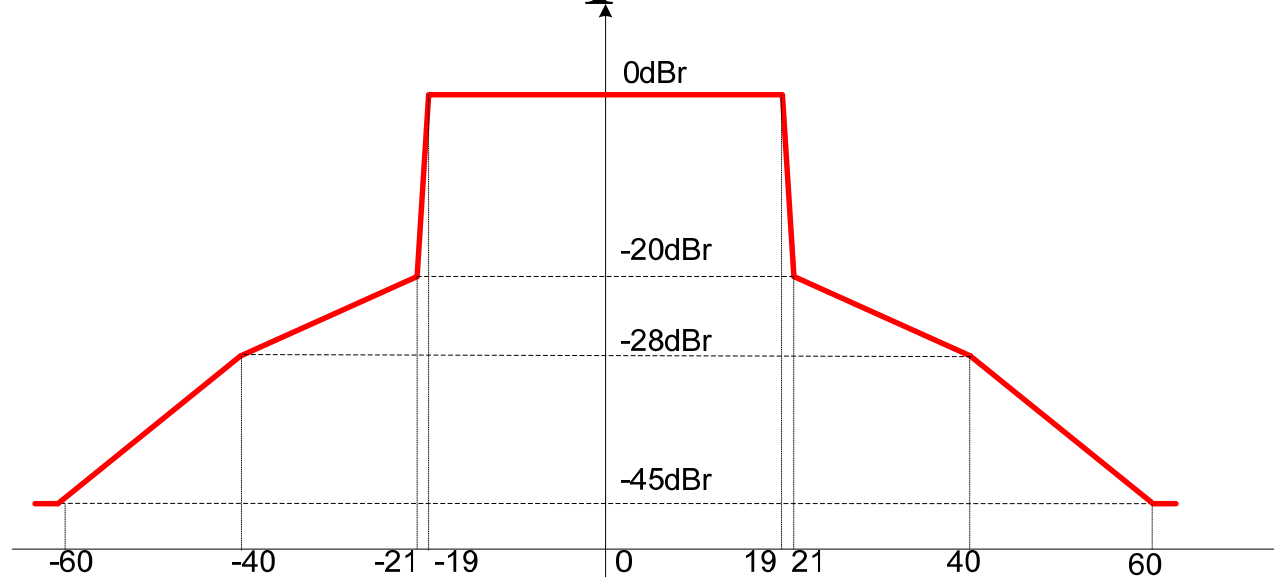


- 40MHz more than doubles peak data rates
- At data rates equivalent to legacy, 40MHz systems can be operated at lower order modulation for added robustness and increased range

20/40MHz Coexistence in the PHY

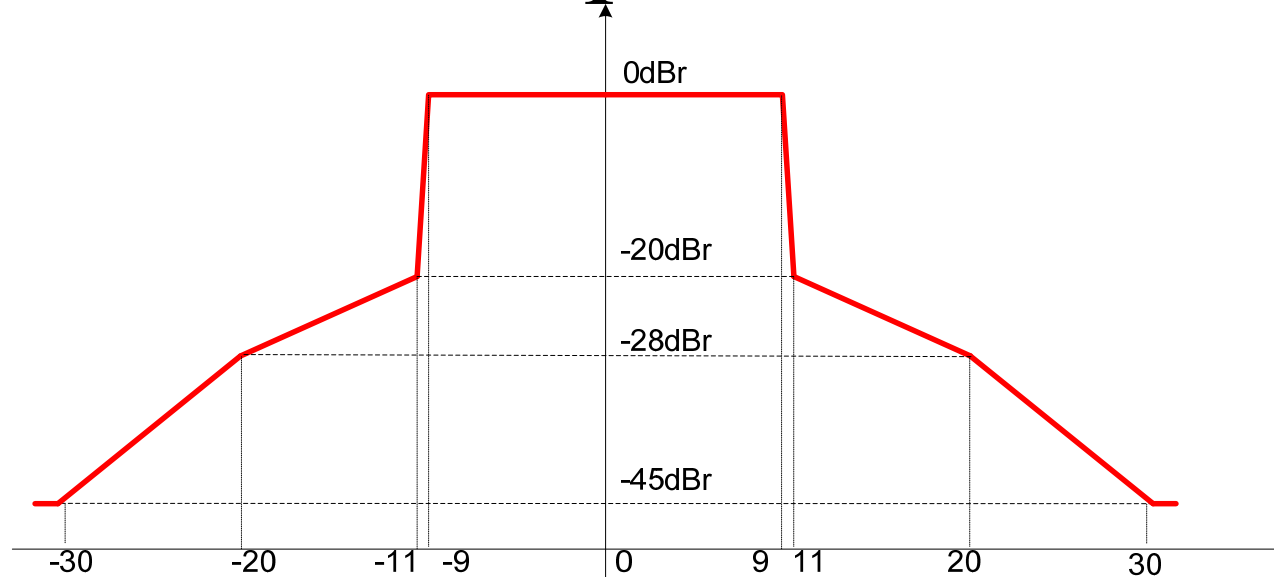
- HT Duplicate Mode (MCS 32)
 - With same output power as 20MHz, 40MHz range will be “3dB worse” than 20MHz due to wider noise bandwidth
 - With HT duplicate mode, the signal is duplicated on the upper and lower channel
 - Combining the tones in the upper and lower channel at the receiver makes the maximum range of 20MHz and 40MHz equal
 - The data is transmitted on one spatial stream with BPSK and rate $\frac{1}{2}$ coding (6Mbps)
- Non-HT Duplicate Mode
 - Used to transmit to legacy devices that may be present in either the upper and lower channels of the 40MHz channel
 - The device operates in a 40MHz channel composed of two adjacent 20MHz channel
 - The packets to be sent are in the legacy 11a format in each of the 20MHz channels

40MHz Spectral Mask



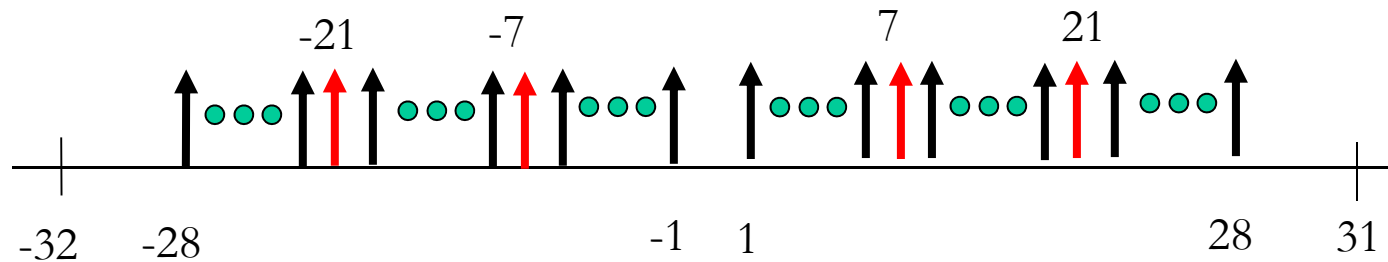
- 40MHz spectral mask provides similar adjacent channel interference performance between two neighboring 40MHz devices as between two neighboring 20MHz devices
- The adjacent channel interference between neighboring 20MHz and 40MHz devices is yet to be determined

20MHz Spectral Mask



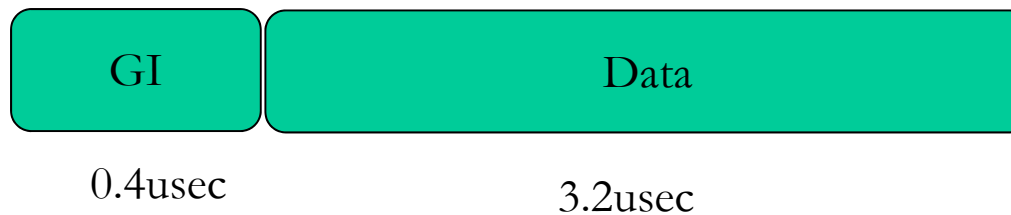
- New 20MHz spectral mask is the same as 11a, except that the floor at 30MHz is tightened from -40 dBr to -45dBr

56 tones (in 20MHz)



- Two additional data tones are added to each end of the spectrum (legacy has 52 tones)
- Increases the data rate of HT relative to legacy by ~10%

$\frac{1}{2}$ Guard Interval



- Standard OFDM symbol is 4 usec in length comprising of a 0.8 usec guard interval and 3.2 usec of data
- With $\frac{1}{2}$ GI mode, the GI is reduced to 0.4 usec, and the overall symbol length is 3.6 usec
- The data rate is increased by 12%
- The guard interval is used to protect against long delay spread and filtering
- This mode is less tolerant to delay spread and can only be used in short delay spread channels

MCS Set

One Spatial Stream

MCS Index	Modulation	R	20MHz Data rate (Mbps)		40MHz Data rate (Mbps)	
			800ns GI	400ns GI	800ns GI	400ns GI
0	BPSK	$\frac{1}{2}$	6.5	7.2	13.5	15.0
1	QPSK	$\frac{1}{2}$	13.0	14.4	27.0	30.0
2	QPSK	$\frac{3}{4}$	19.5	21.7	40.5	45.0
3	16-QAM	$\frac{1}{2}$	26.0	28.9	54.0	60.0
4	16-QAM	$\frac{3}{4}$	39.0	43.3	81.0	90.0
5	64-QAM	$\frac{2}{3}$	52.0	57.8	108.0	120.0
6	64-QAM	$\frac{3}{4}$	58.5	65.0	121.5	135.0
7	64-QAM	$\frac{5}{6}$	65.0	72.2	135.0	150.0

PHY bit rates

Two Spatial Streams

MCS Index	Modulation	R	20MHz Data rate (Mbps)		40MHz Data rate (Mbps)	
			800ns GI	400ns GI	800ns GI	400ns GI
8	BPSK	$\frac{1}{2}$	13.0	14.444	27.0	30.0
9	QPSK	$\frac{1}{2}$	26.0	28.889	54.0	60.0
10	QPSK	$\frac{3}{4}$	39.0	43.333	81.0	90.0
11	16-QAM	$\frac{1}{2}$	52.0	57.778	108.0	120.0
12	16-QAM	$\frac{3}{4}$	78.0	86.667	162.0	180.0
13	64-QAM	$\frac{2}{3}$	104.0	115.556	216.0	240.0
14	64-QAM	$\frac{3}{4}$	117.0	130.000	243.0	270.0
15	64-QAM	$\frac{5}{6}$	130.0	144.444	270.0	300.0

PHY bit rates

- A two antenna device with optional 40MHz mode and $\frac{1}{2}$ GI can achieve 300Mbps

Three Spatial Streams

MCS Index	Modulation	R	20MHz Data rate (Mbps)		40MHz Data rate (Mbps)	
			800ns GI	400ns GI	800ns GI	400ns GI
16	BPSK	$\frac{1}{2}$	19.5	21.7	40.5	45.0
17	QPSK	$\frac{1}{2}$	39.0	43.3	81.0	90.0
18	QPSK	$\frac{3}{4}$	58.5	65.0	121.5	135.0
19	16-QAM	$\frac{1}{2}$	78.0	86.7	162.0	180.0
20	16-QAM	$\frac{3}{4}$	117.0	130.0	243.0	270.0
21	64-QAM	$\frac{2}{3}$	156.0	173.3	324.0	360.0
22	64-QAM	$\frac{3}{4}$	175.5	195.0	364.5	405.0
23	64-QAM	$\frac{5}{6}$	195.0	216.7	405.0	450.0

PHY bit rates

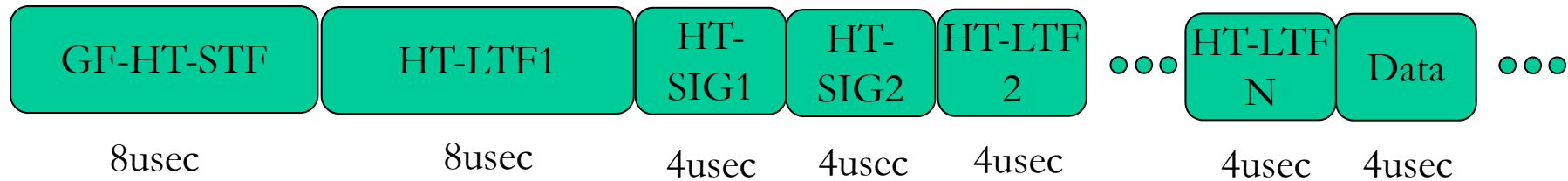
Four Spatial Streams

MCS Index	Modulation	R	20MHz Data rate (Mbps)		40MHz Data rate (Mbps)	
			800ns GI	400ns GI	800ns GI	400ns GI
24	BPSK	$\frac{1}{2}$	26.0	28.9	54.0	60.0
25	QPSK	$\frac{1}{2}$	52.0	57.8	108.0	120.0
26	QPSK	$\frac{3}{4}$	78.0	86.7	162.0	180.0
27	16-QAM	$\frac{1}{2}$	104.0	115.6	216.0	240.0
28	16-QAM	$\frac{3}{4}$	156.0	173.3	324.0	360.0
29	64-QAM	$\frac{2}{3}$	208.0	231.1	432.0	480.0
30	64-QAM	$\frac{3}{4}$	234.0	260.0	486.0	540.0
31	64-QAM	$\frac{5}{6}$	260.0	288.9	540.0	600.0

