802.11ax

What I have learned so far

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Training Agenda

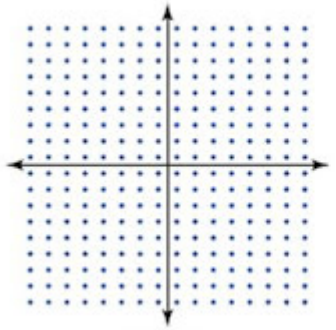
- 802.11ac vs 802.11ax
- What is an 802.11ax PPDU ?
- What is OFDMA ? And how it differs from OFDM ?
- OFDM/CSMA vs OFDM/OFDMA
- Uplink-OFDMA and Downlink OFDMA
- SU-MIMO vs MU-MIMO
- 802.11ac Downlink MU-MIMO vs 802.11ax Downlink MU-MIMO
- BSS Coloring and Spatial Reuse.
- Target Wait Time (TWT)
- What is an AP Scheduler ? And why is it important ?

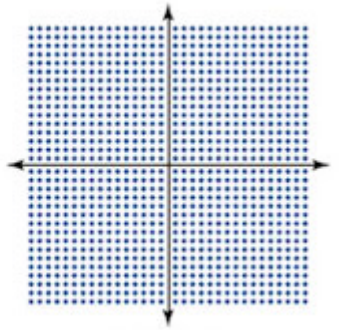
802.11ac vs 802.11ax

	Legacy feature	New 802.11ax features
PHY		
Spectrum	up to 40 MHz at 2.4 (11n), up to 160 MHz at 5 GHz (11ac), or up to 16 MHz at 0.9 GHz (11ah)	up to 40 MHz at 2.4, up to 160 MHz at 5 GHz
OFDM Constellation Order	256-QAM (11ac)	1024-QAM
OFDM Symbol duration	$3.2\,\mu$s	$12.8\,\mu$s
OFDM Guard Interval	0.4 or $0.8\,\mu$s (10 or 20% overhead)	0.8, 1.6 or $3.2\,\mu$s (5, 10 or 20% overhead)
MIMO Order	4 (11n), 8 (11ac)	8
Maximal Data Rate	$\approx$ 7 Gbps	$\approx$ 9.6 Gbps
Channel Access		
Basic channel access	CSMA/CA	OFDMA on top of CSMA/CA
Random Channel Access	DCF, EDCA	UL OFDMA Random Access on top of CSMA/CA
Contention-free Access	PCF, HCCA (not implemented in real devices), RAW (11ah)	Trigger-based UL OFDMA
MU Technology	MU-MIMO (11ac)	MU-MIMO, OFDMA
MU transmission direction	DL (11ac)	DL and UL
Fragmentation	Static	Flexible
Aggregation	A-MSDU, A-MPDU (11n) without fragmentation	A-MPDU, A-MSDU with Fragmentation
HE/Legacy Fairness		2 EDCA Parameter Sets
OBSS Management		
Interference Mitigation	NAV, RTC/CTS, HCCA TXOP Negotiation	Two NAVs, Quiet Period
Spatial Reuse	Sectorization (11ah)	Adaptive Power and Sensitivity Thresholds, Color
Power Management		
Power Management	Many	Enhanced TWT, Enhanced Microsleep

MCS	Modulation	Coding rate
0	BPSK	1/2
1	QPSK	1/2
2	QPSK	3/4
3	16QAM	1/2
4	16QAM	3/4
5	64QAM	2/3
6	64QAM	3/4
7	64QAM	5/6
8	256QAM	3/4
9	256QAM	5/6
10	1024QAM	3/4
11	1024QAM	5/6

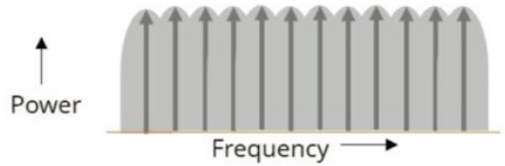
MCS9





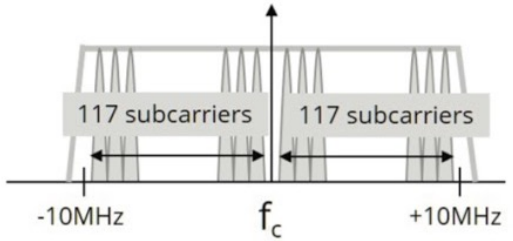
MCS11

802.11ax



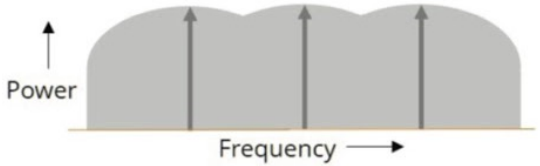
Subcarrier spacing 78.125 kHz
256* subcarriers in a 20 MHz channel

Symbol duration 12.8 usec
With 0.8, 1.6 or 3.2 usec cyclic prefix



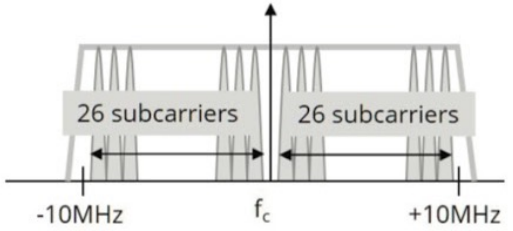
20 MHz channel showing 234 data subcarriers

802.11ac



Subcarrier spacing 312.5 kHz
64* subcarriers in a 20 MHz channel
* Not all usable

Symbol duration 3.2 usec
With 0.4 or 0.8 usec cyclic prefix

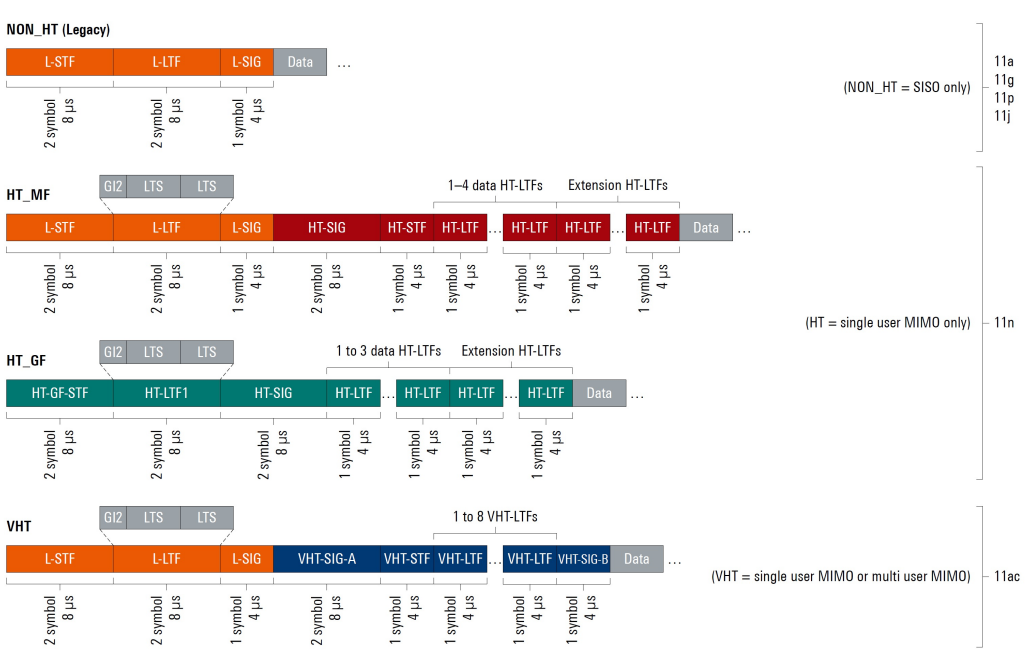


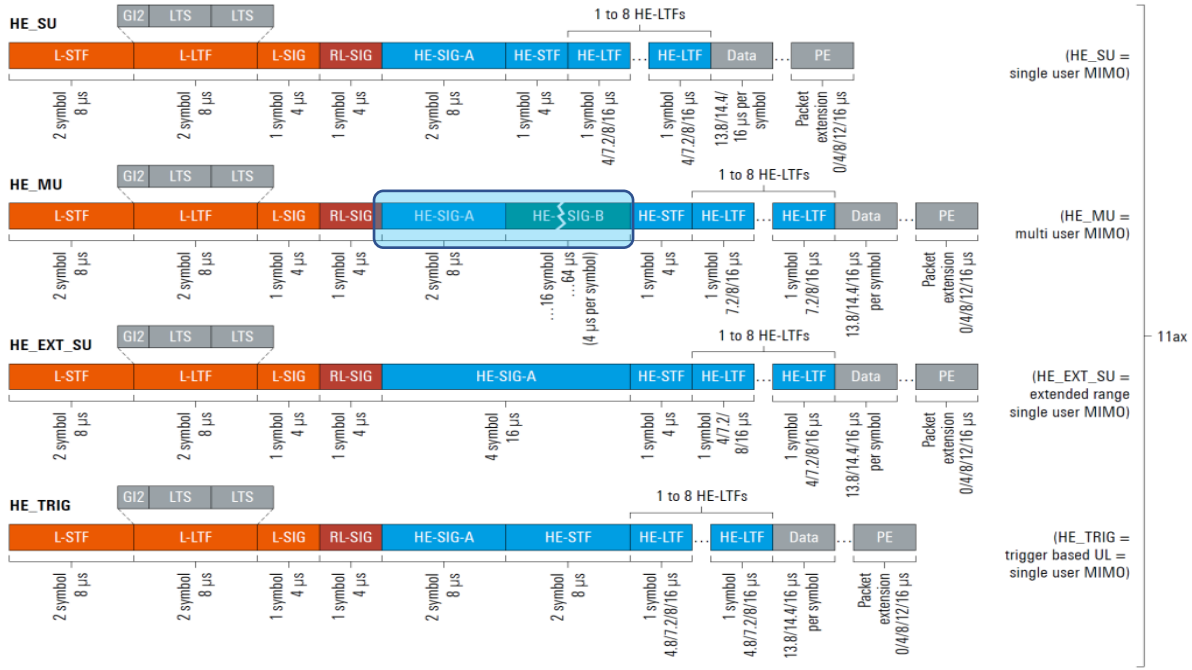
20 MHz channel showing 52 data subcarriers

