Analysing WLAN 802.11n MIMO with AirPcap N

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Session Agenda

- Design Goals for 802.11n
- IEEE 802.11n physical layer improvements
- IEEE 802.11n MAC layer improvements
- Per-Packet Information Header
- Analysing ‘Bad BAR’ and ‘Deadlock’ problem
- Bandwidth Measurement
- Backwards compatibility to a/b/g
- Future of 802.11n

Design Goals for 802.11n

- IEEE 802.11n is a proposed amendment to the IEEE 802.11-2007 wireless networking standard
- Significantly improve PHY layer transmission rate over previous standards, such as 802.11a and 802.11b/g with 'High Throughput' (HT) options
- Increasing the MAC layer transfer rate to achieve a minimum of 100 Mbps data throughput
- Maintain backward compatibility with existing IEEE WLAN legacy solutions (802.11a/b/g)

How the Goals are achieved

A combination of technical functions at PHY and MAC layers are added to the existing 802.11 standard:

- ✓ Increasing the physical transfer rate with new modulation scheme and timing up to 600Mbps
- ✓ New multi-streaming modulation technique using MIMO (multiple input, multiple output antennas)
- ✓ Joining two adjacent channels with Channel bonding
- ✓ Support for frame aggregation A-MPDU & A-MSDU
- ✓ New Block Acknowledgments

PHY layer improvements

Modified OFDM

- The number of OFDM data sub-carriers is increased from 48 to 52 which improves the maximum throughput from 54 to 58.5 Mbps

Forward Error Correction

- FEC is a system of error control whereby the sender adds redundant data to allow the receiver to detect and correct errors. 3/4 coding rate is improved with 5/6 boosting the link rate from 58.5 to 65 Mbps

PHY layer improvements (cont.)

Shorter Guard Interval (GI)

- The GI between OFDM symbols is reduced from 800ns to 400ns and increases throughput from 65 to 72.2 Mbps