PHY bit rates

- A four antenna device with 40MHz mode and $\frac{1}{2}$ GI can achieve 600Mbps

Green field Preamble



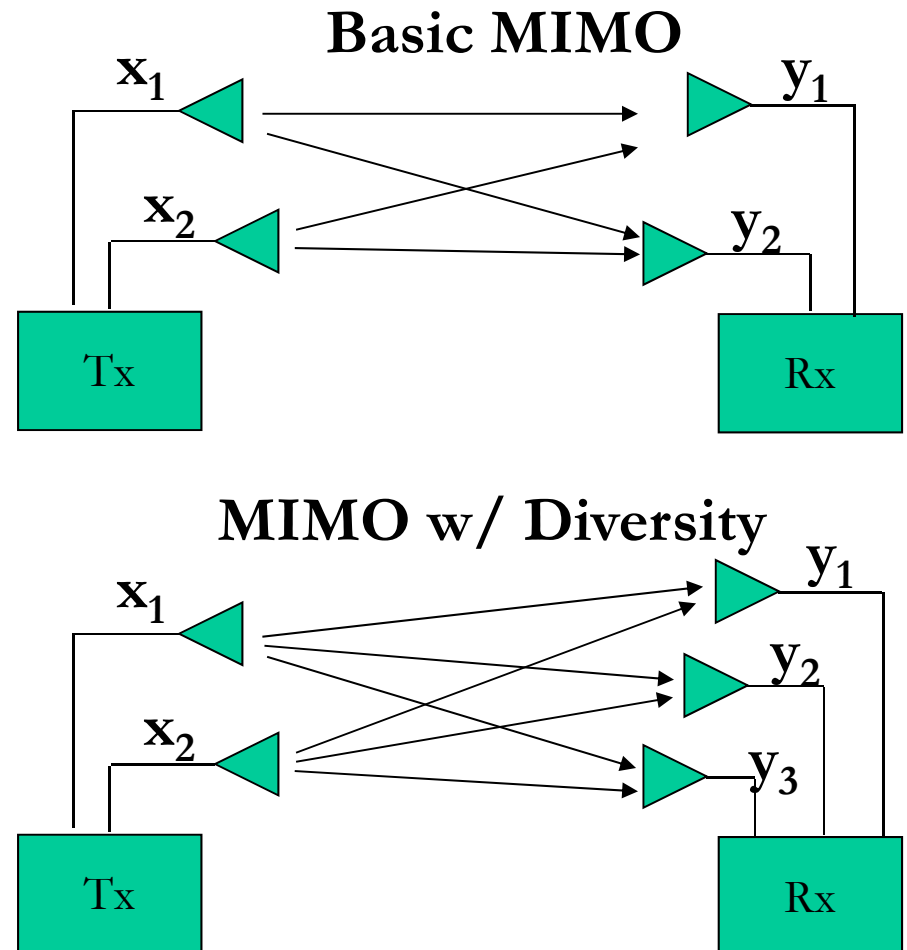
- MM preamble trades throughput efficiency for interoperability between HT and legacy devices
- Green field preamble (GF) provides better efficiency than MM by eliminating the legacy portion of the preamble reducing the preamble by 12usec
 - GF can be used when no legacy devices are associated with the AP
 - GF can also be used during MAC protected transmission period
- Fields:
 - HT-STF: same as L-STF, used for acquisition and AGC setting
 - HT-LTF1: same as HT-LTF in MM, but repeated twice to allow for frequency and timing estimation
 - HT-SIG1 & 2: same as in MM
 - HT-LTF2 – N: same as in MM
 - All fields use the HT cyclic shifts

Robust Performance

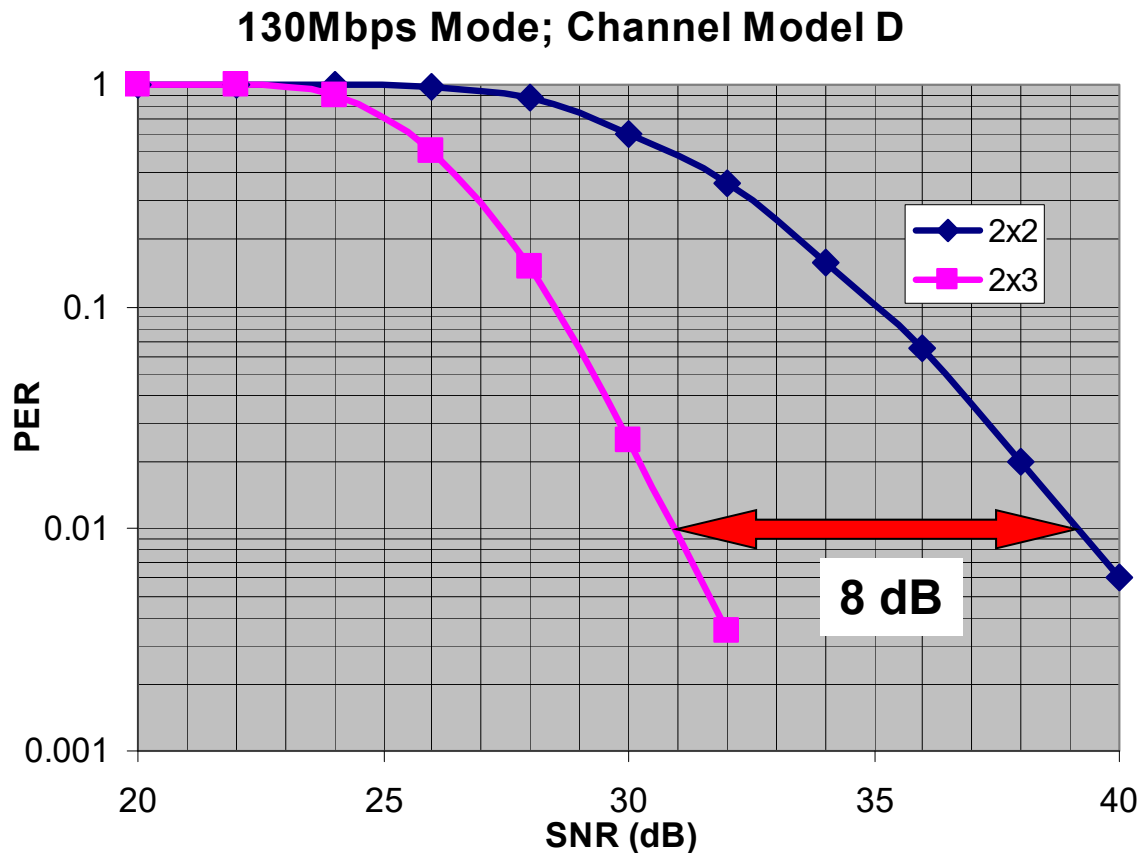
- Receive Diversity
- Transmit Beamforming
- STBC
- LDPC

Receive Diversity

- A basic MIMO/SDM system with a linear receiver requires at least as many receive antennas as transmit data streams
- Extra receive antennas provide receive diversity gain



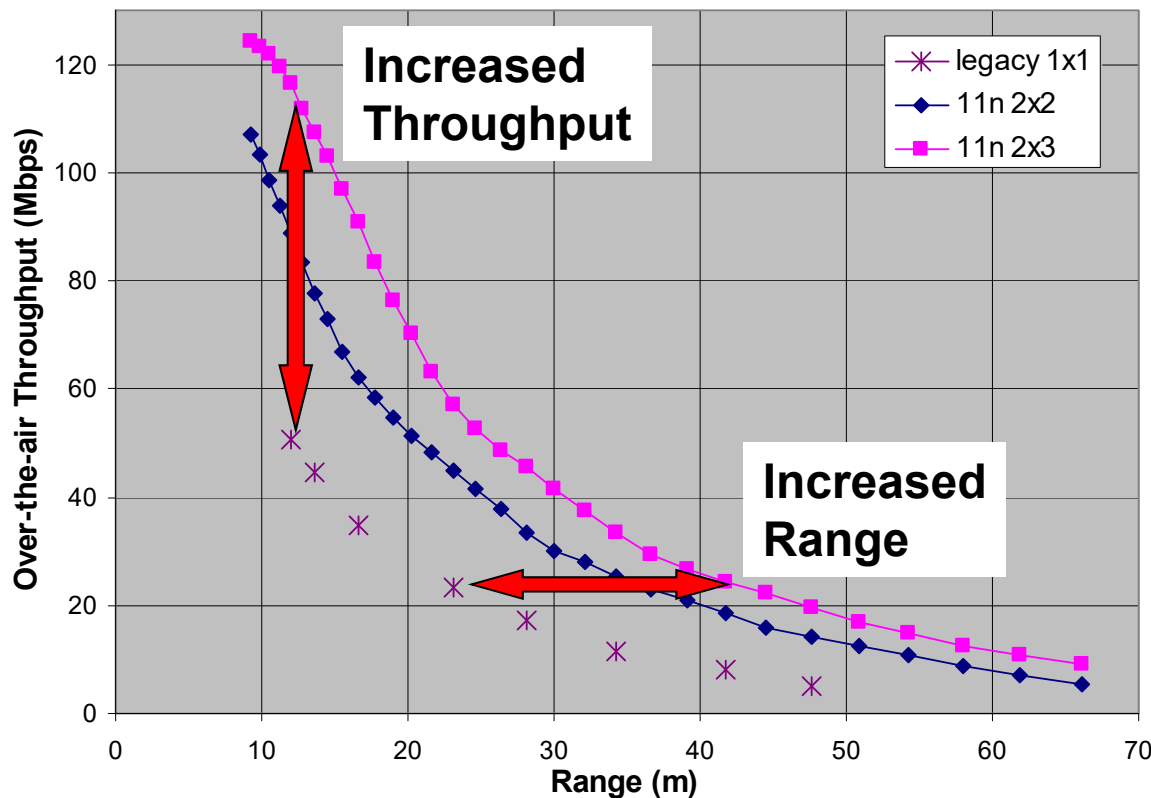
Improved Robustness with Receive Diversity



- With a 2x2 system, the required SNR may be beyond transmitter or receiver capability
- Additional receive antennas reduce required SNR
- Receive diversity enables signal reception of the peak two stream data rate at a feasible SNR

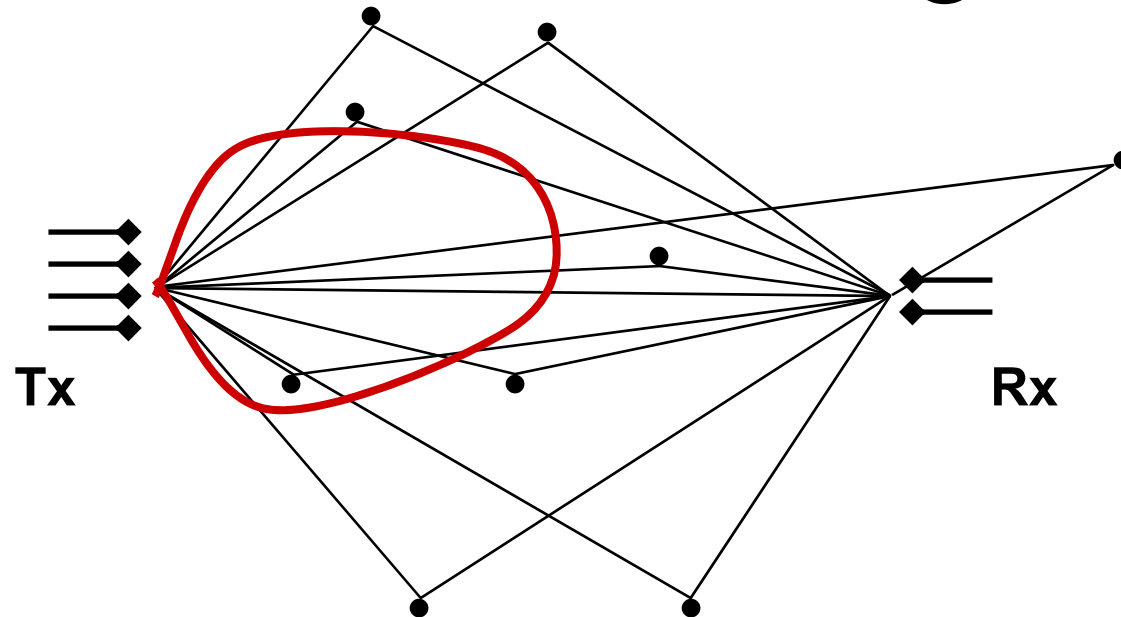
MIMO Performance Improvement with Receive Diversity

20MHz; Channel Model D



- Added robustness from receive diversity enables longer ranges at a given throughput
- At a given range, add robustness achieves higher throughputs
- MIMO increases peak data rates with additional data streams
- At lower data rates, MIMO systems may rate adapt to single stream modes, equivalent to 1x2 receive diversity, for added robustness and increased range