PPDU Format

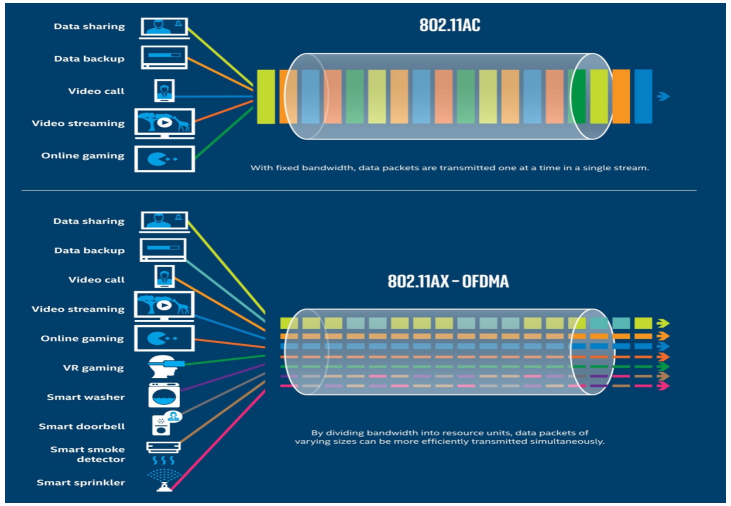
Field	Description
L-STF	legacy short training field
L-LTF	legacy long training field
L-SIG	legacy signal field
RL-SIG	repeated legacy signal field
HE-SIG-A	HE signal A field
HE-SIG-B	HE signal B field
HE-STF	HE short training field
HE-LTF	HE long training field
Data	data
PE	packet extension field
GI	guard interval
LTS	legacy training sequence

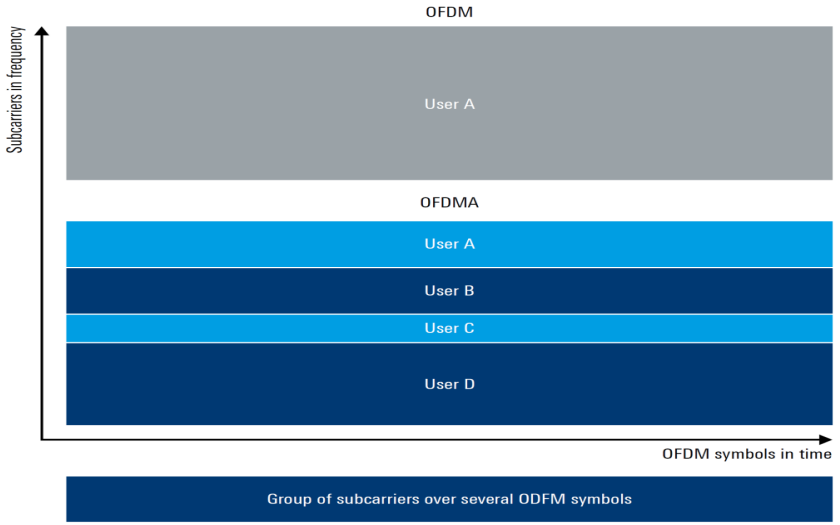
- HE-STF and HE-LTF fields are used for channel estimation to facilitate MIMO transmission
- For UL and DL SU and UL MU transmission, all the necessary information is found in the HE-SIG-A field.
- The SIG-B field contains all the necessary information for MU transmission, DL MU-MIMO, DL OFDMA, and DL OFDMA in MU-MIMO
- PE (Packet Extension) is padding added to give receiver with low processing power more time to reply with ACK with in a SIFS time.

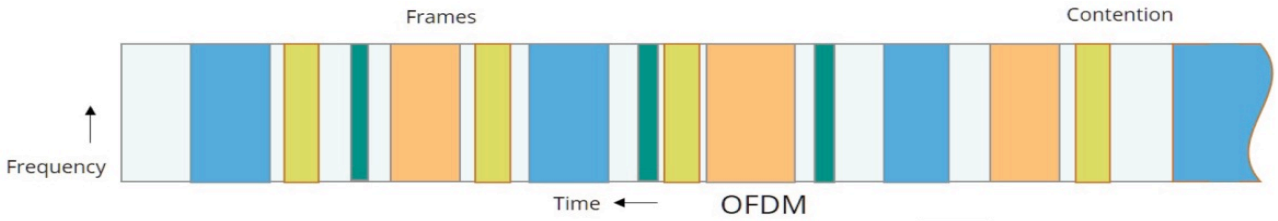




OFDM/CSMA vs OFDM/OFDMA

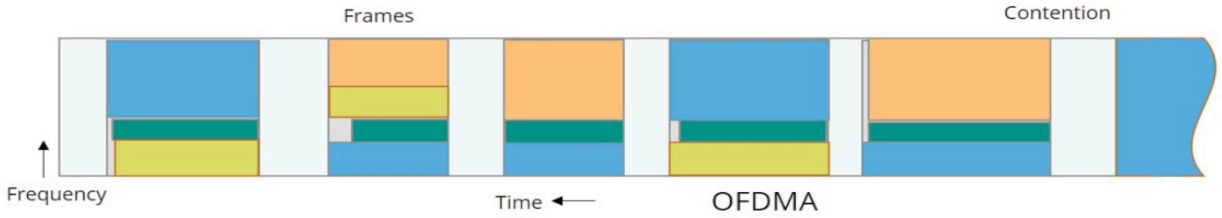


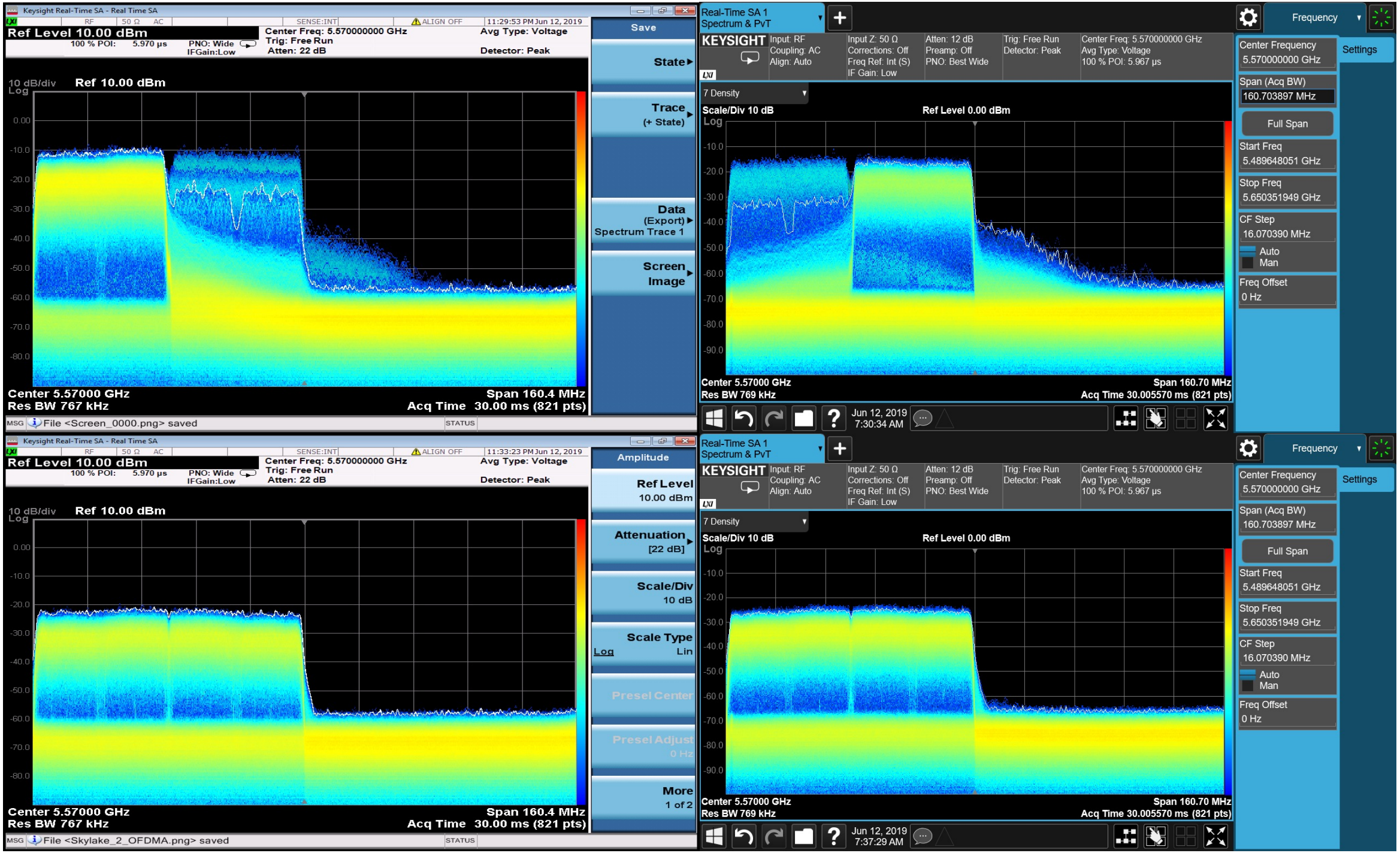




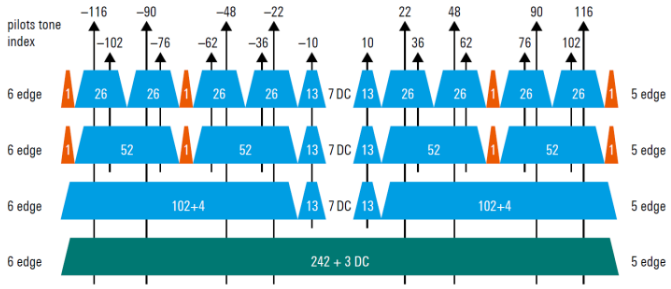
- Each frame is transmitted across the whole channel width.
- Each transmit opportunity requires contention, losing spectral efficiency.
- Low-rate transmissions can block the channel for others, increasing latency and jitter.

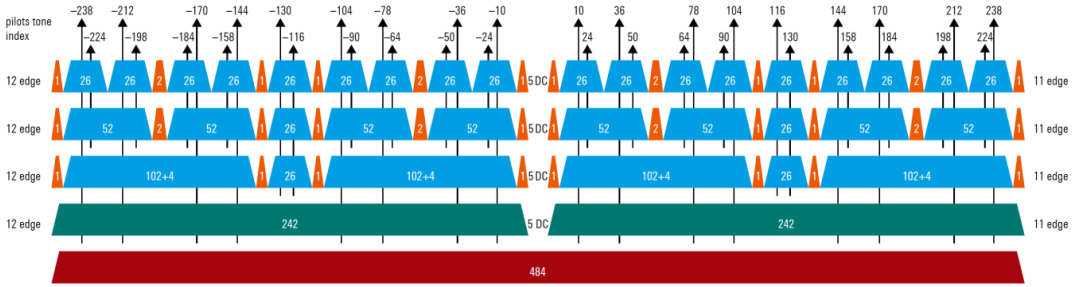
- As each transmit opportunity can be shared across a number of frames, there is less contention overhead.
- Low data-rate traffic can reduce its contention and header overhead.
- Traffic requiring lower latency or jitter can be allocated more frequent transmit opportunities.