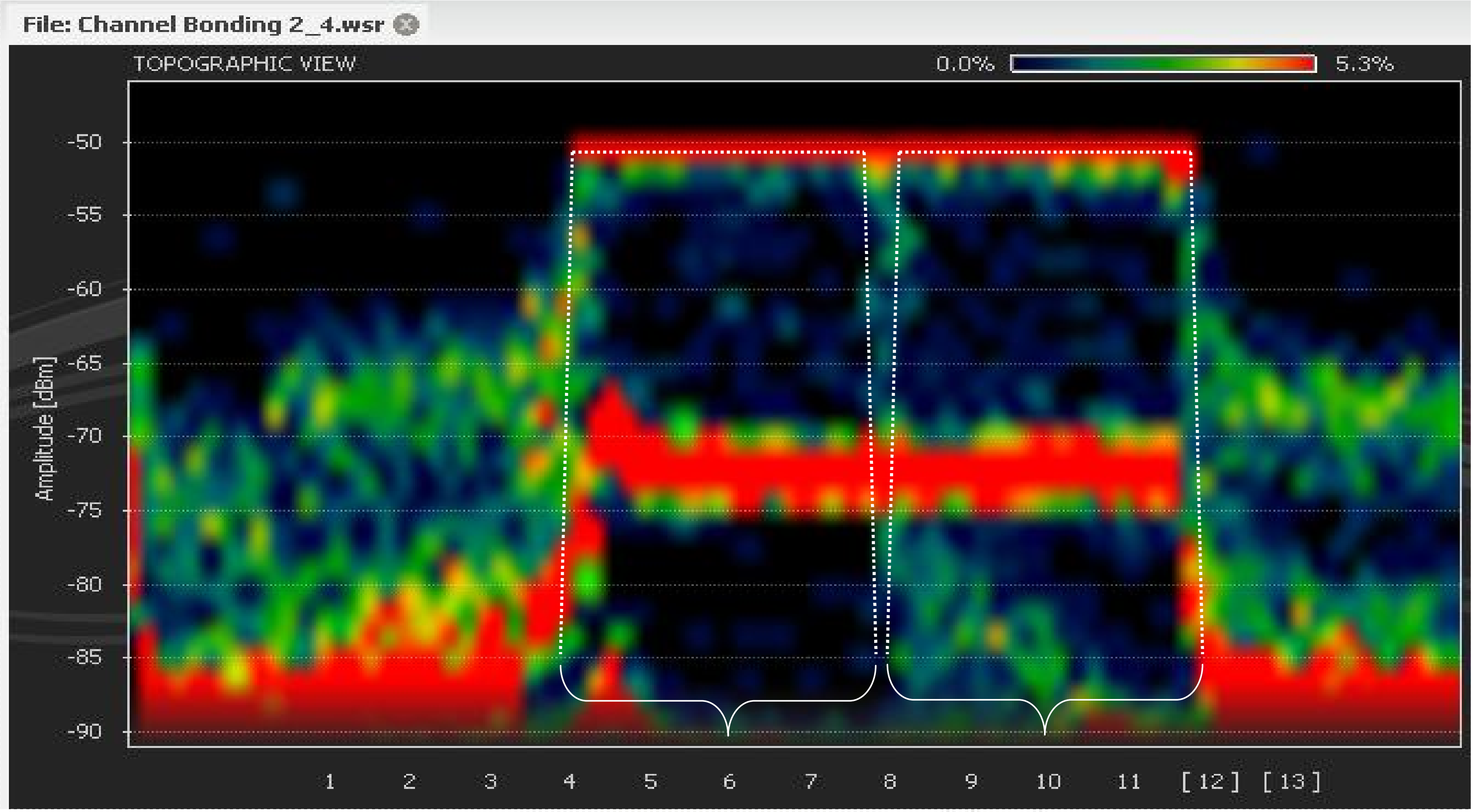
Channel Bonding

- Doubling channel bandwidth from 20 to 40 MHz slightly more than doubles rate from 72.2 to 150 Mbps

Spatial multiplexing

- Support of up to four spatial streams (MIMO) increases throughput up to 4 times 150 to 600 Mbps

Channel Bonding (Channel 6 & 10)

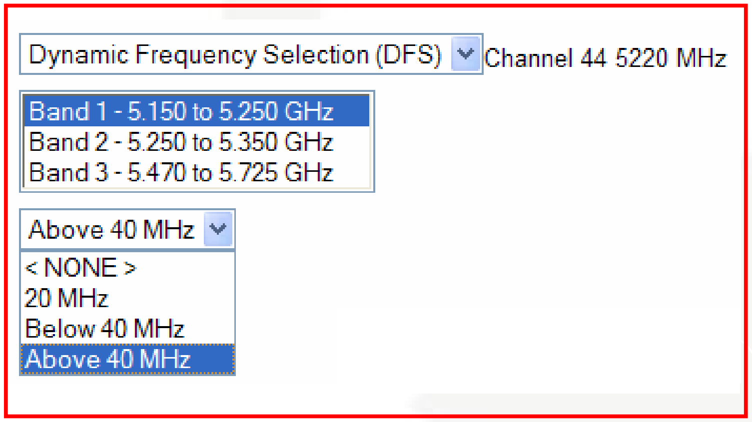


Recorded with Wi-Spy® from MetaGeek

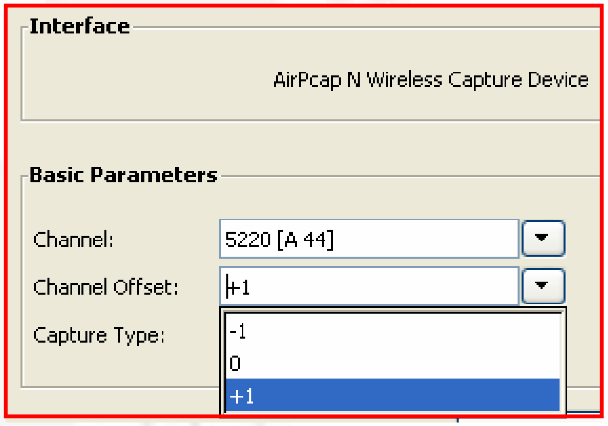
Channel Bonding (configuration)

802.11n supports bundling of two 20 MHz channels

- Select a control channel # and the channel offset
- Both channels must fit inside allowed frequency range
- A-band does not allow to select channel # manually



Configuration on Cisco AP1250



Configuration on AirPcap N

Channel Allocation 5GHz Band

Frequency Band	Channel ID	FCC (GHz)	ETSI (GHz)	MKK (GHz)
Lower Band UNII-1	34	--	--	5.170
	36	5.180	5.180	--
	38	--	--	5.190
	40	5.200	5.200	--
	42	--	--	5.210
	44	5.220	5.220	--
	46	--	--	5.230
	48	5.240	5.240	--
Middle Band UNII-2	52	5.260*	5.260	5.260
	56	5.280*	5.280	5.280
	60	5.300*	5.300	5.300
	64	5.320*	5.320	5.320
High Band UNII-2 extended	100	5.500*	5.500	5.500
	104	5.520*	5.520	5.520
	108	5.540*	5.540	5.540
	112	5.560*	5.560	5.560
	116	5.580*	5.580	5.580
	120	5.600*	5.600	5.600
	124	5.620*	5.620	5.620
	128	5.640*	5.640	5.640
	132	5.660*	5.660	5.660
	136	5.680*	5.680	5.680
	140	5.700*	5.700	5.700
Upper Band UNII-3/ISM	149	5.745	--	--
	153	5.765	--	--
	157	5.785	--	--
	161	5.805	--	--
ISM	165	5.825	--	--

Available non-overlapping channels	
FCC (USA and Canada)	24
ETSI (Europe)	19
MKK (Japan)	19