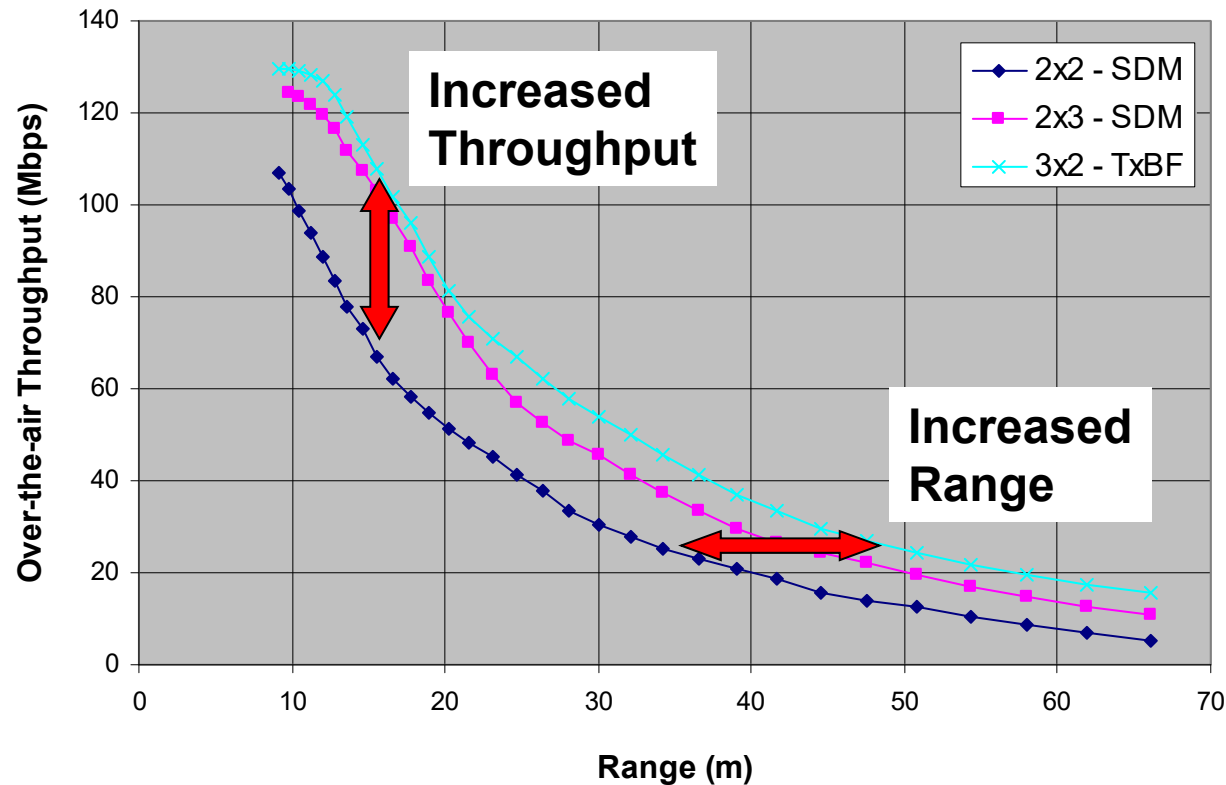
Tx Beamforming



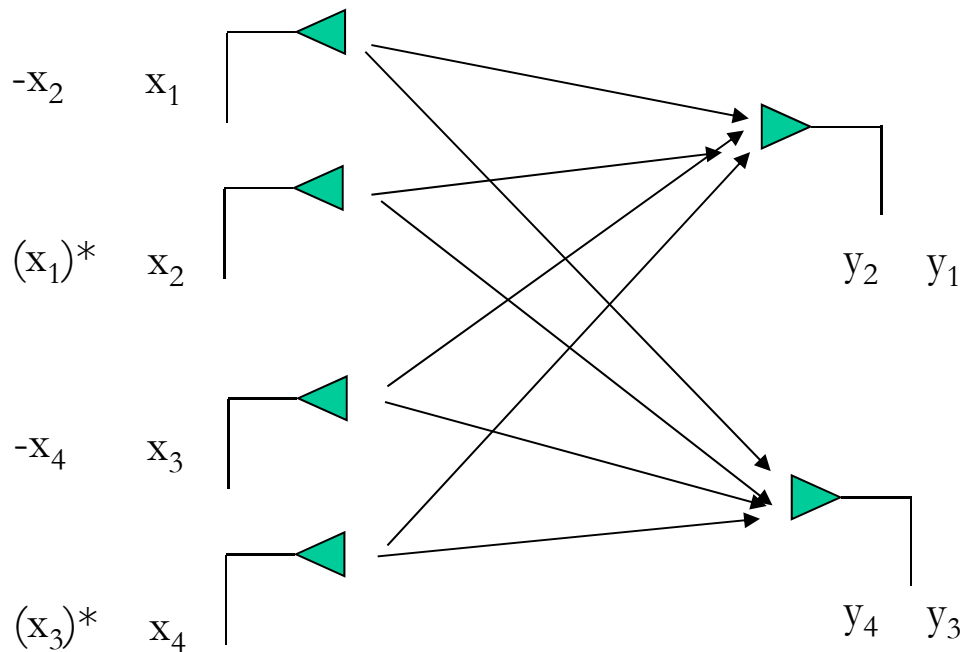
- Phase and magnitude of transmitter signals are dynamically adjusted to maximize combined power received through the receive antennas
- Beamforming is along an aggregation of multiple propagation paths in the environment
- For frequency selective fading, different antenna weights are applied on the individual tone matched to the channel

Improved Performance with Transmit Beamforming

20MHz; Channel Model D



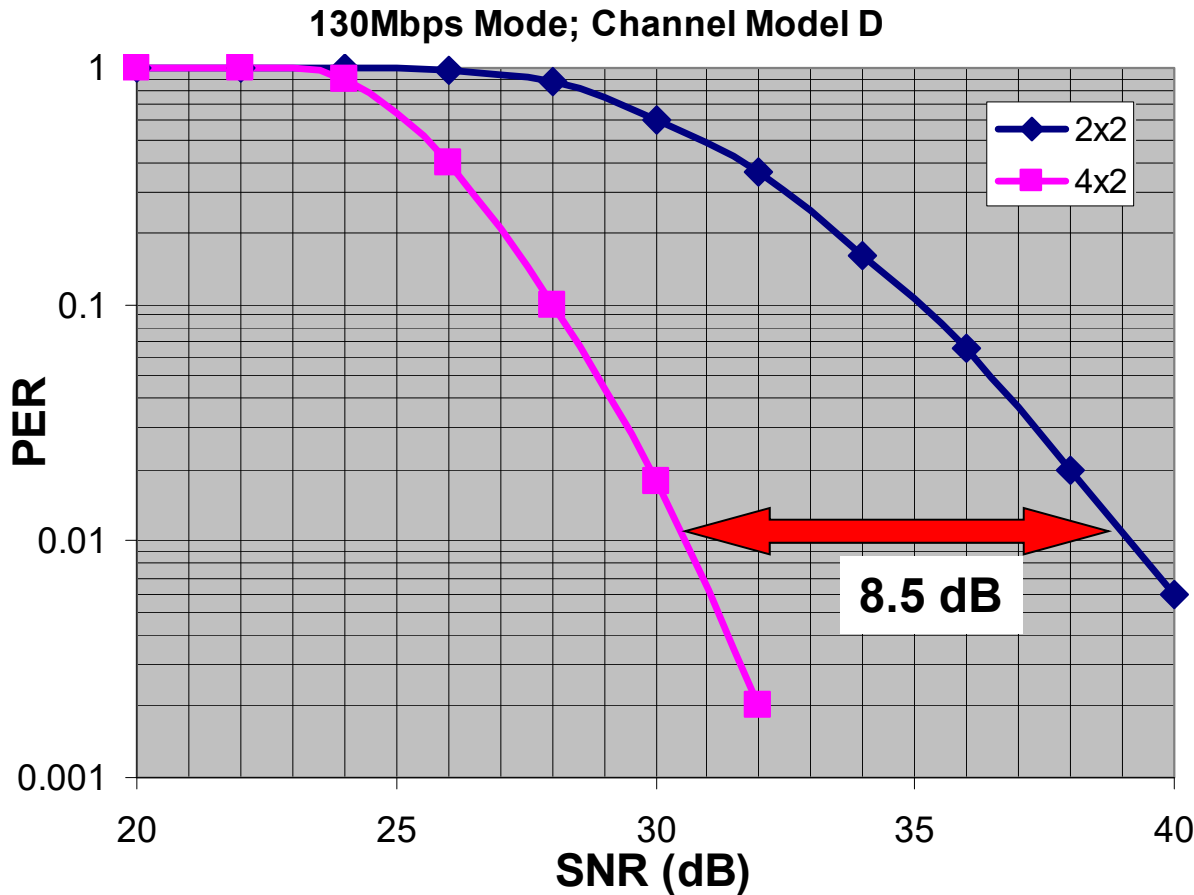
Space-Time Block Coding (STBC)



- Space-time block coding combines signals over two OFDM symbols between multiple antennas for transmit diversity gain
- This provides gain equivalent to received diversity
- However, STBC will have a transmit power penalty with respect to receive diversity
- Configurations include 2x1, 3x2, 4x2, 4x3

Improved Robustness with STBC

Transmit Diversity

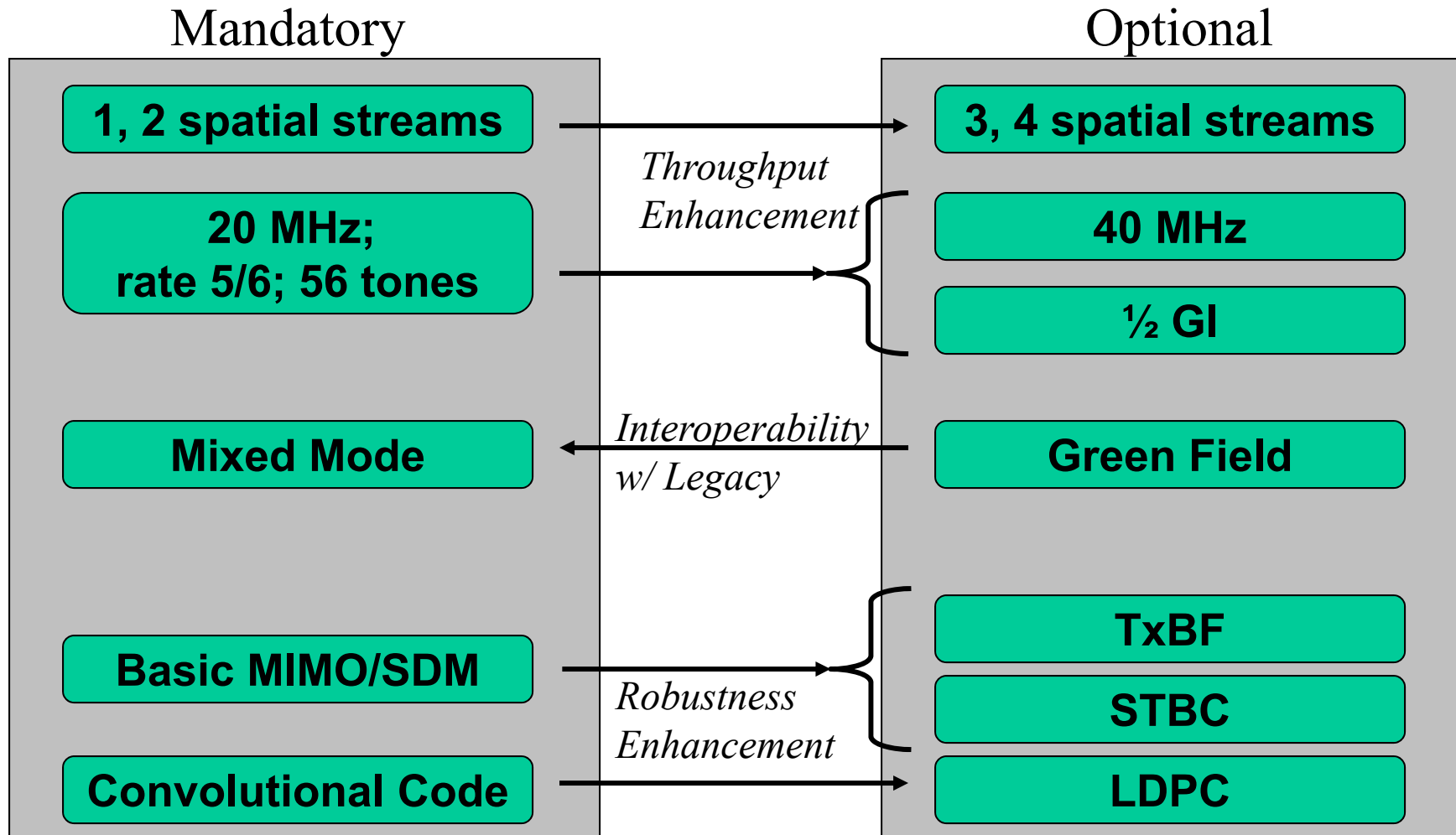


- Transmit diversity gain from STBC enables high data rates at a reasonable SNR received by a device with few receive antennas
- This technique benefits client devices which are size and power constrained

Low Density Parity Check (LDPC) Codes

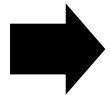
- Advanced, Capacity-Approaching Forward Error Correction scheme
- Iteratively Decoded (like Turbo Codes)
- Binary Block Codes
- Constituent Codes are simple Parity Check relationships
- Originally developed in 1962 (Bob Gallager's PhD Thesis)
 - Rediscovered when Turbo Codes became popular
- ~2-3 dB improvement over current convolutional codes

Mandatory vs. Optional Features



Outline

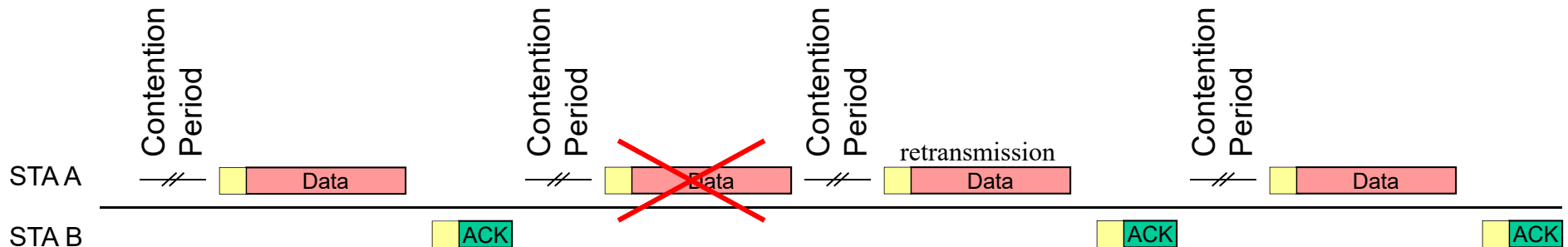
- Introduction
- PHY
 - MIMO/SDM basics
 - 11n PHY design criteria