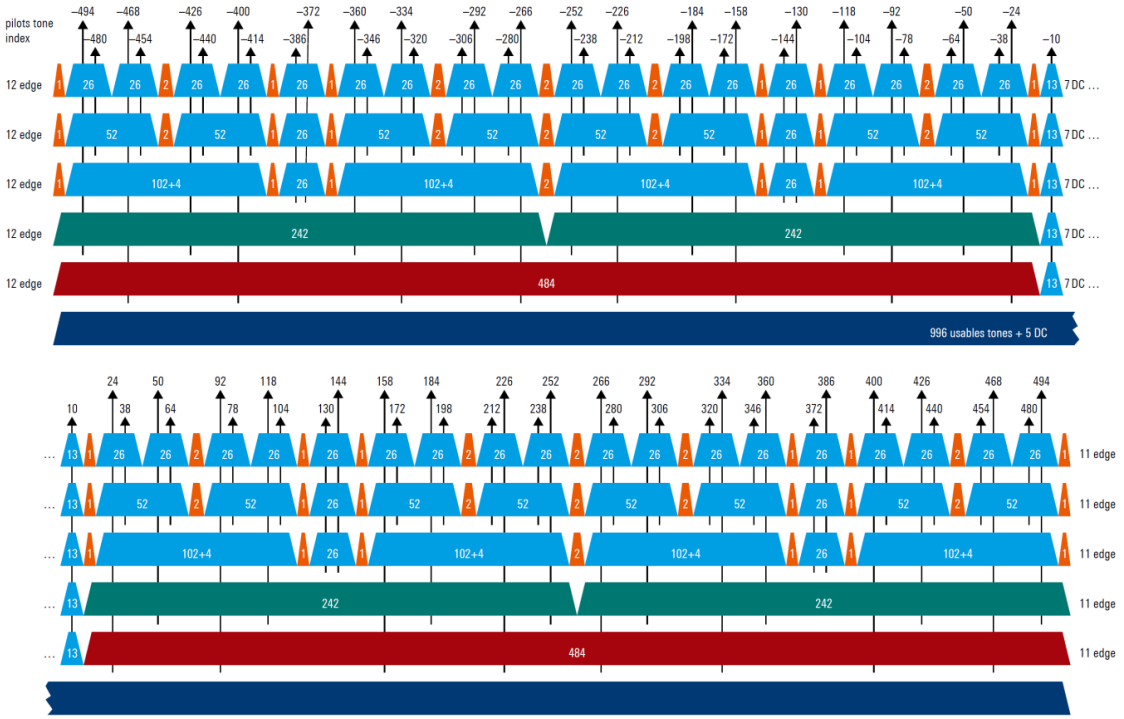



Keysight Real-Time SA - Real Time SA
Ref Level 10.00 dBm
100 % POI: 5.970 µs
PNO: Wide
IFGain:Low
Center Freq: 5.570000000 GHz
Trig: Free Run
Atten: 22 dB
Avg Type: Voltage
Detector: Peak
11:29:53 PM Jun 12, 2019
10 dB/div
Log
Ref 10.00 dBm
Center 5.57000 GHz
Res BW 767 kHz
Span 160.4 MHz
Acq Time 30.00 ms (821 pts)
Save
State
Trace (+ State)
Data (Export) Spectrum Trace 1
Screen Image
MSG
File <Screen_0000.png> saved
STATUS
Real-Time SA 1
Spectrum & PvT
KEYSIGHT
Input: RF
Coupling: AC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
IF Gain: Low
Atten: 12 dB
Preamp: Off
PNO: Best Wide
Trig: Free Run
Detector: Peak
Center Freq: 5.570000000 GHz
Avg Type: Voltage
100 % POI: 5.967 µs
7 Density
Scale/Div 10 dB
Ref Level 0.00 dBm
Center 5.57000 GHz
Res BW 769 kHz
Span 160.70 MHz
Acq Time 30.005570 ms (821 pts)
Jun 12, 2019
7:30:34 AM
Frequency
Settings
Center Frequency
5.570000000 GHz
Span (Acq BW)
160.703897 MHz
Full Span
Start Freq
5.489648051 GHz
Stop Freq
5.650351949 GHz
CF Step
16.070390 MHz
Auto
Man
Freq Offset
0 Hz
Keysight Real-Time SA - Real Time SA
Ref Level 10.00 dBm
100 % POI: 5.970 µs
PNO: Wide
IFGain:Low
Center Freq: 5.570000000 GHz
Trig: Free Run
Atten: 22 dB
Avg Type: Voltage
Detector: Peak
11:33:23 PM Jun 12, 2019
10 dB/div
Log
Ref 10.00 dBm
Center 5.57000 GHz
Res BW 767 kHz
Span 160.4 MHz
Acq Time 30.00 ms (821 pts)
Amplitude
Ref Level 10.00 dBm
Attenuation [22 dB]
Scale/Div 10 dB
Scale Type Log Lin
Presel Center
Presel Adjust 0 Hz
More 1 of 2
MSG
File <Skylake_2_OFDMA.png> saved
STATUS
Real-Time SA 1
Spectrum & PvT
KEYSIGHT
Input: RF
Coupling: AC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
IF Gain: Low
Atten: 12 dB
Preamp: Off
PNO: Best Wide
Trig: Free Run
Detector: Peak
Center Freq: 5.570000000 GHz
Avg Type: Voltage
100 % POI: 5.967 µs
7 Density
Scale/Div 10 dB
Ref Level 0.00 dBm
Center 5.57000 GHz
Res BW 769 kHz
Span 160.70 MHz
Acq Time 30.005570 ms (821 pts)
Jun 12, 2019
7:37:29 AM
Frequency
Settings
Center Frequency
5.570000000 GHz
Span (Acq BW)
160.703897 MHz
Full Span
Start Freq
5.489648051 GHz
Stop Freq
5.650351949 GHz
CF Step
16.070390 MHz
Auto
Man
Freq Offset
0 Hz

OFDMA RU Mapping

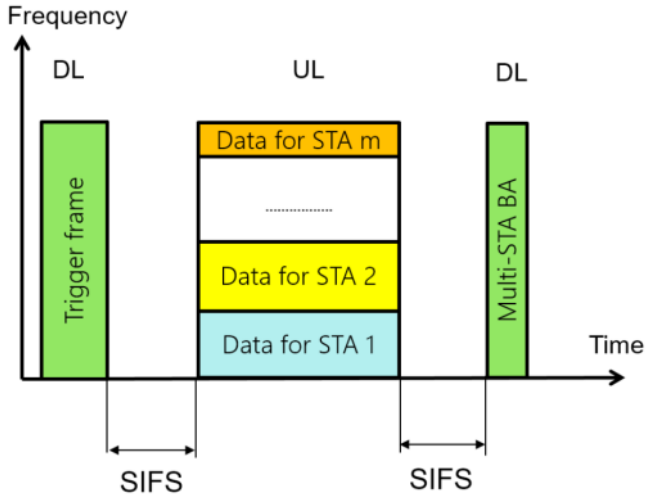




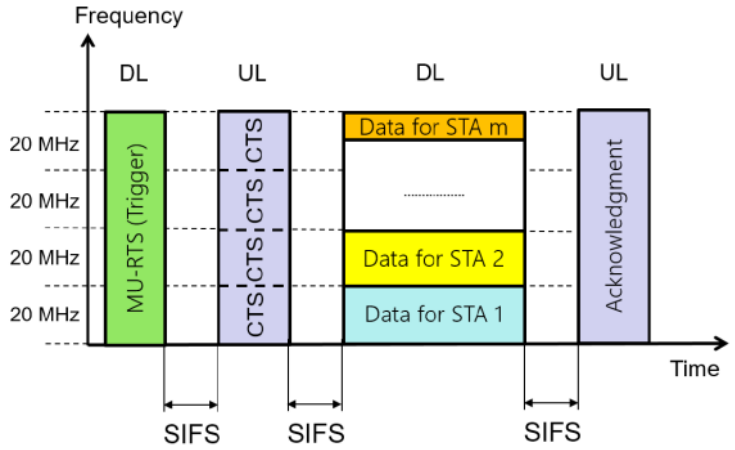


RU type	CBW20	CBW40	CBW80	CBW160 and CBW80+80
26-subcarrier RU	9	18	37	74
52-subcarrier RU	4	8	16	32
106-subcarrier RU	2	4	8	16
242-subcarrier RU	1-SU/MU-MIMO	2	4	8
484-subcarrier RU	N/A	1-SU/MU-MIMO	2	4
996-subcarrier RU	N/A	N/A	1-SU/MU-MIMO	2
2x996 subcarrier RU	N/A	N/A	N/A	1-SU/MU-MIMO

OFDMA in Action

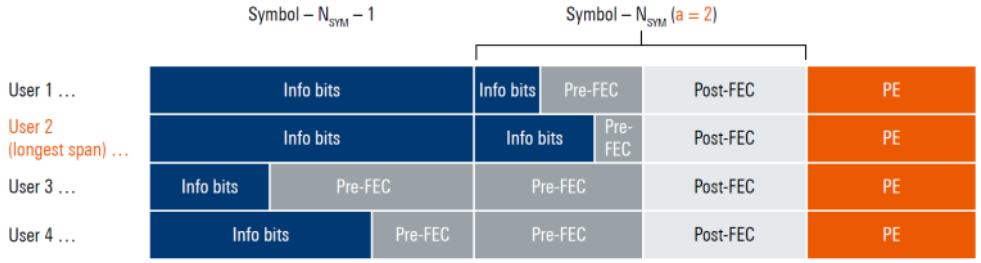


UL OFDMA



DL OFDMA

- In DL OFDMA, not all STAs may have the same data load to keep all symbols the same length, padding is added. Even though this reduces efficiency, it helps with backward compatibility with legacy clients' carrier sensing