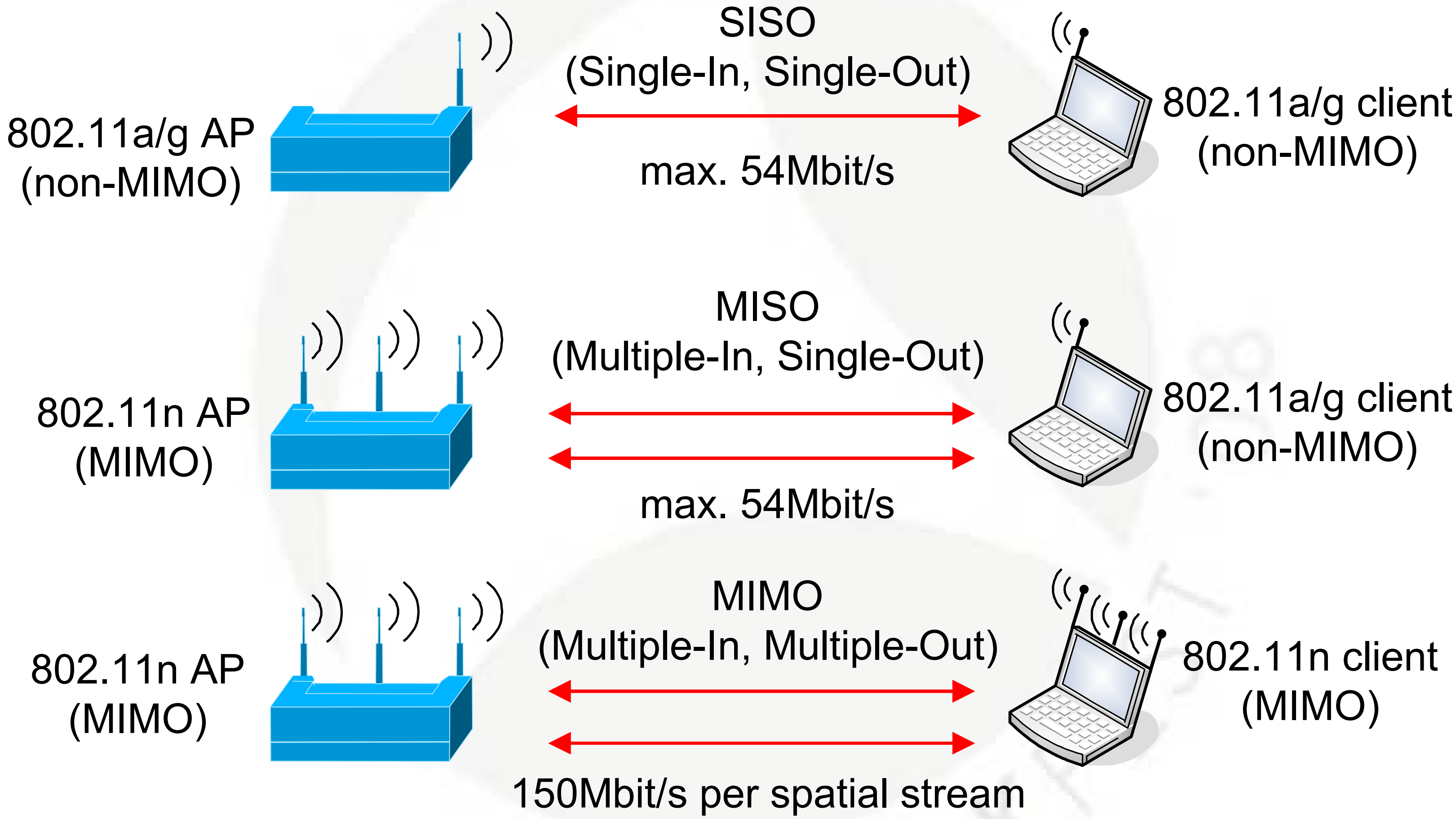
Transmit Power Control (TPC) required for	
FCC (USA and Canada)	Band 2,2e
ETSI (Europe)	Band 1,2,2e
MKK (Japan)	Band 1,2,2e

Dynamic Frequency Selection (DFS) required for	
FCC* (USA and Canada)	Band 2,2e
ETSI (Europe)	Band 1,2,2e
MKK (Japan)	Band 1,2,2e

Some channels only allowed for inhouse use

*New stricter FCC DFS2 rules valid off July 20, 2007

Multi-Streaming Modulation



Modulation Coding Scheme (MCS)

802.11n introduces a new Modulation Coding Scheme

- 802.11 b/g adapts to channel conditions by selecting the highest of 12 possible rates from 1 to 54 Mbps
- The 802.11n standard will allow some 77 possible MCS' - some compulsory, some optional
- MCS selects, based on RF channel conditions, the best combination of 8 data rates, bonded channels, multiple spatial streams, different guard intervals and modulation types