MAC

- Aggregation and Block Ack
- Interoperability / Coexistence
- Advanced Features
- Summary

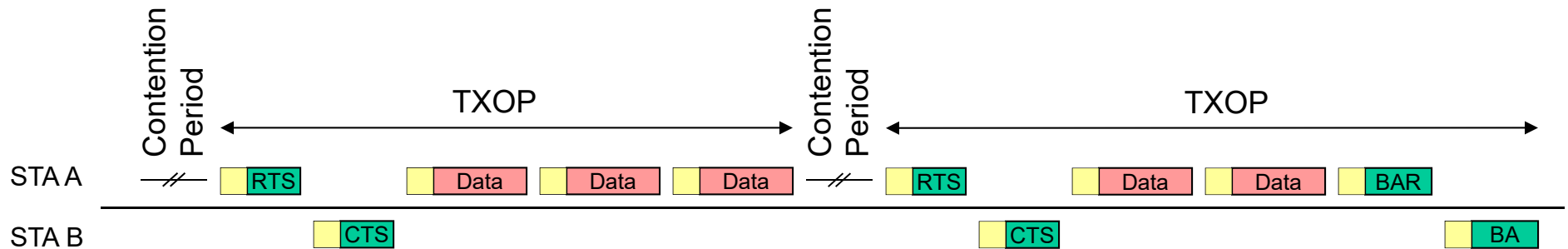
The 802.11 CSMA/CA MAC



- Contention Period: Each station selects random back-off, first station to zero gets to transmit
- STA A sends data, STA B responds with ACK if correctly received
- If STA A does not receive ACK it assumes packet loss due to collision or receive error and retransmits
- High overhead: contention period, preamble, radio turnaround and ack per data packet

 = PHY Preamble

802.11e: Enhanced Efficiency

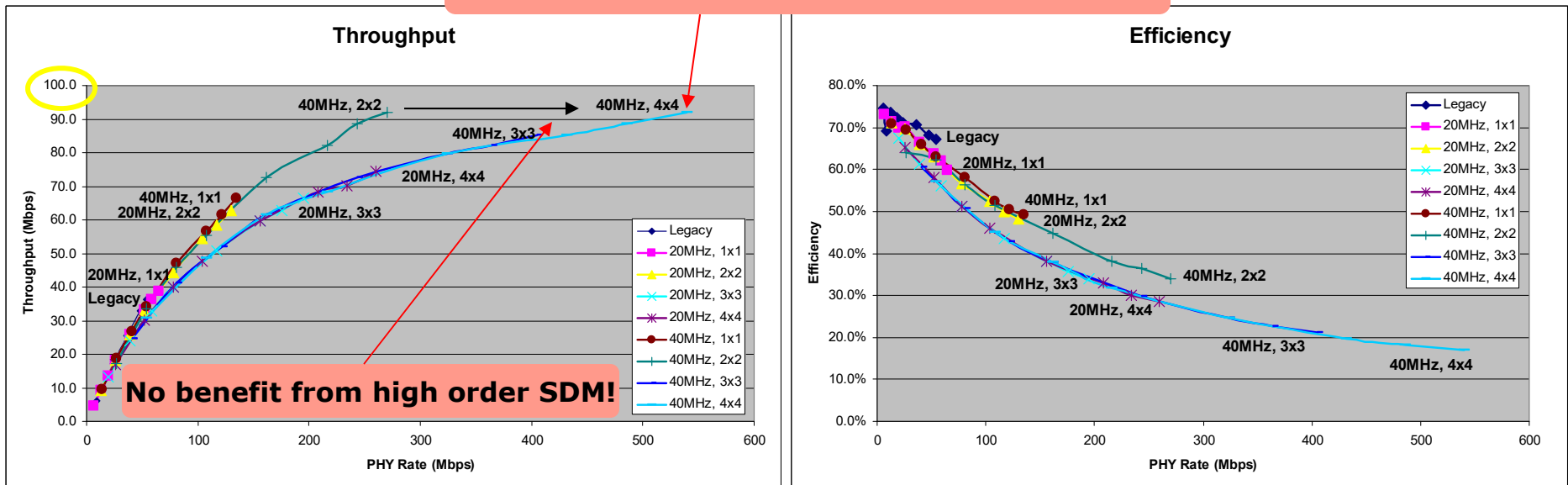


- TXOP: Bounded period during which data of a specific class may be transmitted and control frame responses received
- RTS/CTS exchange: collision detect and NAV protection
- Bursting: Back-to-back data transmission with SIFS spacing
- BAR/BA: Immediate block ack exchange, not necessarily in every TXOP

 = PHY Preamble

802.11e Wasn't Enough

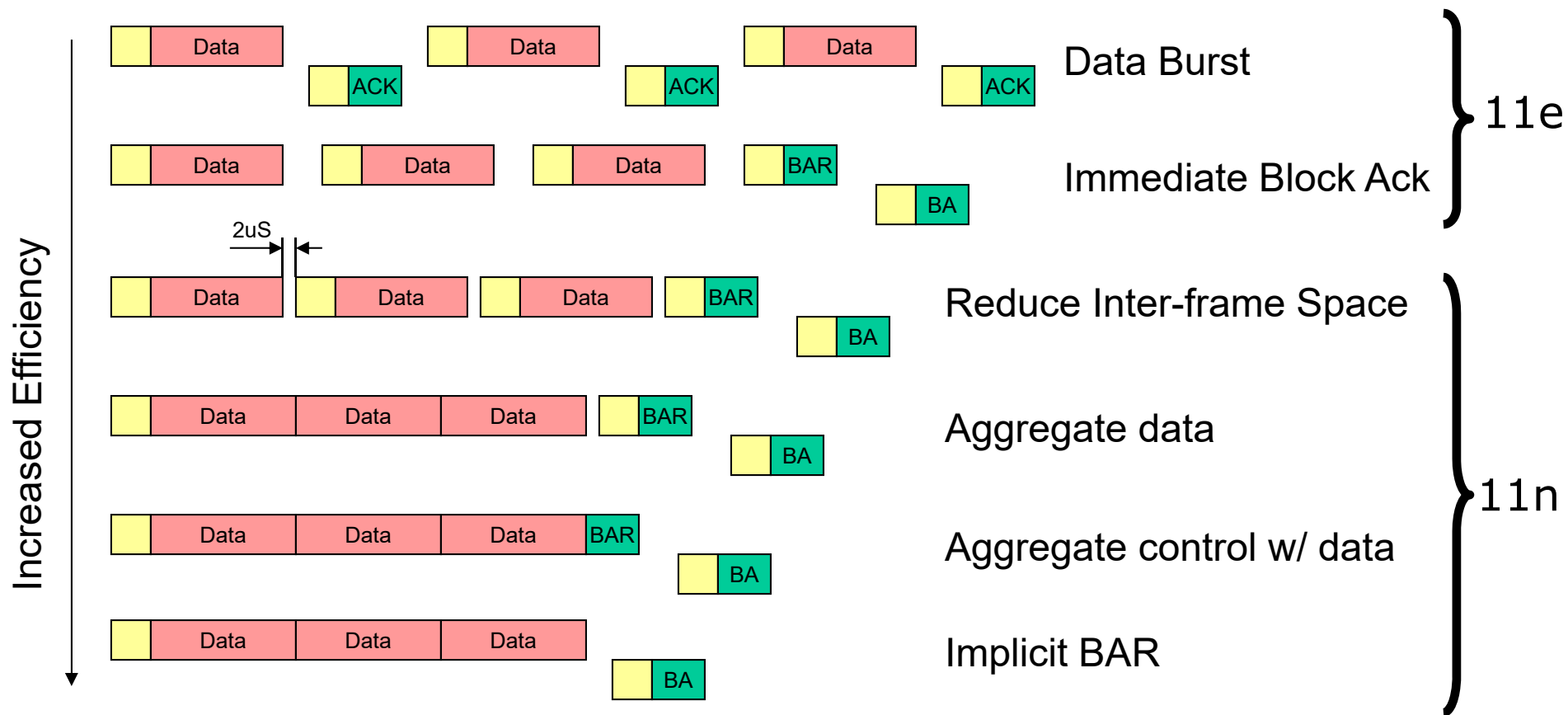
Can't reach 100Mbps even with 540Mbps PHY!



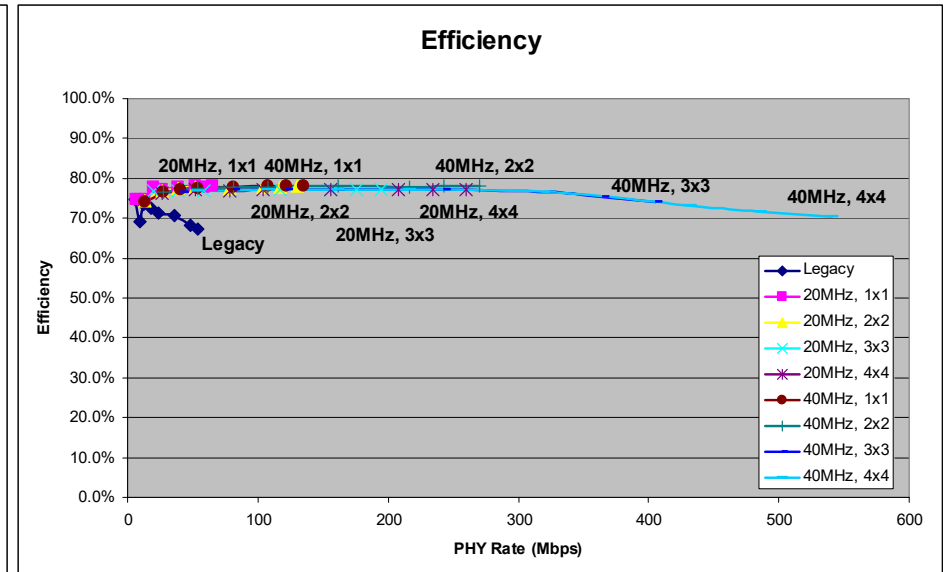
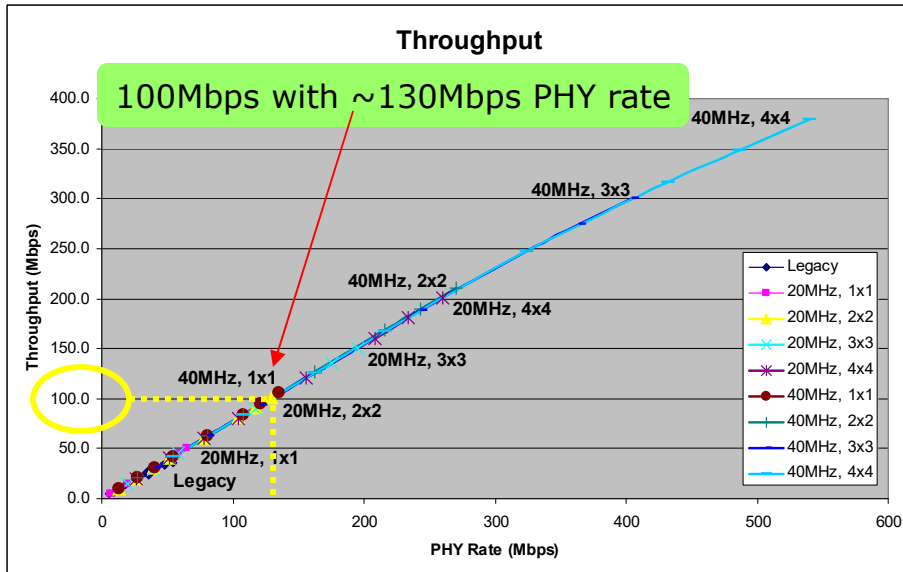
802.11e bursting with 3ms TXOP, Immediate BA, 10% PER

- 802.11e is relatively efficient with legacy (802.11a/g) PHY: 65%-75%
- But... At higher PHY rates efficiency drops considerably

Further TXOP Sequence Enhancements



802.11n: Enhanced Efficiency



802.11n aggregation with 3ms TXOP, enhanced BA, 10% PER

- Efficiency better than 802.11e, even at legacy rates (20MHz, 1x1)
- 70%-80% efficient across all PHY rates