UL-OFDMA : Packet Capture

```
> Frame 303: 142 bytes on wire (1136 bits), 142 bytes captured (1136 bits) on interface moni5a, id 0
> Radiotap Header v0, Length 74
> 802.11 radio information
v IEEE 802.11 Trigger, Flags: ........
    Type/Subtype: Trigger (0x0012)
  > Frame Control Field: 0x2400
    .001 0001 0011 1110 = Duration: 4414 microseconds
    Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
    Transmitter address: Technico_2d:3b:95 (a4:56:cc:2d:3b:95)
  v Common Info
    v HE Trigger Common Info: 0xffc00011f89eca00
        .... .... .... .... .... .... .... .... .... .... .... .... .... .... .... .... 0000 = Trigger Type: Basic (0)
        .... .... .... .... .... .... .... .... .... .... .... .... 1100 1010 0000 .... = UL Length: 3232
        .... .... .... .... .... .... .... .... .... .... .... ...0 .... .... .... .... = More TF: False
        .... .... .... .... .... .... .... .... .... .... .... ..1. .... .... .... .... = CS Required: True
        .... .... .... .... .... .... .... .... .... .... .... 11.. .... .... .... .... = UL BW: 80+80 MHz or 160 MHz (3)
        .... .... .... .... .... .... .... .... .... .... ..01 .... .... .... .... .... = GI And LTF Type: 2x LTF + 1.6 us GI (1)
        .... .... .... .... .... .... .... .... .... .... .0.. .... .... .... .... .... = MU-MIMO LTF Mode: HE single stream pilot HE LTF mode
        .... .... .... .... .... .... .... .... .... .... ..00 1... .... .... .... .... = Number of HE-LTF Symbols and Midamble Periodicity: 0x1
        .... .... .... .... .... .... .... .... .... .... .0.. .... .... .... .... .... = UL STBC: False
        .... .... .... .... .... .... .... .... .... 1... .... .... .... .... .... .... = LDPC Extra Symbol Segment: True
        .... .... .... .... .... .... .... .... ..01 1111 .... .... .... .... .... .... = AP Tx Power: 11 dBm
        .... .... .... .... .... .... .... ...1 00.. .... .... .... .... .... .... .... = Packet Extension: PE disambiguity & pre-FEC padding factor of 4
        .... .... .... ...0 0000 0000 0000 000. .... .... .... .... .... .... .... .... = Spatial Reuse: 0x0000
        .... .... ..0. .... .... .... .... .... .... .... .... .... .... .... .... .... = Doppler: False
        .111 1111 11.. .... .... .... .... .... .... .... .... .... .... .... .... .... = UL HE-SIG-A2 Reserved: 0x1ff
        1... .... .... .... .... .... .... .... .... .... .... .... .... .... .... .... = Reserved: 0x1
  v User Info
    > User Info: 0x4120d82017
    > Basic Trigger Dependent User Info: 0x04
    > User Info: 0x4620184015
    > Basic Trigger Dependent User Info: 0x04
    > User Info: 0x3f20183019
    > Basic Trigger Dependent User Info: 0x04
    > User Info: 0x3f2118500f
    > Basic Trigger Dependent User Info: 0x04
```

Trigger Frame: Basic Trigger

```
v User Info
  v User Info: 0x4120d82017
      .... .... .... .... .... .... .... .... .... .... 0000 0001 0111 = AID12: 0x017
      .... .... .... .... .... .... .... ...0 .... .... .... .... = RU Allocation Region: primary 80MHz channel for 80+80 and 160MHz
      .... .... .... .... .... .... .... .... 1000 001. .... .... .... = RU Allocation: 65 (484 tones)
      .... .... .... .... .... .... .... ...1 .... .... .... .... = Coding Type: LDPC
      .... .... .... .... .... .... ...0 110. .... .... .... .... = MCS: 0x6
      .... .... .... .... .... .... ..0. .... .... .... .... .... = DCM: False
      .... .... .... .... .... .... ...0 00.. .... .... .... .... = Starting Spatial Stream: 1
      .... .... .... .... .... .... 001. .... .... .... .... .... = Number Of Spatial Streams: 2
      .100 0001 .... .... .... .... .... .... .... .... .... .... = Target RSSI: -45dBm
      0... .... .... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
  v Basic Trigger Dependent User Info: 0x04
      .... ..00 = MPDU MU Spacing Factor: 0
      ...0 01.. = TID Aggregation Limit: 1
      ..0. .... = Reserved: 0x0
      00.. .... = Preferred AC: AC_BE (0x0)
  > User Info: 0x4620184015
  > Basic Trigger Dependent User Info: 0x04
  v User Info: 0x3f20183019
      .... .... .... .... .... .... .... .... .... .... 0000 0001 1001 = AID12: 0x019
      .... .... .... .... .... .... .... ...1 .... .... .... .... = RU Allocation Region: secondary 80MHz channel for 80+80 and 160MHz
      .... .... .... .... .... .... .... .... 1000 001. .... .... .... = RU Allocation: 65 (484 tones)
      .... .... .... .... .... .... .... ...1 .... .... .... .... = Coding Type: LDPC
      .... .... .... .... .... .... ...0 000. .... .... .... .... = MCS: 0x0
      .... .... .... .... .... .... ..0. .... .... .... .... .... = DCM: False
      .... .... .... .... .... .... ...0 00.. .... .... .... .... = Starting Spatial Stream: 1
      .... .... .... .... .... .... 001. .... .... .... .... .... = Number Of Spatial Streams: 2
      .011 1111 .... .... .... .... .... .... .... .... .... .... = Target RSSI: -47dBm
      0... .... .... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
  v Basic Trigger Dependent User Info: 0x04
      .... ..00 = MPDU MU Spacing Factor: 0
      ...0 01.. = TID Aggregation Limit: 1
      ..0. .... = Reserved: 0x0
      00.. .... = Preferred AC: AC_BE (0x0)
  > User Info: 0x3f2118500f
  > Basic Trigger Dependent User Info: 0x04
```

Trigger Frame: Basic Trigger

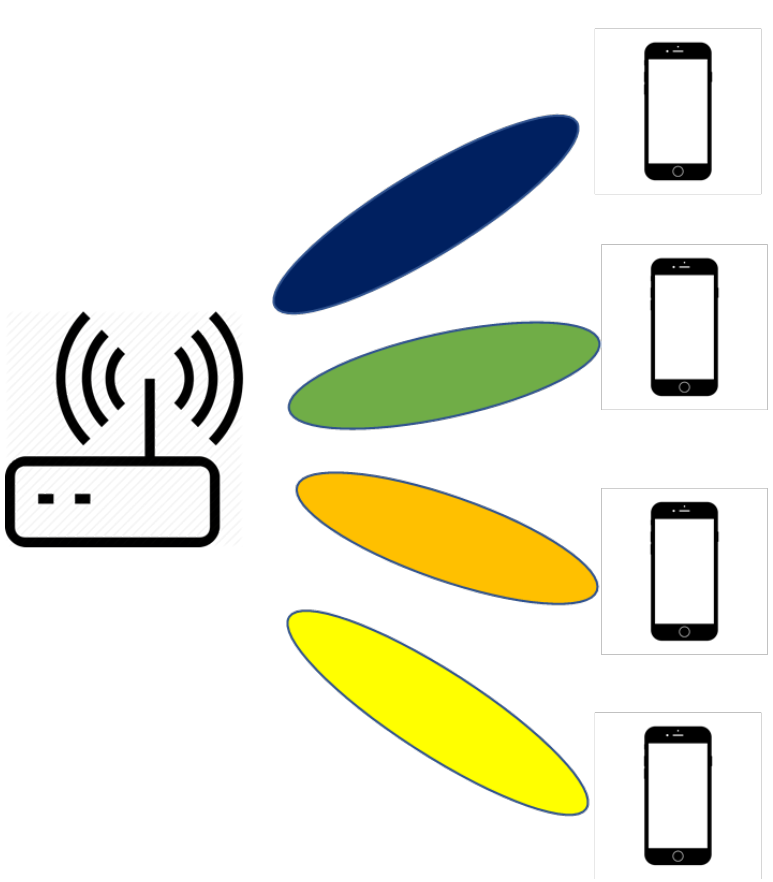
```
> Frame 7758: 120 bytes on wire (960 bits), 120 bytes captured (960 bits) on interface moni5a, id 0
> Radiotap Header v0, Length 74
> 802.11 radio information
v IEEE 802.11 802.11 Block Ack, Flags: ........C
    Type/Subtype: 802.11 Block Ack (0x0019)
  > Frame Control Field: 0x9400
    .000 0000 0000 0000 = Duration: 0 microseconds
    Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
    Transmitter address: Technico_2d:3b:95 (a4:56:cc:2d:3b:95)
  v Multi-STA BlockAck Response
    v Block Ack Control: 0x0016
        .... .... .... ...0 = BA Ack Policy: Immediate Acknowledgement Required
        .... .... ...1 011. = BA Type: Multi-STA BlockAck (0xb)
        .... 0000 000. .... = Reserved: 0x00
        0000 .... .... .... = TID for which a Basic BlockAck frame is requested: 0x0
    v Per AID TID Info: 0x17
      v AID TID Info: 0x0017
          .... .000 0001 0111 = AID11: 0x017
          .... 0... .... .... = Ack Type: 0x0
          0000 .... .... .... = TID: 0x0
      v Block Ack Starting Sequence Control (SSC): 0x7710
          .... .... .... 0000 = Fragment: 0
          0111 0111 0001 .... = Starting Sequence Number: 1905
      > Block Ack Bitmap: ffffffffff0f0000
    v Per AID TID Info: 0xf
      v AID TID Info: 0x000f
          .... .000 0000 1111 = AID11: 0x00f
          .... 0... .... .... = Ack Type: 0x0
          0000 .... .... .... = TID: 0x0
      v Block Ack Starting Sequence Control (SSC): 0x9a40
          .... .... .... 0000 = Fragment: 0
          1001 1010 0100 .... = Starting Sequence Number: 2468
      > Block Ack Bitmap: ffffffffff7f0000
    Frame check sequence: 0x0fa98d62 [unverified]
    [FCS Status: Unverified]
```