MCS Configuration

Data Rates: [Best Range] [Best Throughput] [Default]

6.0Mb/sec	◉ Require	○ Enable	○ Disable
9.0Mb/sec	◉ Require	○ Enable	○ Disable
12.0Mb/sec	◉ Require	○ Enable	○ Disable
18.0Mb/sec	◉ Require	○ Enable	○ Disable
24.0Mb/sec	◉ Require	○ Enable	○ Disable
36.0Mb/sec	◉ Require	○ Enable	○ Disable
48.0Mb/sec	◉ Require	○ Enable	○ Disable
54.0Mb/sec	◉ Require	○ Enable	○ Disable

MCS Rates:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Enable	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉
Disable	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

MCS 0–7: 1 spatial stream

MCS 8–15: 2 spatial streams

Screenshot Cisco AP1250

MCS Rate Chart

MCS Rate Chart		20 MHz Channel								40 MHz Channel							
		1 Stream (non MIMO)				2 Streams (MIMO)				1 Stream (non MIMO)				2 Streams (MIMO)			
802.11n 2.4GHz GI = 800ns	MCS Rate	0	1	2	3	8	9	10	11	n.a.				n.a.			
	Mbps	6.5	13	19.5	26	13	26	39	52								
	Mbps	39	52	58.5	65	78	104	117	130								
	MCS Rate	4	5	6	7	12	13	14	15								
802.11n 5GHz GI = 800ns	MCS Rate	0	1	2	3	8	9	10	11	0	1	2	3	8	9	10	11
	Mbps	6.5	13	19.5	26	13	26	39	52	13.5	27	40.5	54	27	54	81	108
	Mbps	39	52	58.5	65	78	104	117	130	81	108	121.5	135	162	216	243	270
	MCS Rate	4	5	6	7	12	13	14	15	4	5	6	7	12	13	14	15
802.11n 5GHz GI = 400ns	MCS Rate	0	1	2	3	8	9	10	11	0	1	2	3	8	9	10	11
	Mbps	7.2	14.4	21.7	28.9	14.4	28.9	43.3	57.8	15	30	45	60	30	60	90	120
	Mbps	43.3	57.8	65	72.2	86.7	115.6	130	144.4	90	120	135	150	180	240	270	300
	MCS Rate	4	5	6	7	12	13	14	15	4	5	6	7	12	13	14	15

MAC layer improvements

Frame Aggregation Mechanisms

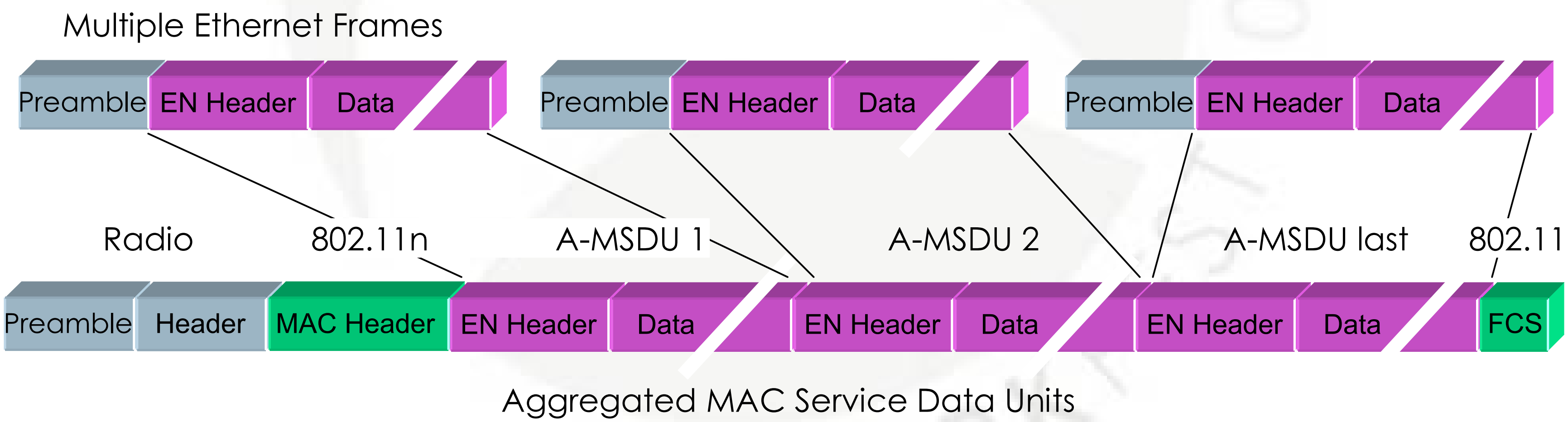
- Aggregate-MAC Service Data Unit (A-MSDU) wraps multiple Ethernet frames in a 802.11 frame up to 8KB
- Aggregate-MAC Protocol Data Unit (A-MPDU) allows bursting 802.11 frames up to 64KB
- A-MPDU is performed in the software whereas A-MSDU is performed in the hardware