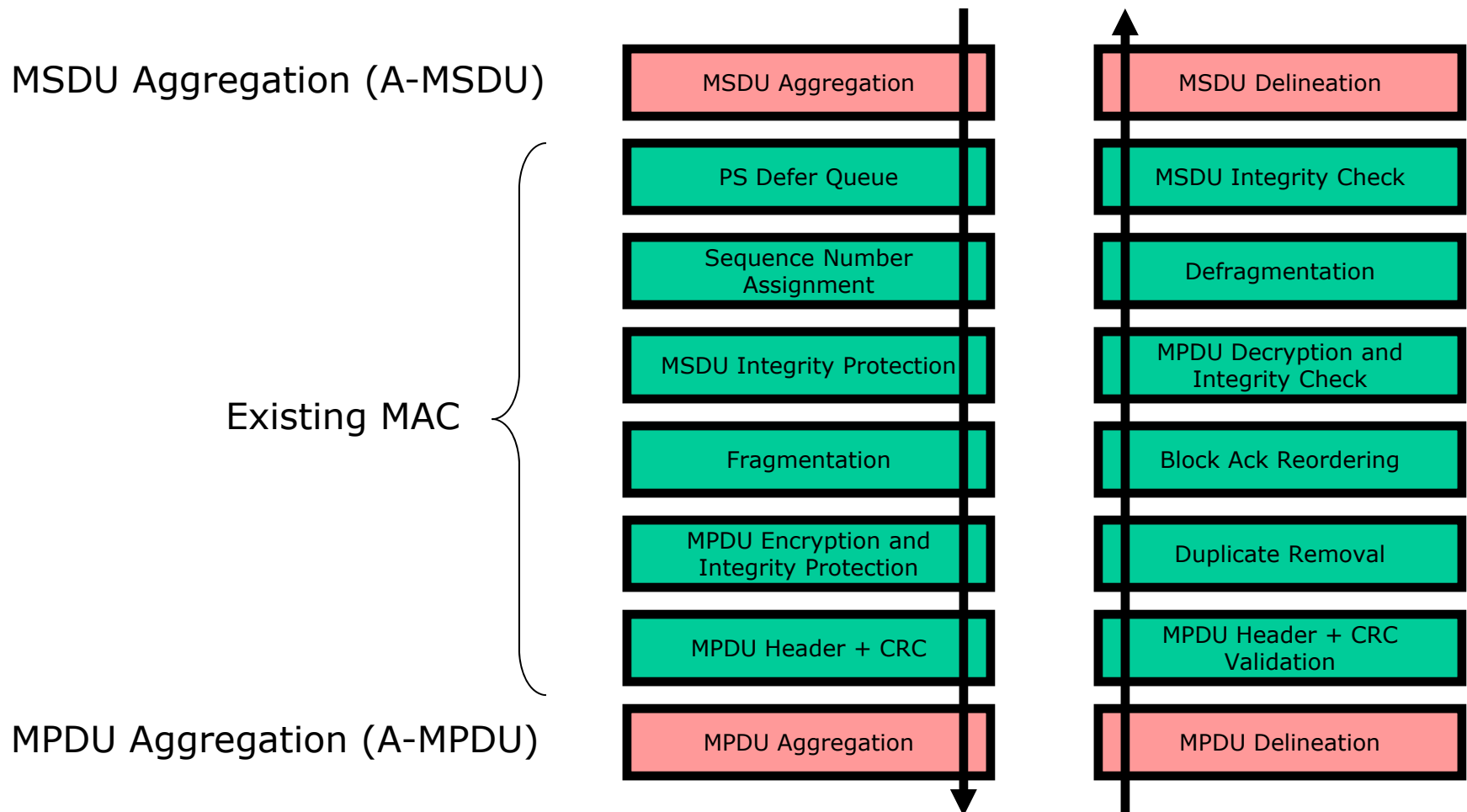
Additional Problems

- Legacy Interoperability
 - Accommodating legacy stations on 40MHz AP
- Legacy protection
 - New HT frame formats
 - RIFS bursting
- 40MHz operation with nearby 20MHz BSS

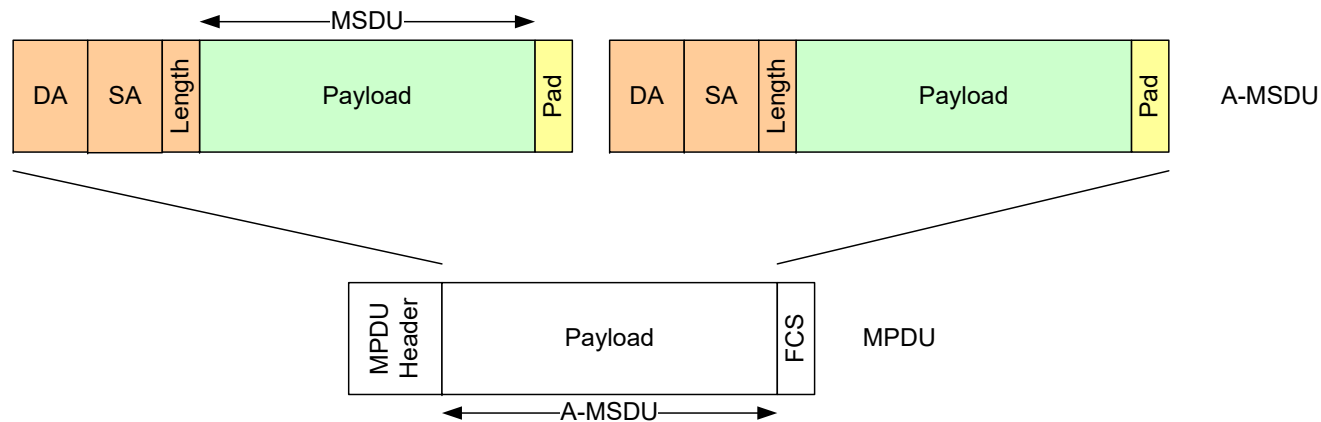
Outline

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Aggregation: Two New Layers

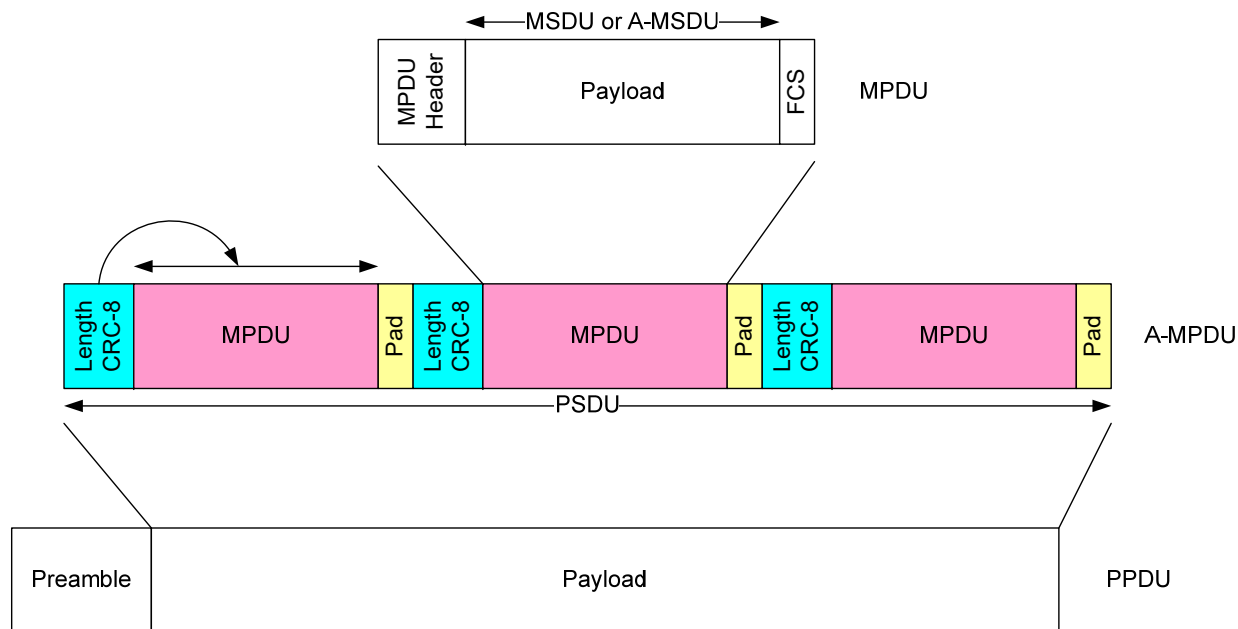


MSDU Aggregation



- MSDUs of the same TID can be aggregated
- MSDUs with differing source/destination address can be aggregated
- Maximum A-MSDU length
 - 3839 bytes (mandatory)
 - 7935 bytes (optional)

MPDU Aggregation



- PHY has no knowledge of MPDU boundaries
- Portions of the transmission can be corrupted without losing all MPDUs
- Resync is possible on with corrupt delimiter by scanning forward for next valid delimiter

A-MSDU Vs A-MPDU

	A-MSDU	A-MPDU
Advantages	Software implementation Can be used with normal ack ➔ No block ack setup ➔ Easier link adaptation Can be used with legacy preamble	Efficient TXOP utilization Lower retransmission overhead Scales well with PHY rate
Disadvantages	Inefficient TXOP utilization ➔ Sequencer working with 4KB or 8KB chunks Higher retransmission overhead Doesn't scale to high PHY rates	Hardware implementation Block ack required MAC header per frame

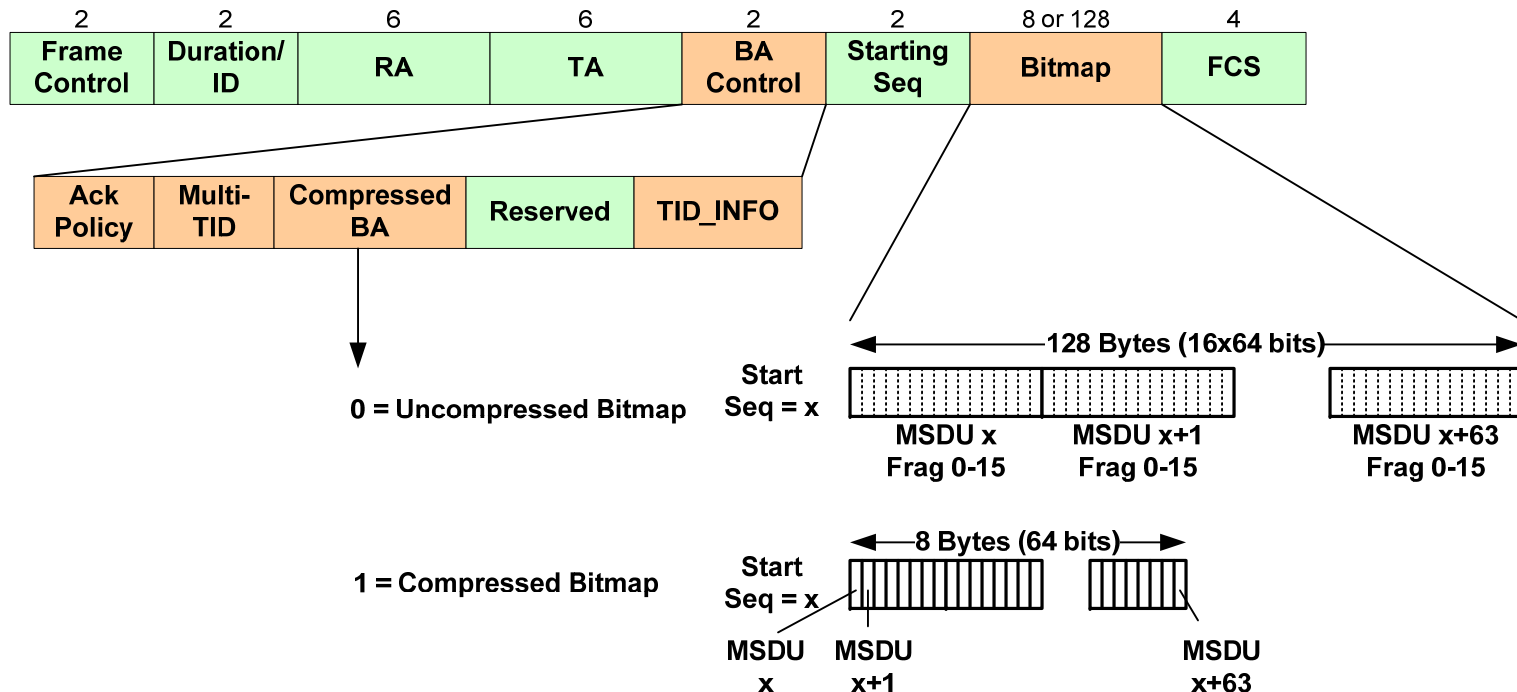
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Block Ack Enhancements

- Compressed BA: Defines a compressed variant of the 802.11e BA MPDU
- Implicit BAR: The originator may omit the inclusion of a BAR frame in an aggregated frame and set QoS ack policy to “Normal Ack”
- Partial State Immediate BA: Reduces recipient memory requirements
- “No Ack” Delayed BA: Reduces delayed BA overhead

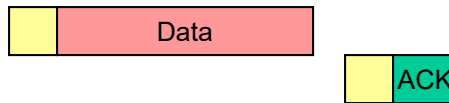
Compressed BA



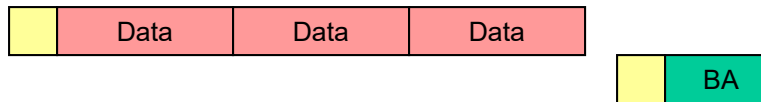
- At higher data rates, fragmentation is no longer effective
- Compressed BA eliminates fragment bitmap, creating a shorter frame