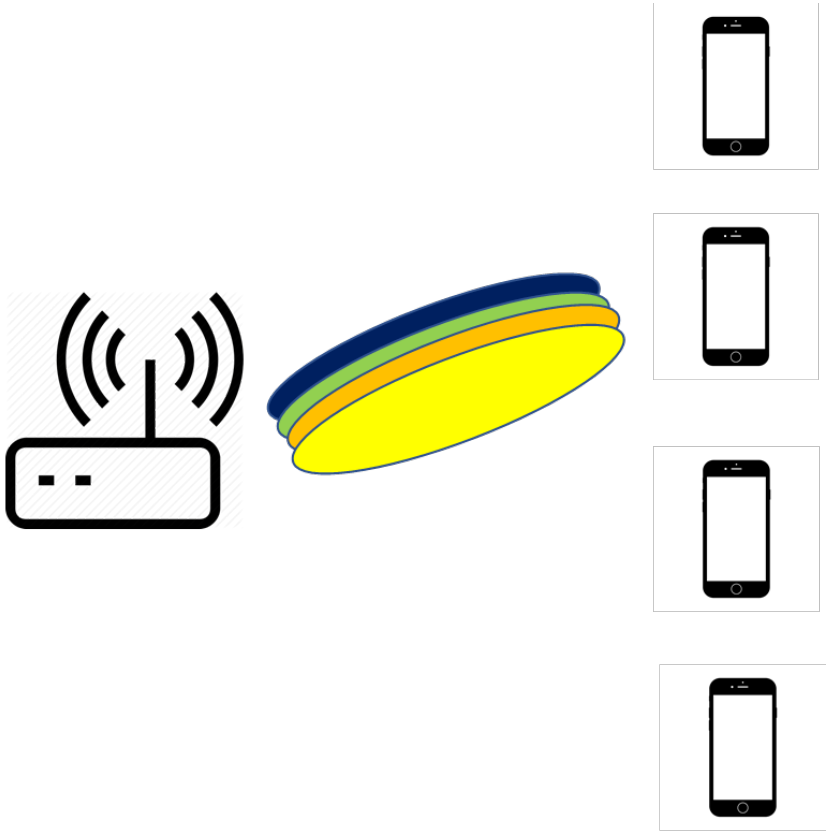
Multi-STA BlockAck Response

```
v Per AID TID Info: 0x17
  v AID TID Info: 0x0017
      .... .000 0001 0111 = AID11: 0x017
      .... 0... .... .... = Ack Type: 0x0
      0000 .... .... .... = TID: 0x0
  v Block Ack Starting Sequence Control (SSC): 0x7710
      .... .... .... 0000 = Fragment: 0
      0111 0111 0001 .... = Starting Sequence Number: 1905
  v Block Ack Bitmap: ffffffffff0f0000
      Missing frame: 1949
      Missing frame: 1950
      Missing frame: 1951
      Missing frame: 1952
      Missing frame: 1953
      Missing frame: 1954
      Missing frame: 1955
      Missing frame: 1956
      Missing frame: 1957
      Missing frame: 1958
      Missing frame: 1959
      Missing frame: 1960
      Missing frame: 1961
      Missing frame: 1962
      Missing frame: 1963
      Missing frame: 1964
      Missing frame: 1965
      Missing frame: 1966
      Missing frame: 1967
      Missing frame: 1968
v Per AID TID Info: 0xf
  v AID TID Info: 0x000f
      .... .000 0000 1111 = AID11: 0x00f
      .... 0... .... .... = Ack Type: 0x0
      0000 .... .... .... = TID: 0x0
  v Block Ack Starting Sequence Control (SSC): 0x9a40
      .... .... .... 0000 = Fragment: 0
```

Multi-STA BlockAck Response

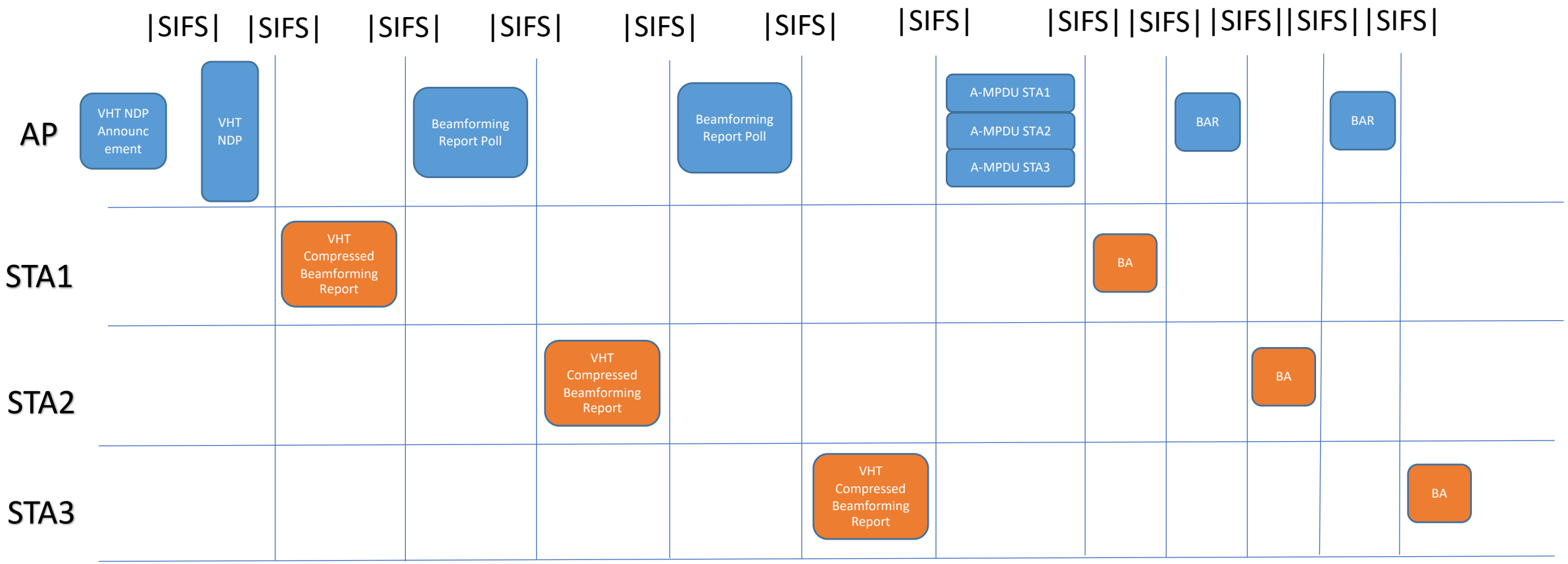
SU-MIMO vs MU-MIMO



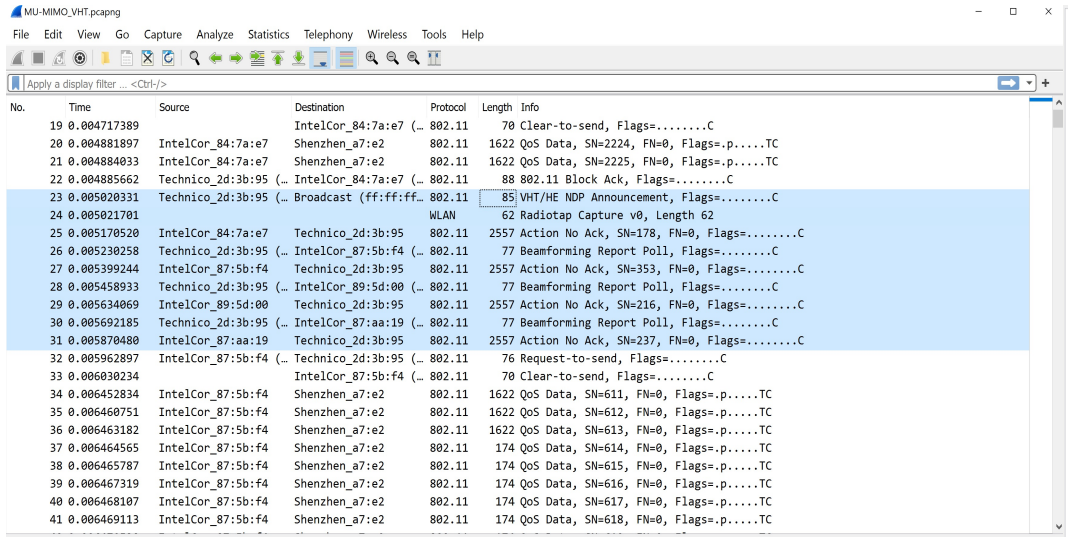


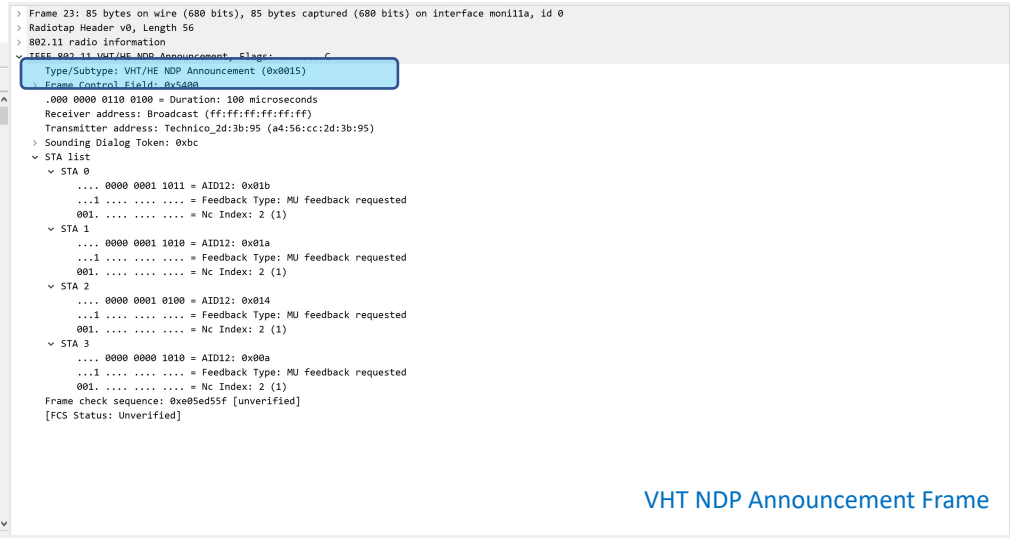
The main key to MU-MIMO is Beamforming . Beamforming is used to create nulls in the Antenna pattern to help separate the data streams in space.