Block Acknowledgement

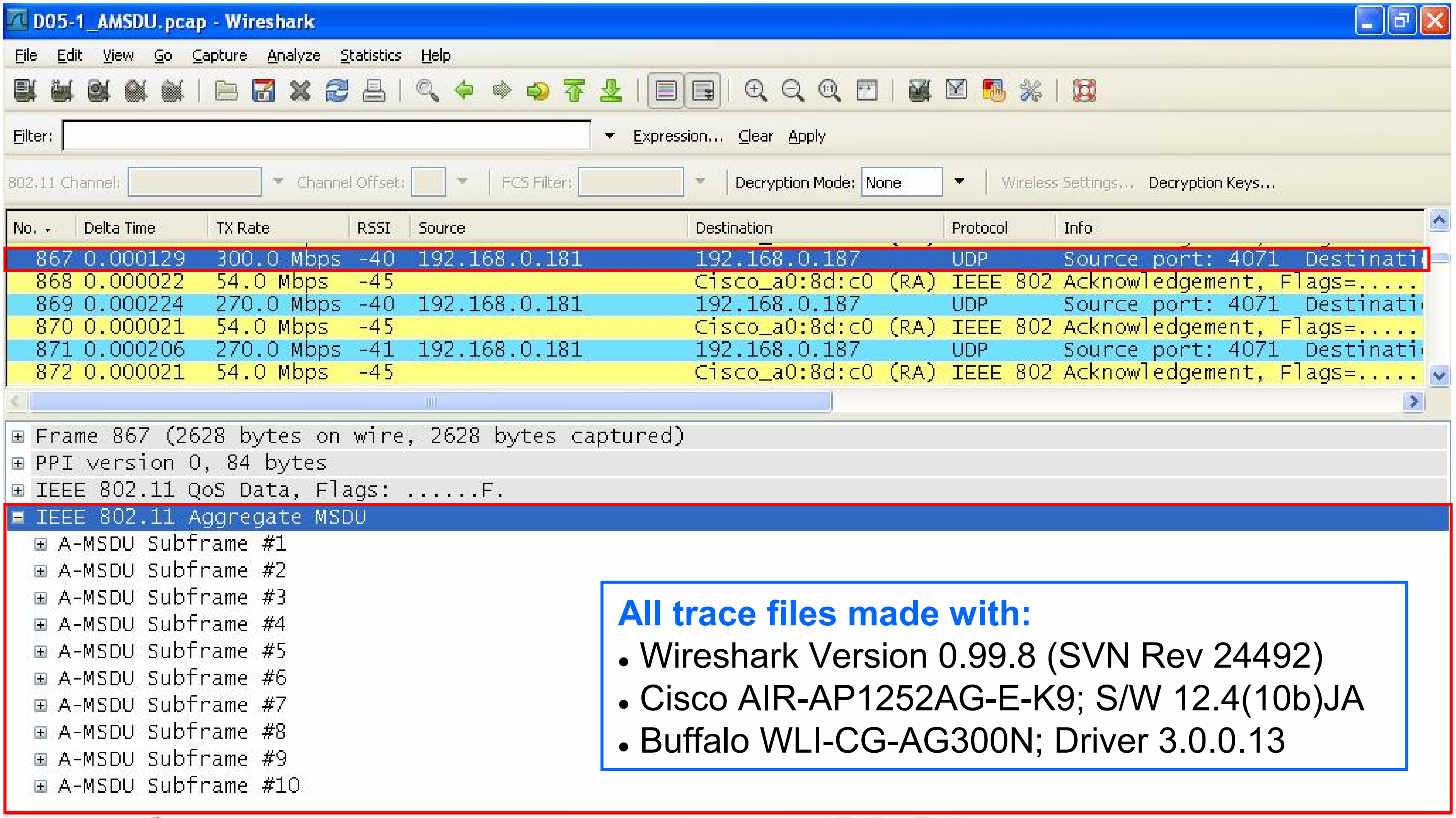
- Block ACK effectively eliminates the need to initiate a new transfer for every MPDU

MSDU Aggregation

- Multiple Ethernet frames for a common destination are wrapped in a single 802.11 frame
- More efficient than A-MPDU as only one radio- and 802.11 MAC header is applied
- Whole frame must be retransmitted if no acknowledge