Implicit BAR

Non-aggregate with “normal ack” policy on QoS Data frame solicits ACK



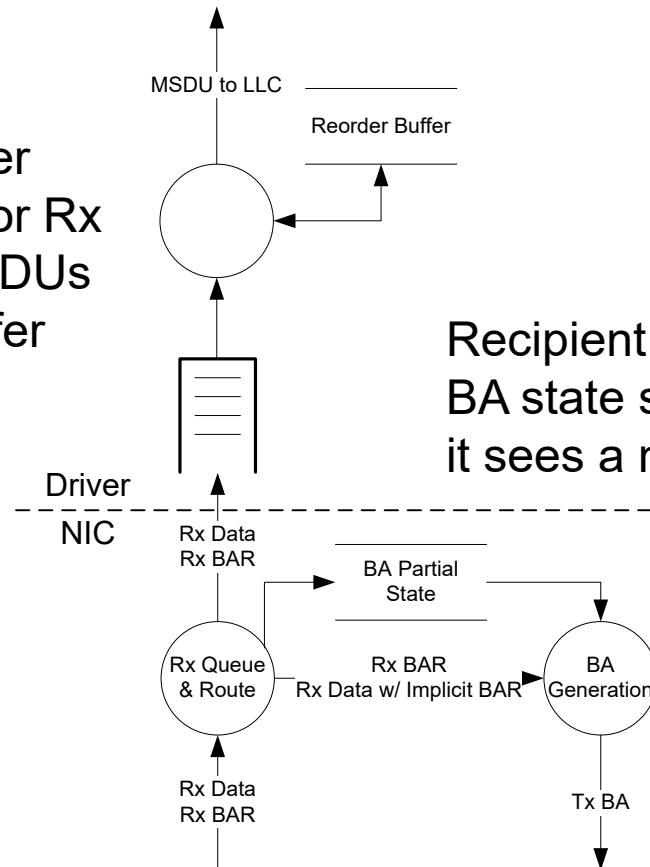
Aggregate with “normal ack” policy on QoS Data frames solicits BA



- Implicit BAR = Aggregate + “normal ack” policy on QoS Data frames
- BAR still needed to shift recipient window or to solicit BA if not received after implicit BAR

Partial State BA: Recipient Model

Rx Data with sequence number outside window or Rx BAR pushes MSDUs from reorder buffer



Recipient may reuse BA state storage when it sees a new TA

Recipient responds with immediate BA to Rx Data w/ implicit BAR or Rx BAR

Recipient Behavior

- Keep one set of BA state for current TA
- The partial state may be reset when an MPDU is received with a different TA
- When BAR MPDU is received generate an immediate BA containing partial state
- When Data MPDU with implicit BAR is received generate an immediate BA containing partial state

Originator Behavior

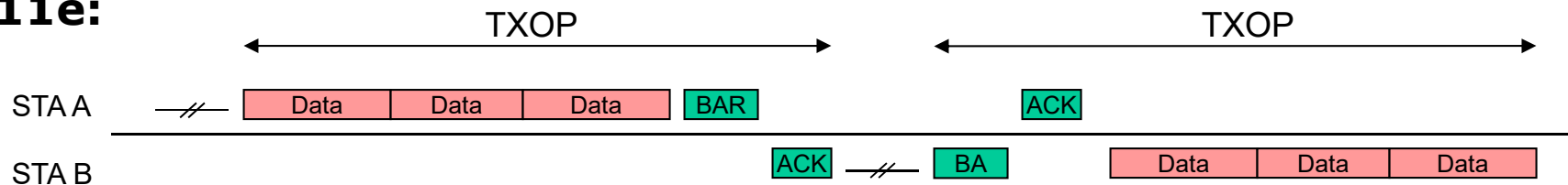
- Originator should attempt to retrieve state in current TXOP
 - State may not be available in a subsequent TXOP necessitating a full retransmit
 - On missing BA,
 - Transmit BAR or more data with implicit BAR in current TXOP
 - If cannot get state in current TXOP then regain channel access and either
 - Retransmit data (assume state lost)
- Or
- Send more data w/ implicit BAR or BAR (good chance that state will still be available)

Partial State BA

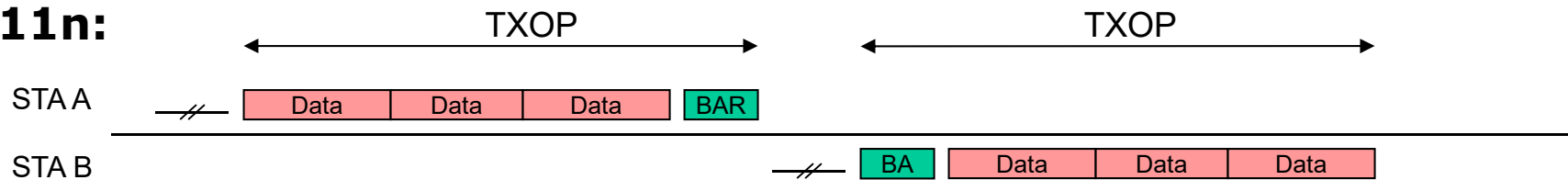
- Reduces memory requirement in recipient for immediate BA implementation
- ➔ On-chip BA state memory is reused for multiple peers: scales to support large number of peers
- ➔ Small modification to 11e BA and compatible with full state BA implementation

No Ack Delayed BA

11e:



11n:



- 802.11e Delayed BA allows BA response to BAR to be sent in a later TXOP
 - However, BAR and BA are acked
 - No Ack Delayed BA allows for a delayed BA response without the overhead of the ACK frame
- ➔ BA can be efficiently aggregated with data in separate TXOP

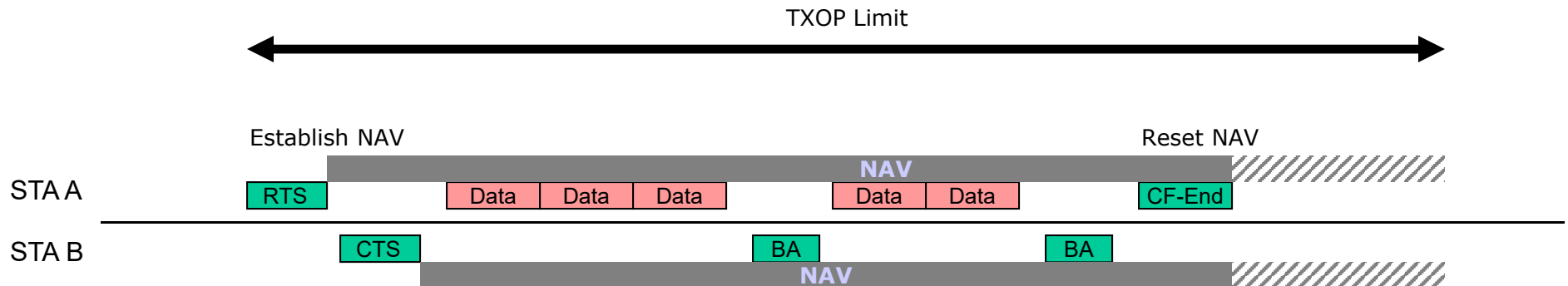
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Interoperability/Coexistence

- Long NAV Protection
- L-SIG TXOP Protection
- Greenfield & RIFS operation
- Rules for response MPDU / EIFS
- 20MHz/40MHz Phased Coexistence Operation
- Channel width Management

Long NAV Protection

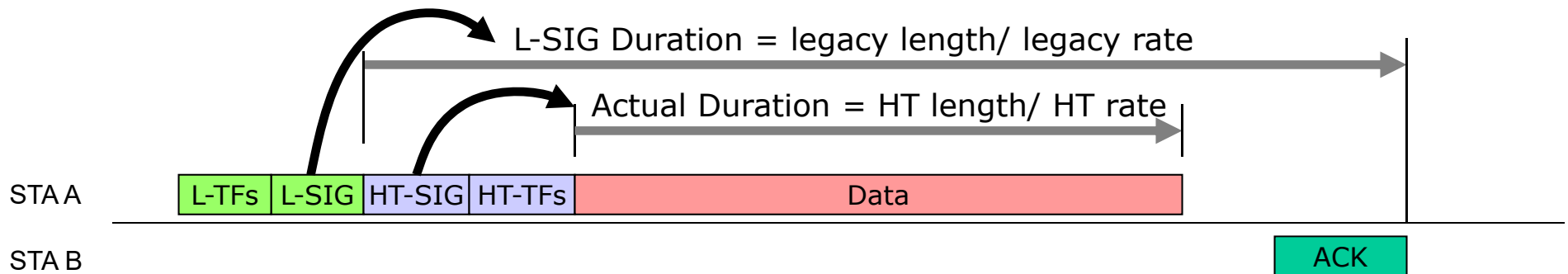


- Allows for NAV protection when the exact duration is not known at the time RTS is sent, for example
 - Retries of failed transmissions
 - Adjusting transmit parameters during TXOP
 - Sending MSDUs that arrive during TXOP
- NAV is typically set to TXOP Limit in RTS and echoed in CTS
- If TXOP is not completely used, then the initiator sends a CF-End to reset the NAV

L-SIG TXOP Protection

- Optional Feature
- Establishes PHY-layer protection using HT Mixed mode (MM) PPDU
- AP indication in beacon if all STA in its BSS support it
- Duration implied by legacy SF length value in MM PPDU conveys a duration $>$ current PPDU
- Value protected also indicated in MAC duration field and all PPDU (except RTS) locate the same protection end point
- RTS protection extends to end of CTS to avoid unfairness problems when comparing CCA (legacy) to NAV (HT)
- Not used with LongNAV rules

L-SIG TXOP Protection



- Use the L-SIG length/rate to indicate a duration longer than the actual frame duration
- Legacy station will defer for the indicated duration assuming it is receiving a long frame
- HT station will recognize HT frame and use L-SIG length/rate to set its NAV
- Max duration: $2304\text{B}/6\text{Mbps} = \sim 3\text{ms}$

RIFS Protection

- Shorter gap (2us) than SIFS between PPDUs sent by the same TA
- AP controls use of RIFS in BSS through “RIFS Mode” bit in Additional HT Info Field
 - RIFS not permitted when there are legacy APSD devices. These may wake and transmit frames during MM RIFS burst
 - Legacy devices may not be able to handle RIFS separation
- Any RIFS sequence requires prior protection (MAC or L-SIG) when legacy devices are associated (signalled in “Operating Mode” field).

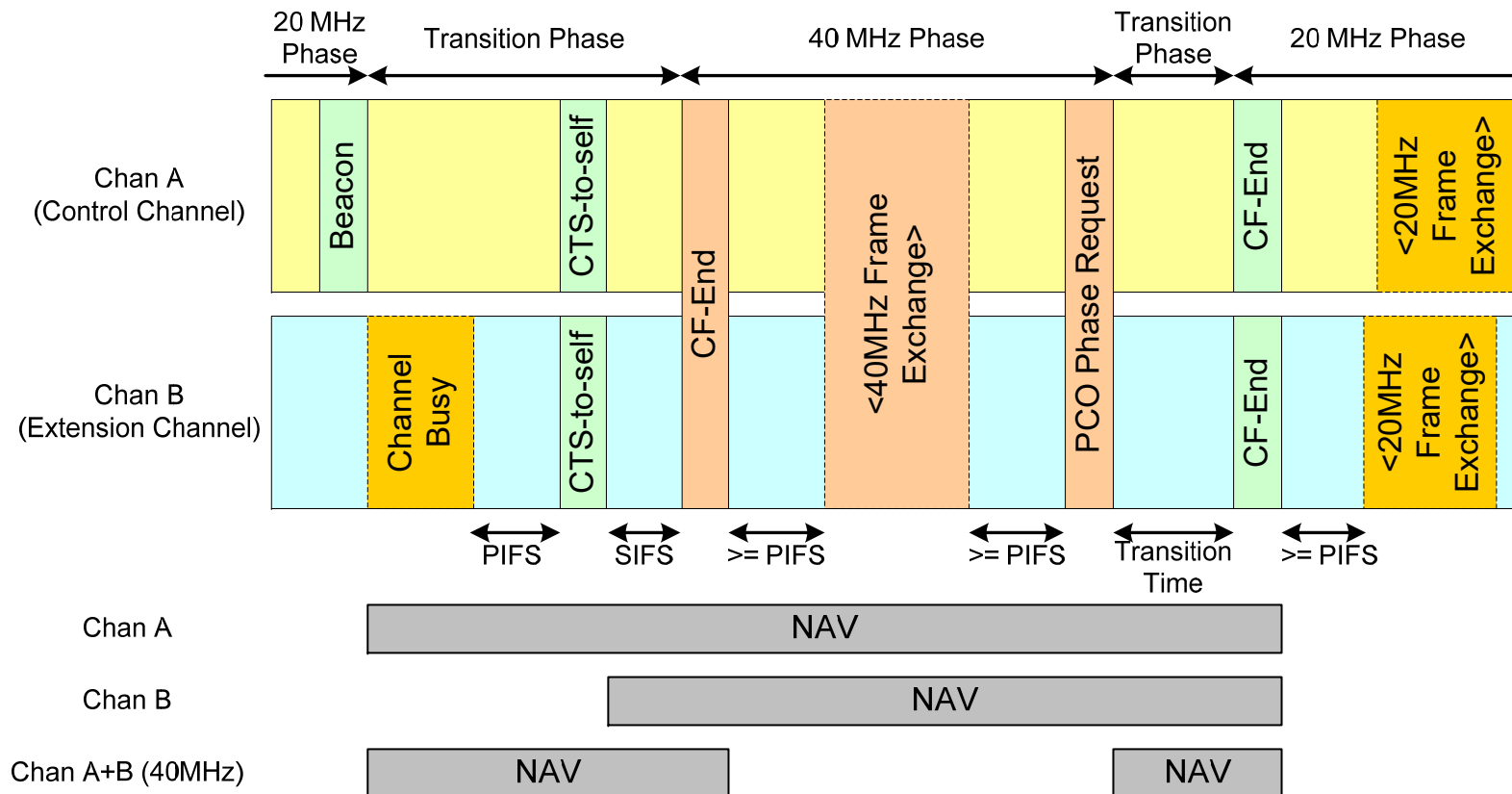
Greenfield Protection

- Ability to receive Green Field PPDU types is an option – signalled in HT Capabilities
- Shortens PHY overhead, but does not support legacy devices or L-SIG protection
- STA shall protect any sequence containing GF PPDU using prior MAC or L-SIG protection if there are legacy devices or non-GF devices present.
 - Such conditions signalled by the AP