802.11ac Beamforming / DL MU-MIMO



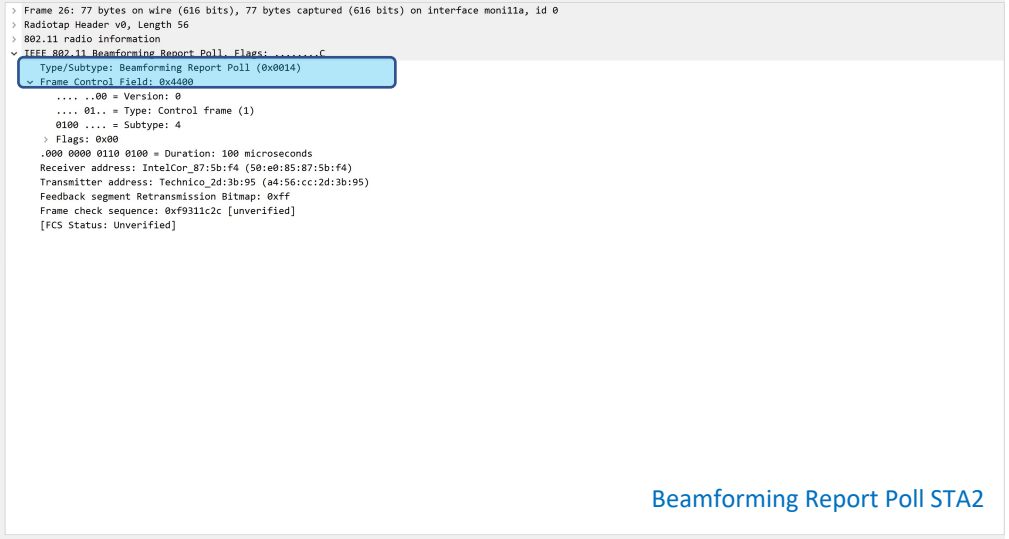
VHT MU-MIMO : Packet Capture





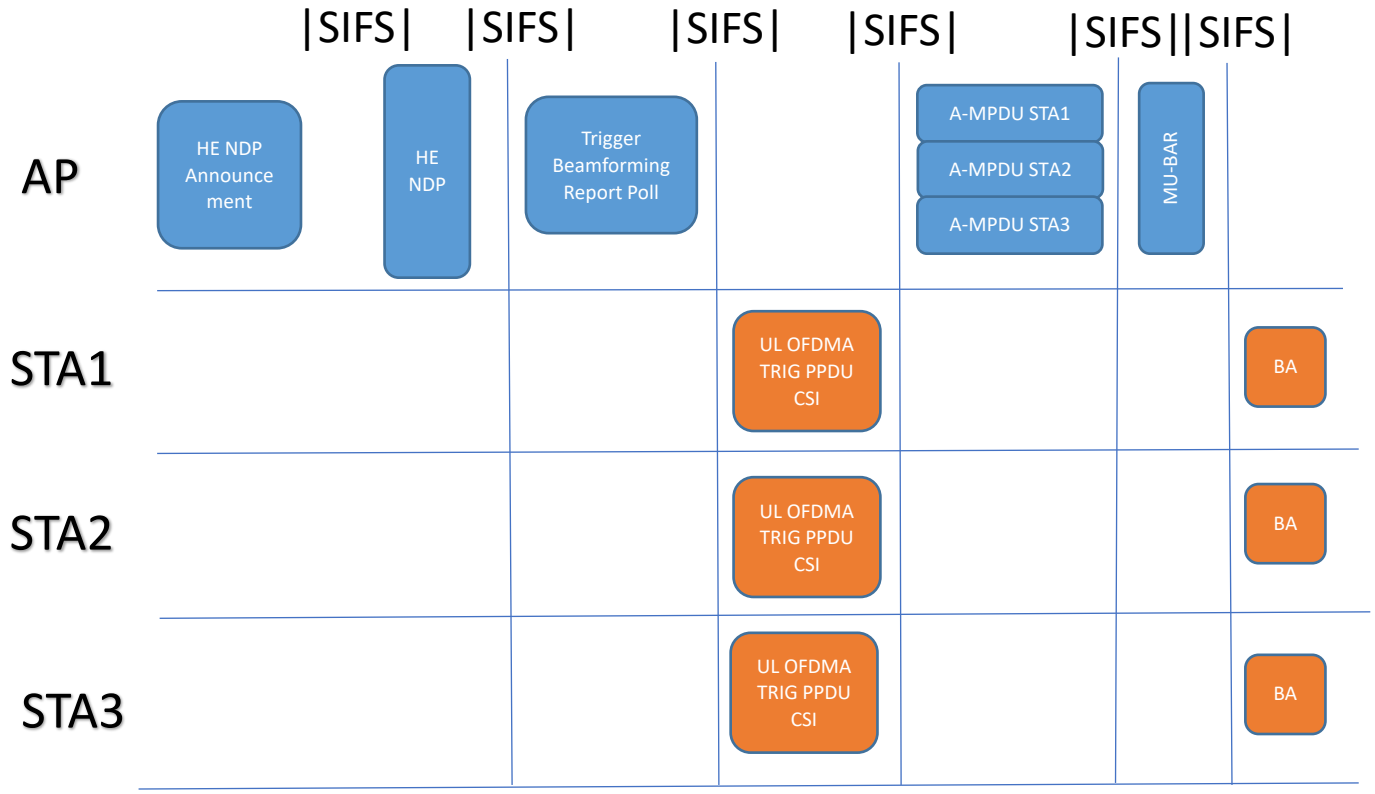
VHT NDP Announcement Frame

Action Frame : Beamforming Feedback STA1



Beamforming Report Poll STA2

802.11ax Beamforming / DL MU-MIMO



HE MU-MIMO : Packet Capture

```
> Frame 85: 93 bytes on wire (744 bits), 93 bytes captured (744 bits) on interface moni11a, id 0
> Radiotap Header v0, Length 56
> 802.11 radio information
v IEEE 802.11 VHT/HE NDP Announcement, Flags: ........C
    Type/Subtype: VHT/HE NDP Announcement (0x0015)
    Frame Control Field: 0x5400
    .000 0000 0110 0100 = Duration: 100 microseconds
    Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
    Transmitter address: Technico_2d:3b:95 (a4:56:cc:2d:3b:95)
  v Sounding Dialog Token: 0x5e
      .... ...0 = Reserved: 0x0
      .... ..1. = HE: HE NDP Announcement frame
      0101 11.. = Sounding Dialog Token Number: 23
  v STA list
    v STA 0
      > STA Info: 0x38900014
    v STA 1
      > STA Info: 0x38900018
    v STA 2
      > STA Info: 0x38900008
    v STA 3
      > STA Info: 0x3890001b
    Frame check sequence: 0x9b683069 [unverified]
    [FCS Status: Unverified]
```

HE NDP Announcement Frame

```
> Frame 87: 156 bytes on wire (1248 bits), 156 bytes captured (1248 bits) on interface moni11a, id 0
> Radiotap Header v0, Length 56
> 802.11 radio information
v IEEE 802.11 Trigger, Flags: ........
    Type/Subtype: Trigger (0x0012)
  > Frame Control Field: 0x2400
    .000 0001 0111 0110 = Duration: 374 microseconds
    Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
    Transmitter address: Technico_2d:3b:95 (a4:56:cc:2d:3b:95)
  v Common Info
    v HE Trigger Common Info: 0x00000012192a0d61
        .... .... .... .... .... .... .... .... .... .... .... .... .... .... .... 0001 = Trigger Type: Beamforming Report Poll (BRP) (1)
        .... .... .... .... .... .... .... .... .... .... .... .... 0000 1101 0110 .... = UL Length: 214
        .... .... .... .... .... .... .... .... .... .... .... ...0 .... .... .... .... = More TF: False
        .... .... .... .... .... .... .... .... .... .... .... ..1. .... .... .... .... = CS Required: True
        .... .... .... .... .... .... .... .... .... .... .... 10.. .... .... .... .... = UL BW: 80 MHz (2)
        .... .... .... .... .... .... .... .... .... .... ..10 .... .... .... .... .... = GI And LTF Type: 4x LTF + 3.2 us GI (2)
        .... .... .... .... .... .... .... .... .... .... .0.. .... .... .... .... .... = MU-MIMO LTF Mode: HE single stream pilot HE LTF mode
        .... .... .... .... .... .... .... .... .... ..01 0... .... .... .... .... .... = Number of HE-LTF Symbols and Midamble Periodicity: 0x2
        .... .... .... .... .... .... .... .... .... .0.. .... .... .... .... .... .... = UL STBC: False
        .... .... .... .... .... .... .... .... .... 1... .... .... .... .... .... .... = LDPC Extra Symbol Segment: True
        .... .... .... .... .... .... .... ..10 0001 .... .... .... .... .... .... .... = AP Tx Power: 13 dBm
        .... .... .... .... .... .... ...1 00.. .... .... .... .... .... .... .... .... = Packet Extension: PE disambiguity & pre-FEC padding factor of 4
        .... .... ...0 0000 0000 0000 000. .... .... .... .... .... .... .... .... .... = Spatial Reuse: 0x0000
        .... .... ..0. .... .... .... .... .... .... .... .... .... .... .... .... .... = Doppler: False
        .000 0000 00.. .... .... .... .... .... .... .... .... .... .... .... .... .... = UL HE-SIG-A2 Reserved: 0x000
        0... .... .... .... .... .... .... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
  v User Info
    > User Info: 0x4500f7a014
      Feedback Segment Retransmission Bitmap: 0xff
    > User Info: 0x450137c018
      Feedback Segment Retransmission Bitmap: 0xff
    > User Info: 0x4500f7e008
      Feedback Segment Retransmission Bitmap: 0xff
    > User Info: 0x450138001b
      Feedback Segment Retransmission Bitmap: 0xff
```

Trigger : Beamforming Report Poll

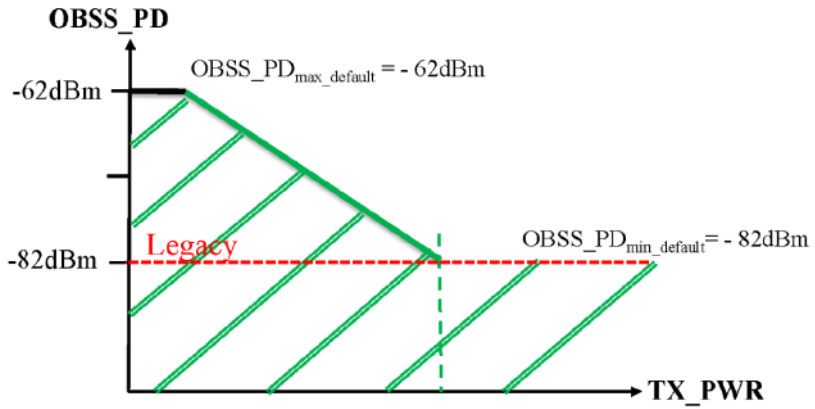
```
    Type/Subtype: Trigger (0x0012)
  > Frame Control Field: 0x2400
    .000 0001 0111 0110 = Duration: 374 microseconds
    Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
    Transmitter address: Technico_2d:3b:95 (a4:56:cc:2d:3b:95)
  v Common Info
    > HE Trigger Common Info: 0x00000012192a0d61
  v User Info
    v User Info: 0x4500f7a014
        .... .... .... .... .... .... .... 0000 0001 0100 = AID12: 0x014
        .... .... .... .... .... .... ...0 .... .... .... = RU Allocation Region: Not used for 20, 40 or 80MHz
        .... .... .... .... .... 0111 101. .... .... .... = RU Allocation: 61 (242 tones)
        .... .... .... .... ...1 .... .... .... .... .... = Coding Type: LDPC
        .... .... .... ...0 111. .... .... .... .... .... = MCS: 0x7
        .... .... .... ..0. .... .... .... .... .... .... = DCM: False
        .... .... ...0 00.. .... .... .... .... .... .... = Starting Spatial Stream: 1
        .... .... 000. .... .... .... .... .... .... .... = Number Of Spatial Streams: 1
        .100 0101 .... .... .... .... .... .... .... .... = Target RSSI: -41dBm
        0... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
      Feedback Segment Retransmission Bitmap: 0xff
    v User Info: 0x450137c018
        .... .... .... .... .... .... .... 0000 0001 1000 = AID12: 0x018
        .... .... .... .... .... .... ...0 .... .... .... = RU Allocation Region: Not used for 20, 40 or 80MHz
        .... .... .... .... .... 0111 110. .... .... .... = RU Allocation: 62 (242 tones)
        .... .... .... .... ...1 .... .... .... .... .... = Coding Type: LDPC
        .... .... .... ...1 001. .... .... .... .... .... = MCS: 0x9
        .... .... .... ..0. .... .... .... .... .... .... = DCM: False
        .... .... ...0 00.. .... .... .... .... .... .... = Starting Spatial Stream: 1
        .... .... 000. .... .... .... .... .... .... .... = Number Of Spatial Streams: 1
        .100 0101 .... .... .... .... .... .... .... .... = Target RSSI: -41dBm
        0... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
      Feedback Segment Retransmission Bitmap: 0xff
    > User Info: 0x4500f7e008
      Feedback Segment Retransmission Bitmap: 0xff
    > User Info: 0x450138001b
      Feedback Segment Retransmission Bitmap: 0xff
```