A-MSDU Analysis

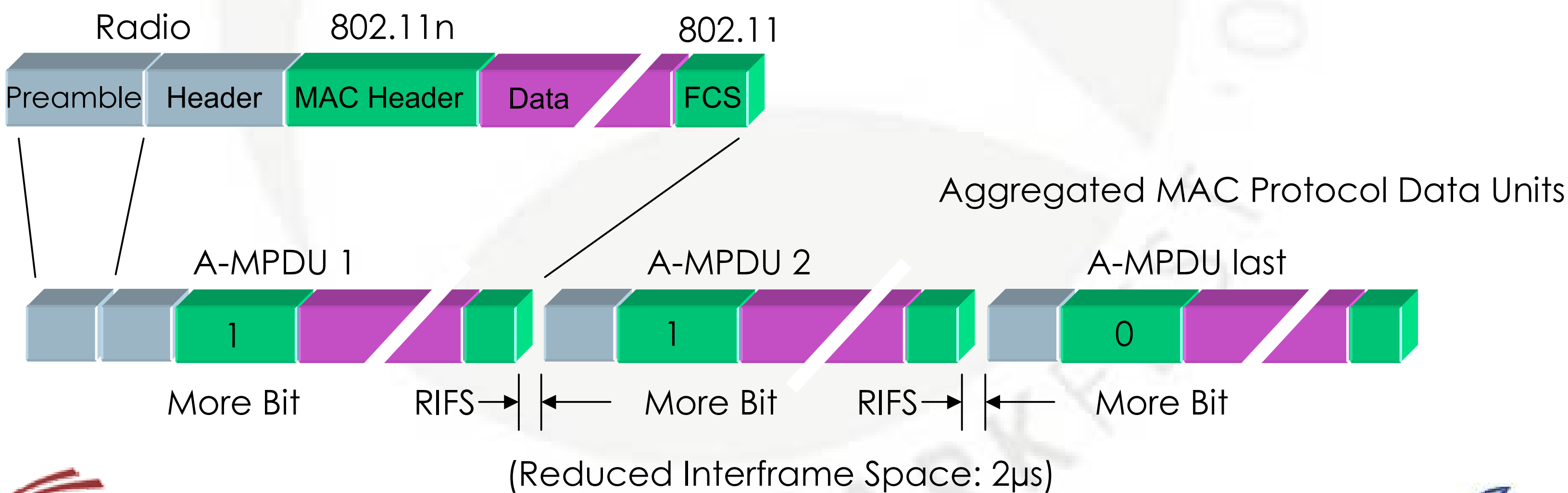


All trace files made with:

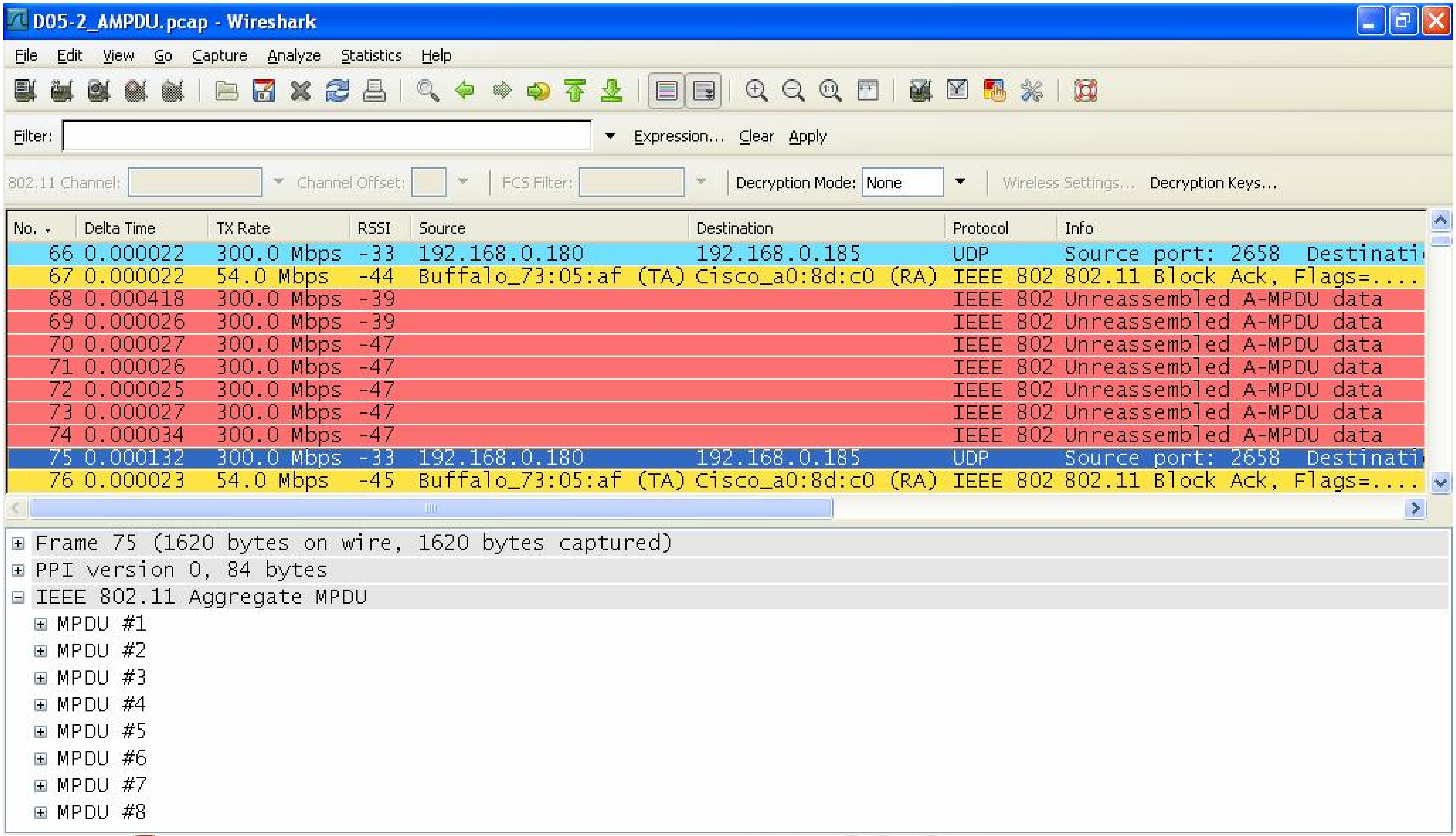
- Wireshark Version 0.99.8 (SVN Rev 24492)
- Cisco AIR-AP1252AG-E-K9; S/W 12.4(10b)JA
- Buffalo WLI-CG-AG300N; Driver 3.0.0.13