20/40MHz Operational Modes

- 20/40MHz Mode
 - BSS occupies two adjacent 20MHz channels
 - 40MHz HT stations may associate
 - 20MHz HT and non-HT stations associate on primary 20MHz channel
 - Assume that there are no nearby BSSs on secondary 20MHz channel
- 20MHz Mode
 - BSS occupies a 20MHz channel
 - All stations (HT and non-HT) operate in 20MHz mode
- PCO (Phased Coexistence Operation) Mode
 - Alternating 20MHz and 40MHz phases of operation
 - May be nearby BSSs on secondary channel
 - Protection mechanism used to ensure both channels are clear during 40MHz phase

PCO Operation



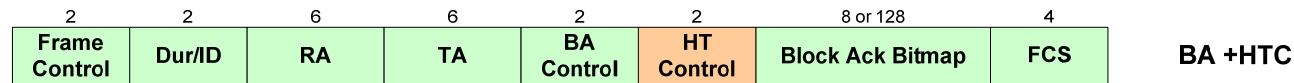
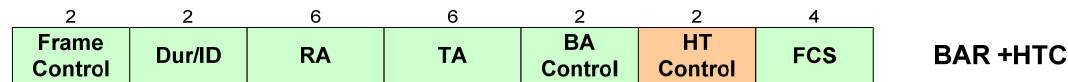
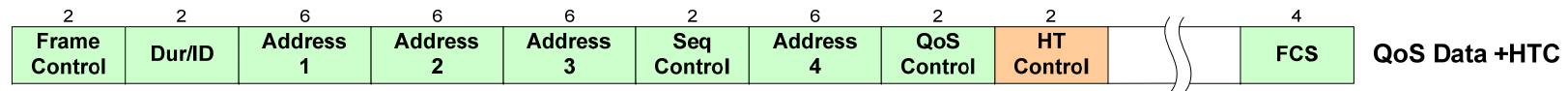
Channel Width Management

- AP controls permitted channel width of the BSS statically (non-PCO) or dynamically (PCO)
- STA can provide a recommendation to its peer to transmit to it using 20MHz even when it is in a 20/40 mode, for example, due to interference in its locality on the extension channel
- Uses “Set recommended transmission channel width” management action frame for this purpose
- There is an issue with 25MHz spacing in 2.4GHz band

Outline

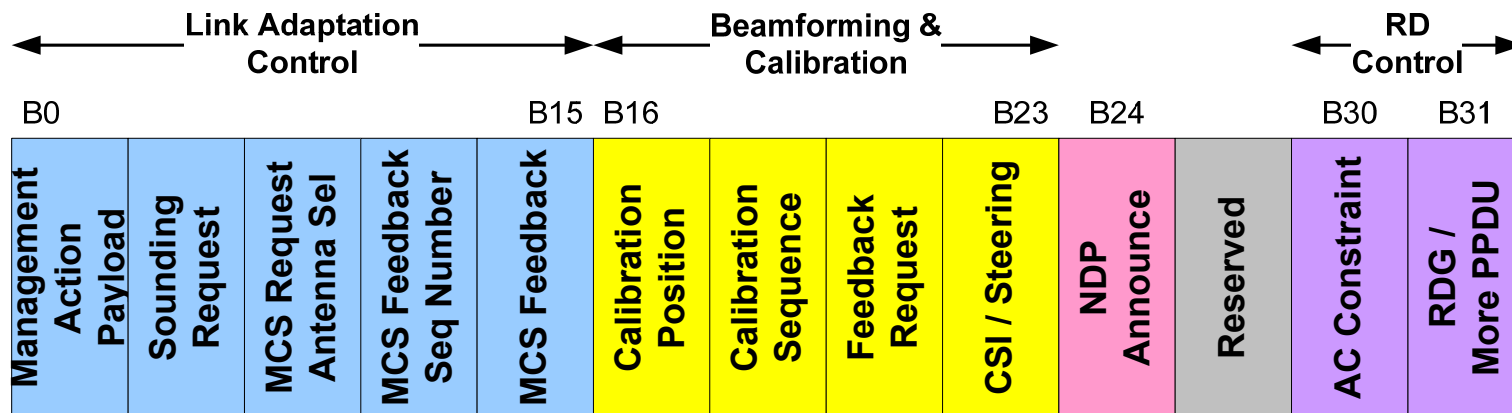
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HT Control Field



- New MAC header field: High Throughput Control (+HTC)
- Presence indicated by Order bit in Frame Control

HT Control Field: Format



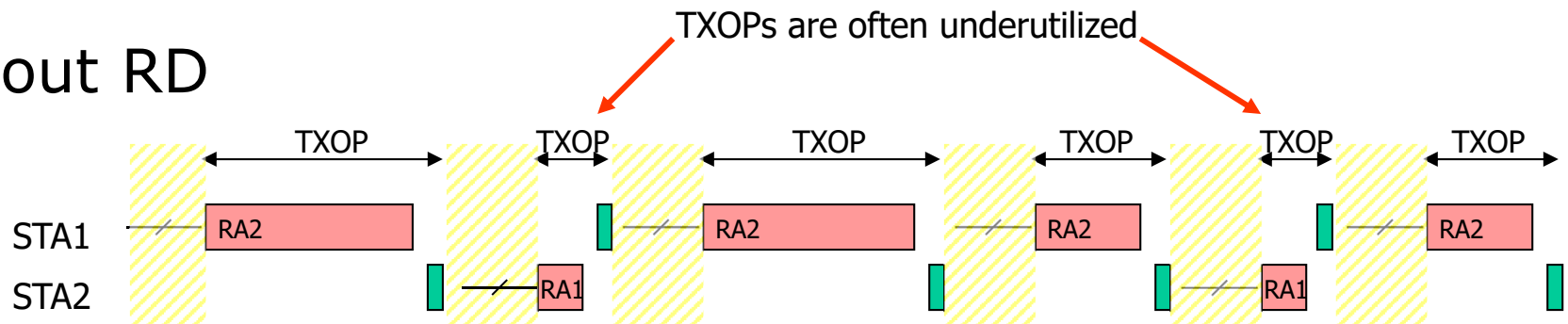
- Supports advanced features
 - Reverse direction protocol
 - Fast link adaptation
 - Beamforming control

Reverse Direction Protocol

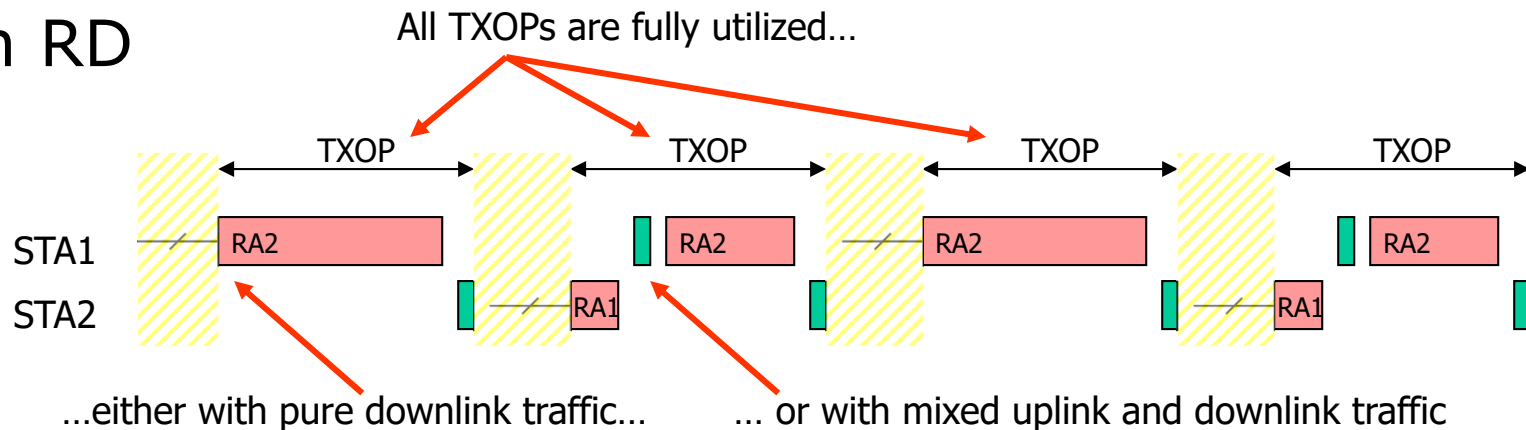
- Allows a STA to share its TXOP with another STA
 - Significantly reduces the number of channel access attempts for typical traffic patterns
 - Some benefit from aggregating BA and Data together
- Signalled by:
 - Duration/ID field, which carries the remaining duration of the TXOP
 - HT control Field, which carries: RDG / More PPDU, AC constraint
 - QoS Control field, which carries TID of traffic allowed in this RD