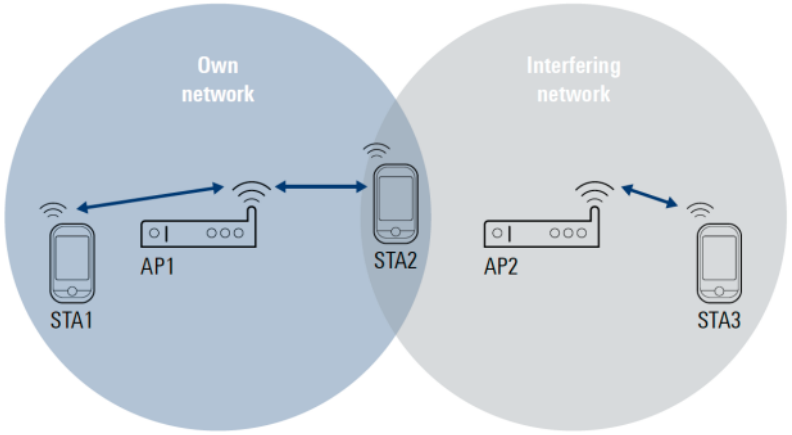
Trigger : Beamforming Report Poll

```
    Type/Subtype: Trigger (0x0012)
  > Frame Control Field: 0x2400
    .000 0001 0111 0110 = Duration: 374 microseconds
    Receiver address: Broadcast (ff:ff:ff:ff:ff:ff)
    Transmitter address: Technico_2d:3b:95 (a4:56:cc:2d:3b:95)
  v Common Info
    > HE Trigger Common Info: 0x00000012192a0d61
  v User Info
    > User Info: 0x4500f7a014
      Feedback Segment Retransmission Bitmap: 0xff
    > User Info: 0x450137c018
      Feedback Segment Retransmission Bitmap: 0xff
    v User Info: 0x4500f7e008
        .... .... .... .... .... .... .... 0000 0000 1000 = AID12: 0x008
        .... .... .... .... .... .... ...0 .... .... .... = RU Allocation Region: Not used for 20, 40 or 80MHz
        .... .... .... .... .... 0111 111. .... .... .... = RU Allocation: 63 (242 tones)
        .... .... .... .... ...1 .... .... .... .... .... = Coding Type: LDPC
        .... .... .... ...0 111. .... .... .... .... .... = MCS: 0x7
        .... .... .... ..0. .... .... .... .... .... .... = DCM: False
        .... .... ...0 00.. .... .... .... .... .... .... = Starting Spatial Stream: 1
        .... .... 000. .... .... .... .... .... .... .... = Number Of Spatial Streams: 1
        .100 0101 .... .... .... .... .... .... .... .... = Target RSSI: -41dBm
        0... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
      Feedback Segment Retransmission Bitmap: 0xff
    v User Info: 0x450138001b
        .... .... .... .... .... .... .... 0000 0001 1011 = AID12: 0x01b
        .... .... .... .... .... .... ...0 .... .... .... = RU Allocation Region: Not used for 20, 40 or 80MHz
        .... .... .... .... .... 1000 000. .... .... .... = RU Allocation: 64 (242 tones)
        .... .... .... .... ...1 .... .... .... .... .... = Coding Type: LDPC
        .... .... .... ...1 001. .... .... .... .... .... = MCS: 0x9
        .... .... .... ..0. .... .... .... .... .... .... = DCM: False
        .... .... ...0 00.. .... .... .... .... .... .... = Starting Spatial Stream: 1
        .... .... 000. .... .... .... .... .... .... .... = Number Of Spatial Streams: 1
        .100 0101 .... .... .... .... .... .... .... .... = Target RSSI: -41dBm
        0... .... .... .... .... .... .... .... .... .... = Reserved: 0x0
      Feedback Segment Retransmission Bitmap: 0xff
```

Trigger : Beamforming Report Poll

BSS Coloring and Spatial Reuse





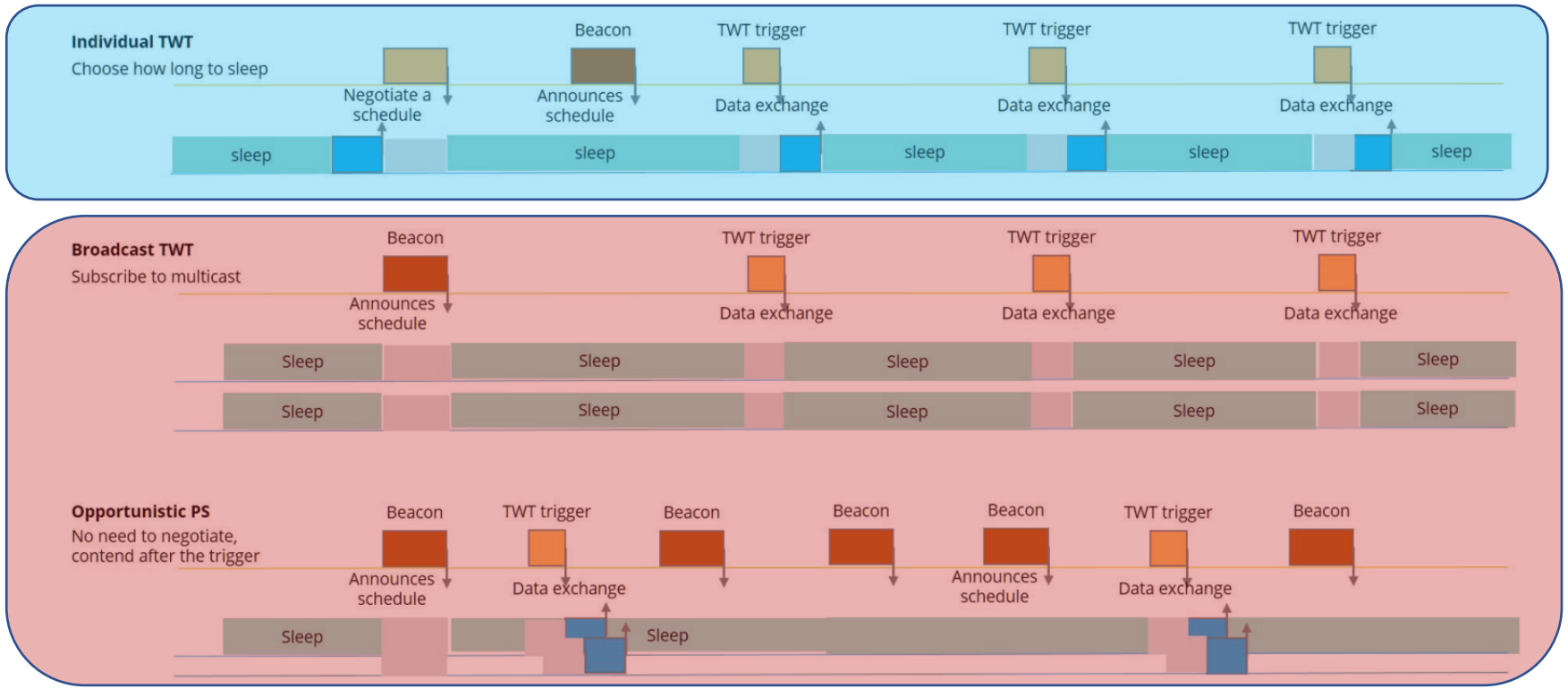

```
    HE Operation Parameters: 0x000004
        .... .... .... .... .... .100 = Default PE Duration: 4
        .... .... .... .... .... 0... = TWT Required: Not required
        .... .... ..00 0000 0000 .... = TXOP Duration RTS Threshold: 0
        .... .... .0.. .... .... .... = VHT Operation Information Present: False
        .... .... 0... .... .... .... = Co-Located BSS: False
        .... ...0 .... .... .... .... = ER SU Disable: False
        0000 000. .... .... .... .... = Reserved: 0x00
    BSS Color Information: 0x1a
        ..01 1010 = BSS Color: 0x1a
        .0.. .... = Partial BSS Color: False
        0... .... = BSS Color Disabled: False
    Basic HE-MCS and NSS Set: 0xfffc
        .... .... .... ..00 = Max HE-MCS for 1 SS: Support for HE-MCS 0-7 (0)
        .... .... .... 11.. = Max HE-MCS for 2 SS: Not supported for HE PPDUs (3)
        .... .... ..11 .... = Max HE-MCS for 3 SS: Not supported for HE PPDUs (3)
        .... .... 11.. .... = Max HE-MCS for 4 SS: Not supported for HE PPDUs (3)
        .... ..11 .... .... = Max HE-MCS for 5 SS: Not supported for HE PPDUs (3)
        .... 11.. .... .... = Max HE-MCS for 6 SS: Not supported for HE PPDUs (3)
        ..11 .... .... .... = Max HE-MCS for 7 SS: Not supported for HE PPDUs (3)
        11.. .... .... .... = Max HE-MCS for 8 SS: Not supported for HE PPDUs (3)
Ext Tag: MU EDCA Parameter Set
    Tag Number: Element ID Extension (255)
    Ext Tag length: 13
    Ext Tag Number: MU EDCA Parameter Set (38)
  QoS Information (AP): 0x08
  MUAC_BE Parameter Record
  MUAC_BK Parameter Record
  MUAC_VI Parameter Record
  MUAC_VO Parameter Record
Tag: Vendor Specific: Microsoft Corp.: WPS
    Tag Number: Vendor Specific (221)
    Tag length: 29
    OUI: 00:50:f2 (Microsoft Corp.)
    Vendor Specific OUI Type: 4
    Type: WPS (0x04)
  Version: 0x10
```