Reverse Direction Protocol

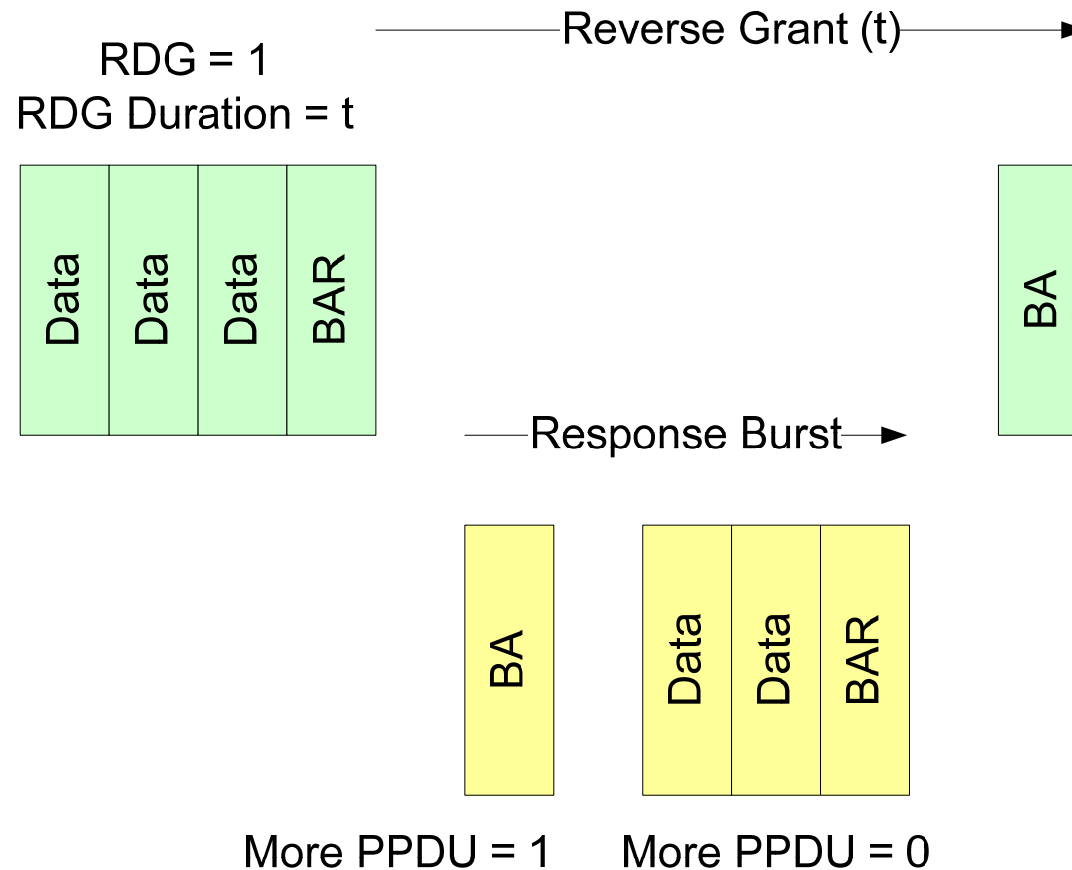
Without RD



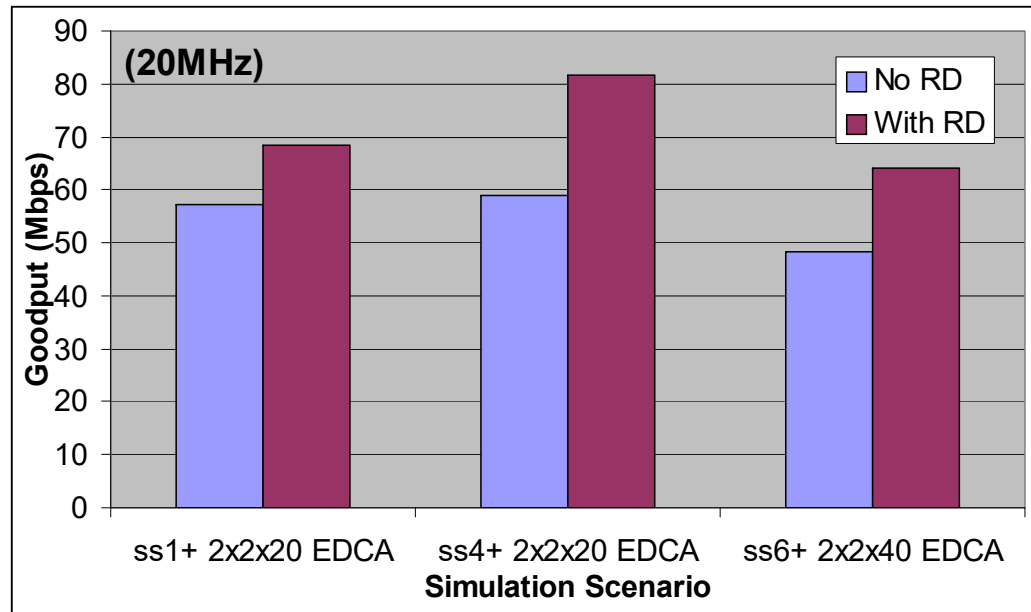
With RD



RD Example Exchange

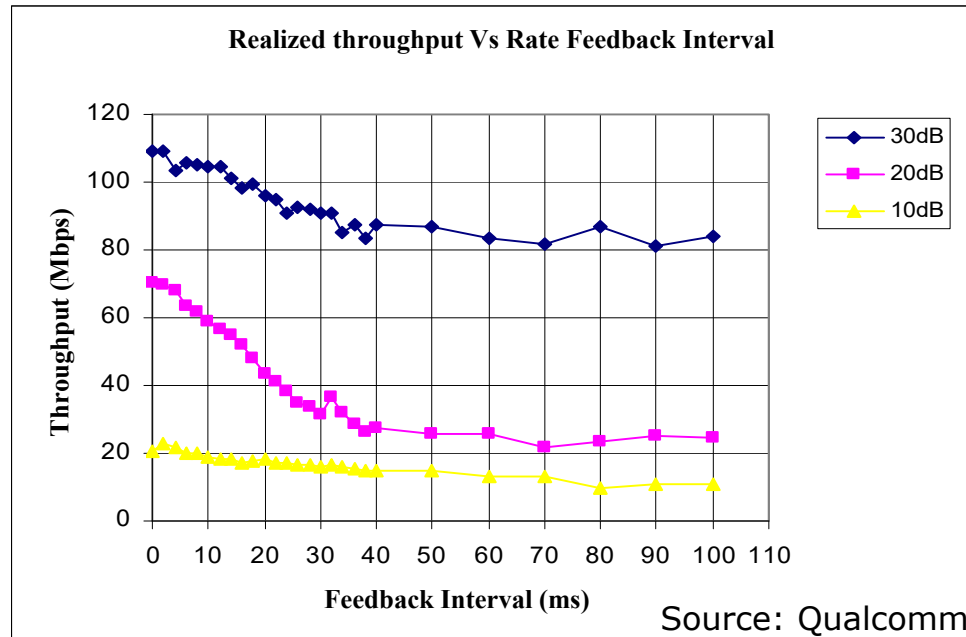


RD Simulation Results



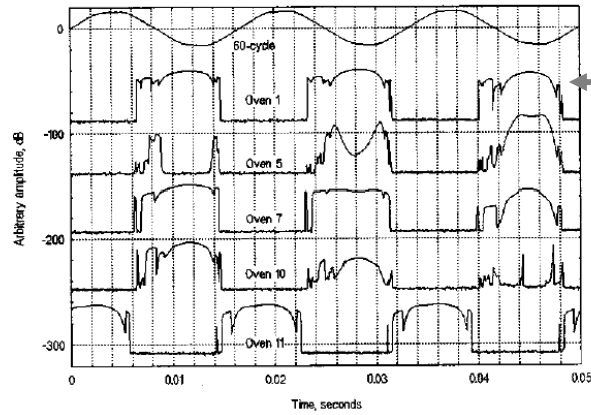
- Simulation scenarios with various mixes of video, voice and data traffic
- Simple heuristic: initiator grants remaining TXOP to peer, peer opportunistically uses it to return data of same AC
- Shows significant performance gain

Fast Link Adaptation



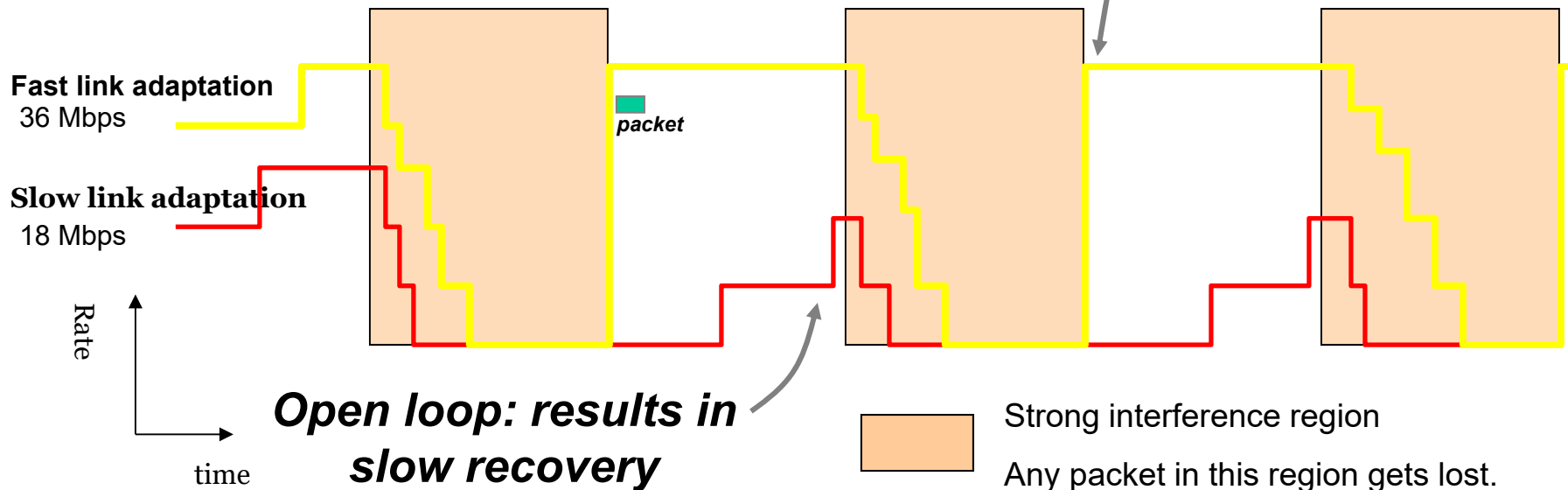
- Slow link adaptation: Packet error feedback allows the transmitter to select best rate averaged over a long period
- Fast link adaptation: Significant gain is achieved by feeding back periodic channel information to allow transmitter to rapidly track channel changes

Fast Link Adaptation



Ex: microwave oven interference pattern

Closed loop: optimal rate selected with first successful exchange

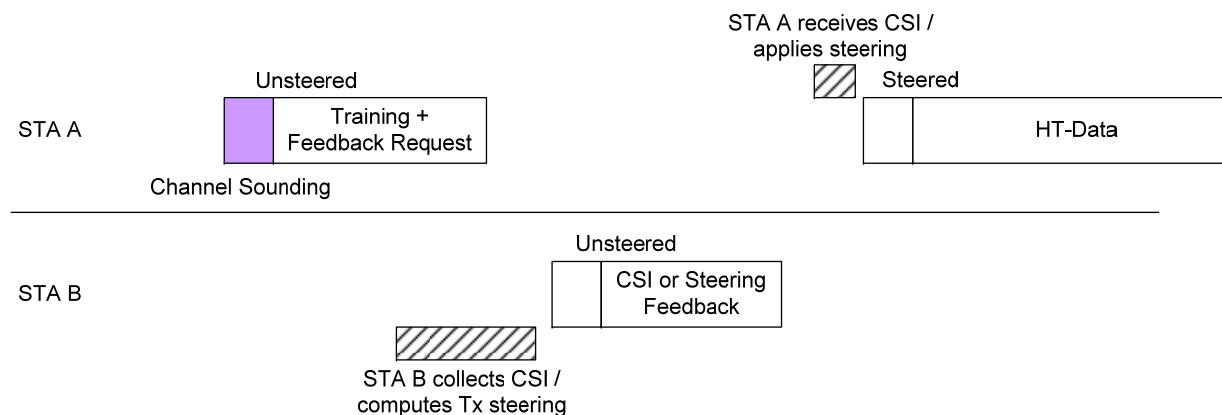


Fast Link Adaptation

- In 802.11n feedback is in the form of an MCS suggestion
- Signalled in HTC
 - Timing of response is unconstrained
 - Unsolicited response permitted
 - Sequence number to pair MRQ and MFB response

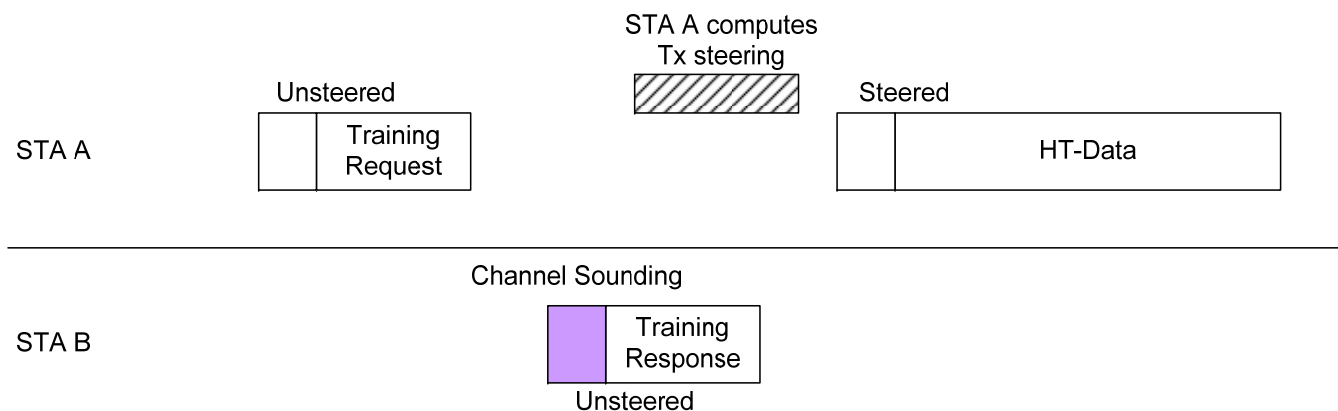
HTC Field	Description
MRQ	MCS request
MSI	Sequence number of MCS request 000-110
MFS	Sequence number of MCS feedback or “unsolicited” (111)
MFB	MCS feedback

Transmit Beamforming: Explicit Feedback



- STA A begins with sounding packet that includes feedback request
- STA B computes channel estimate and returns channel state OR steering matrices
- STA A applies feedback to data transmission

Transmit Beamforming: Implicit Feedback



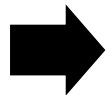
- STA A begins with training request
- STA B responds with sounding packet
- STA A computes channel estimate and applies steering to data transmission

Explicit Vs Implicit Beamforming

	Explicit Feedback	Implicit Feedback
Advantages	• Calibration not required	• Low overhead • Steering calculation not defined (implementation dependent)
Disadvantages	• High overhead • Steering calculation defined (limits implementation flexibility) • Burdens receiver with steering computation	• Calibration may be required

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Summary

Summary

- 802.11n provides...
- Increased throughput with
 - MIMO and spatial multiplexing
 - 40MHz operation
 - Aggregation
 - Enhanced Block Acknowledgement
 - Reverse direction protocol

Summary

- Increased robustness with
 - Additional receive diversity
 - More robust codes: LDPC
 - Space-time diversity: STBC
 - Transmit beamforming
 - Fast link adaptation
- Result is much improved performance with ability to support glitch-free video streaming and other high bandwidth application

Acronyms (1/2)

- ACI: adjacent channel interference
- ADC: analog digital converter
- AGC: automated gain controller
- AWGN: additive white Gaussian noise
- BCC: binary convolutional code
- BA: Block Acknowledgement
- BAR: Block Acknowledge Request
- CC: comparison criteria
- CCI: co-channel interference
- CE: consumer electronics
- CSD: cyclic shift diversity
- DCF: distributed coordination function
- ETSI: European telecommunications standards institute
- EVM: error vector magnitude
- FR: functional requirements
- GF: green field
- GI: guard interval
- HT: high throughput
- IQ: inphase quadrature
- LDPC: low density parity check
- LO: local oscillator
- LOS: line of sight
- LTF: long training field
- LTS: long training symbol
- MAC: medium access control layer
- MCS: modulation coding scheme
- MIMO: multiple input multiple output
- MMSE: minimum mean square error
- MRC: maximal ratio combining
- NLOS: non line of sight
- NDP: Null Data Packet

Acronyms (2/2)

- OFDM: orthogonal frequency division multiplexing
- PAPR: peak to average power ratio
- PAR: project authorization request
- PCO: Phased Coexistence Operation
- PHY: physical layer
- PIFS: PCF Inter-frame Space
- PLCP: physical layer convergence procedure
- PLR: packet loss rate
- PPDU: PLCP protocol data unit
- PSDU: PLCP service data unit
- RD: Reverse Direction
- RIFS: Reduced Inter-frame Space
- RMS: root mean square
- Rx: receiver
- SAP: service access point
- SDM: spatial division multiplexing
- SIFS: Short Inter-frame Space
- SIG: signal field
- SISO: single input single output
- SNR: signal to noise ratio
- STA: station
- STBC: space time block code
- STF: short training field
- SVD: singular value decomposition
- Tx: transmitter
- TxBF: transmit beamforming
- TG: task group
- UNII: unlicensed national information infrastructure
- WLAN: wireless local area network
- ZF: zero forcing

References

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- Alamouti, S., “A Simple Transmit Diversity Technique for Wireless Communications,” IEEE JSAC, Vol. 16, No. 8, Oct. 1998.
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