Power-based Spatial Reuse. Depending on the BSS color of the received PPDU. The AP can determine whether it is an intra or an inter transmission. An STA can choose to ignore an inter transmission and transmit on top by lowering its TX as showing in the OBSS_PD - TX_PWR curve.

```
        .... .... 0... .... = Ng = 16 MU Feedback: Not supported
        .... ...1 .... .... = Codebook Size SU Feedback: Supported
        .... ..0. .... .... = Codebook Size MU Feedback: Not supported
        .... .1.. .... .... = Triggered SU Beamforming Feedback: Supported
        .... 0... .... .... = Triggered MU Beamforming Feedback: Not supported
        ...1 .... .... .... = Triggered CQI Feedback: Supported
        ..0. .... .... .... = Partial Bandwidth Extended Range: Not supported
        .0.. .... .... .... = Partial Bandwidth DL MU-MIMO: Not supported
        1... .... .... .... = PPE Threshold Present: True
    Bits 56 to 71: 0x0018
        .... .... .... ...0 = SRP-based SR Support: Not supported
        .... .... .... ..0. = Power Boost Factor ar Support: Not supported
        .... .... .... .0.. = HE SU PPDU & HE MU PPDU w 4x HE-LTF & 0.8us GI: Not supported
        .... .... .01 1... = Max Nc: Supported
        .... .... .0.. .... = STBC Tx > 80 MHz: Not supported
        .... .... 0... .... = STBC Rx > 80 MHz: Not supported
        .... ...0 .... .... = HE ER SU PPDU W 4x HE-LTF & 0.8us GI: Not supported
        .... ..0. .... .... = 20 MHz In 40 MHz HE PPDU In 2.4GHz Band: Not supported
        .... .0.. .... .... = 20 MHz In 160/80+80 MHz HE PPDU: Not supported
        .... 0... .... .... = 80 MHz In 160/80+80 MHz HE PPDU: Not supported
        ...0 .... .... .... = HE ER SU PPDU W 1x HE-LTF & 0.8us GI: Not supported
        ..0. .... .... .... = Midamble Rx 2x & 1x HE-LTF: Not supported
        00.. .... .... .... = DCM Max BW: 0x0
    Bits 72 to 87: 0x000c
        .... .... .... ...0 = Longer Than 16 HE SIG-B OFDM Symbols Support: Not supported
        .... .... .... ..0. = Non-Triggered CQI Feedback: Not supported
        .... .... .... .1.. = Tx 1024-QAM Support < 242-tone RU: Supported
        .... .... .... 1... = Rx 1024-QAM Support < 242-tone RU: Supported
        .... .... ...0 .... = Rx Full BW SU Using HE MU PPDU With Compressed SIGB: Not supported
        .... .... ..0. .... = Rx Full BW SU Using HE MU PPDU With Non-Compressed SIGB: Not supported
        .... .... 00.. .... = Nominal Packet Padding: 0 µs for all Constellations (0)
        0000 0000 .... .... = Reserved: 0x00
  Supported HE-MCS and NSS Set
    Rx and Tx MCS Maps <= 80 MHz
    Rx and Tx MCS Maps 160 MHz
  PPE Thresholds
Ext Tag: HE Operation (IEEE Std 802.11ax/D3.0)
```

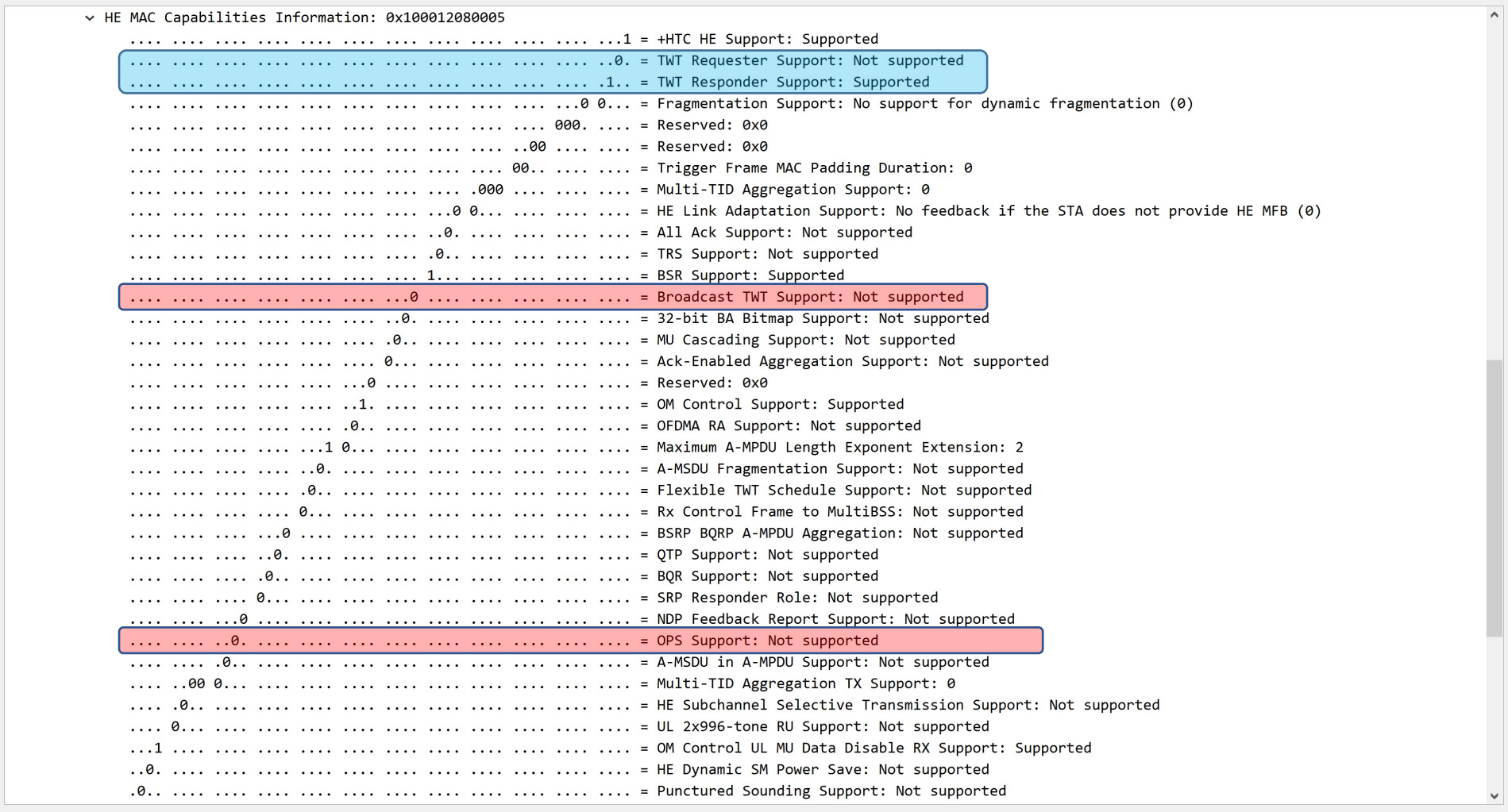
SRP-Based SR is an opportunistic Spatial Reuse were an AP scheduling an UL OFDMA transmission can inform neighboring AP through the trigger frame that they are allowed to transmit on top of the UL OFDMA PPDU if they meet the TX power constraints in the trigger frame.

TWT (Target Wait Time)

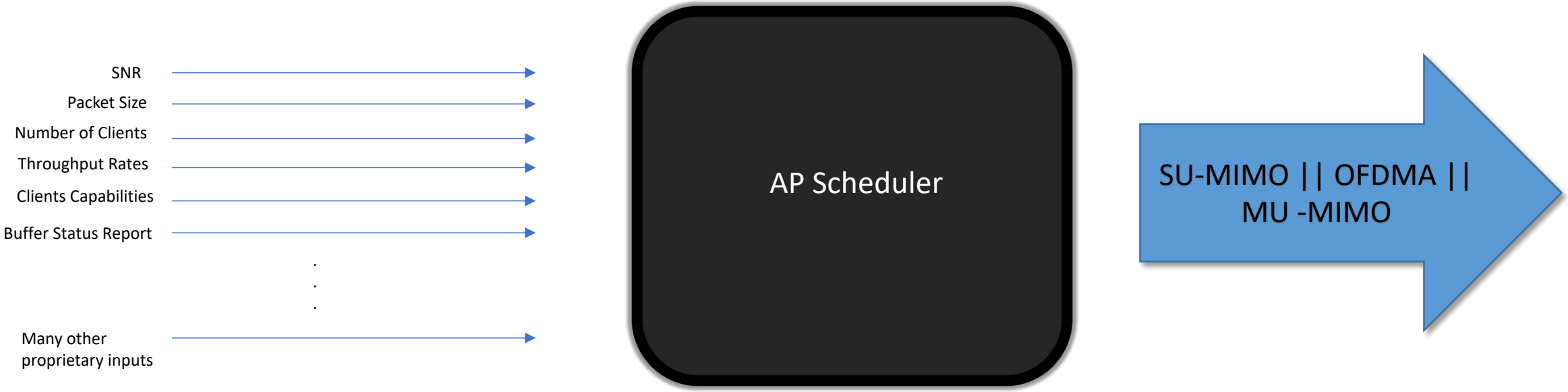


- TWT was adopt by the 802.11ax TaskGroup to help integrate IoT into the WiFi Ecosystem.
- TWT allows a requesting STA (IoT device) to negotiate with a responding STA (AP) a service period SP.
- During the service period a STA can wake, exchange data with the AP and then go back to sleep.
- Sleep and service periods are independent of the beacon interval unlike legacy DTIM.
- This allows the clients theoretically to sleep for hours even days.

TWT Support in Beacon Element



The Scheduler



- Small Frame sizes (128-512): Higher possibility of OFDMA
- Large Frame sizes (1024-1500) :Higher possibility of SU or MU MIMO
- High RSSI Values (-35 to -65): Higher possibility of DL MU-MIMO
- Low RSSI Values (-75 to -90): Higher possibility of OFDMA