MPDU Aggregation

- Multiple Ethernet frames for a common destination are translated to 802.11 format and sent as burst
- Elements of an A-MPDUs burst can be acknowledged individually with one single Block-Acknowledge
- Only not-acknowledged A-MPDUs are retransmitted



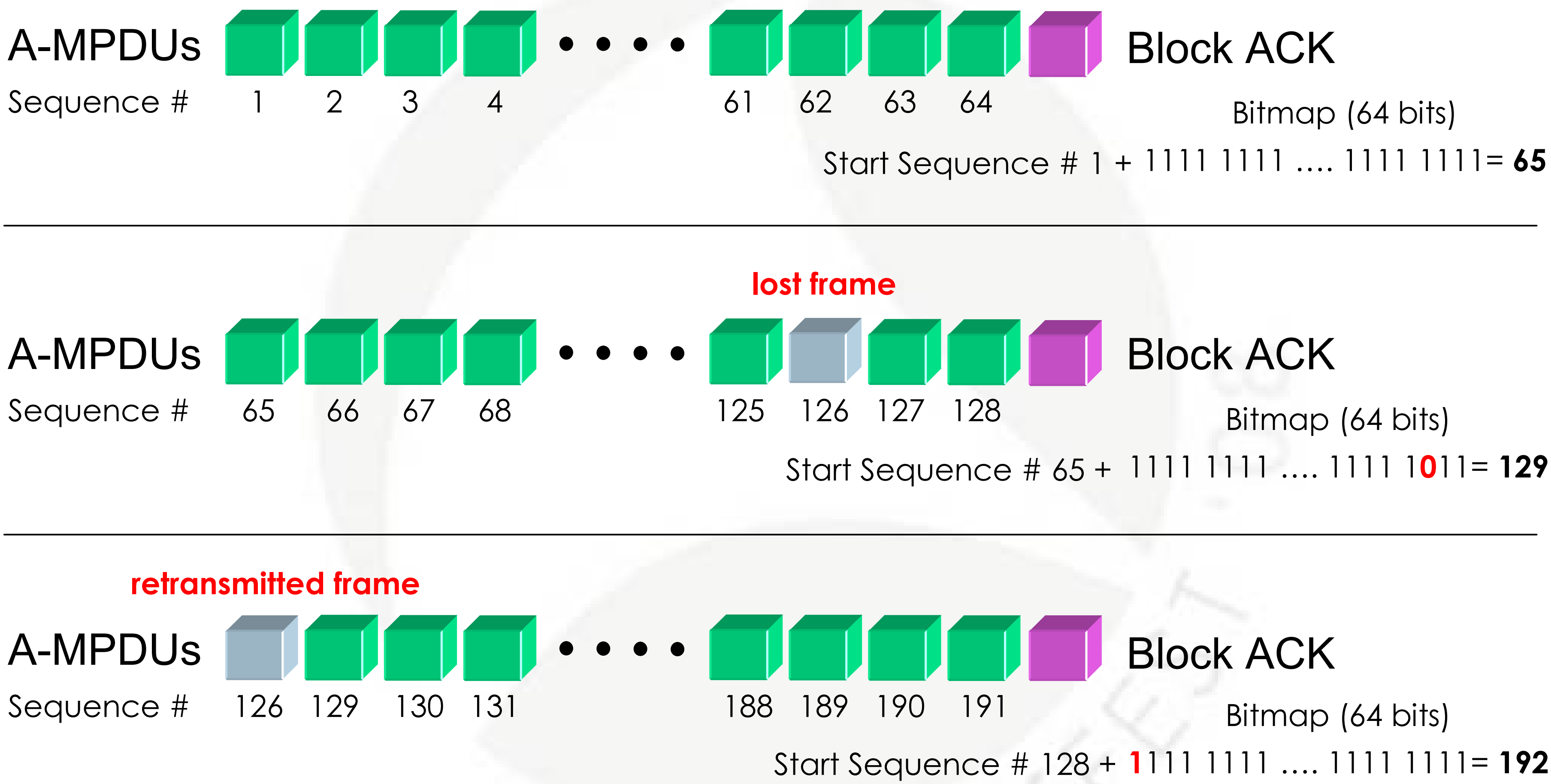
A-MPDU Analysis



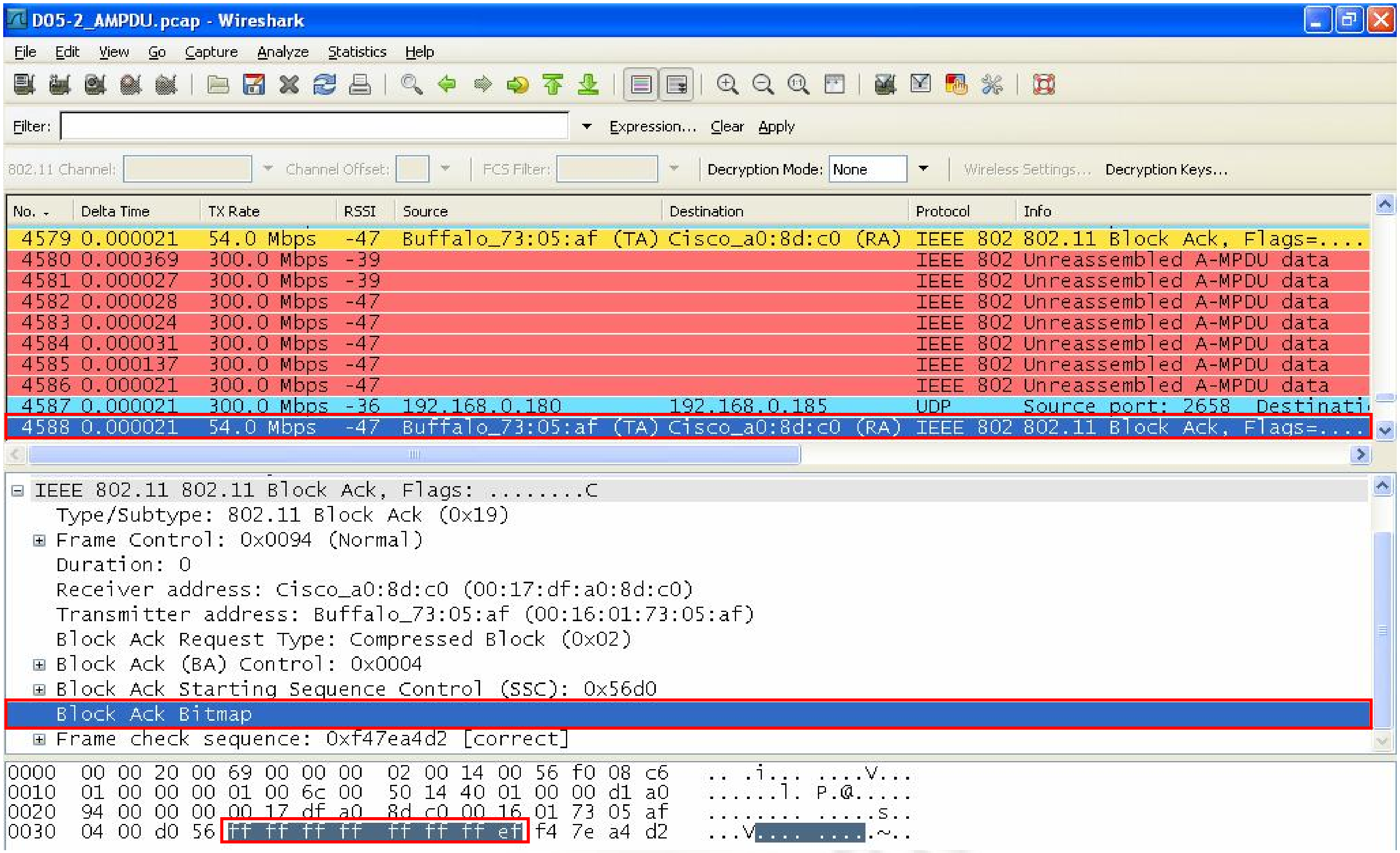
Block-ACK Mechanism

- Rather than sending an individual acknowledge following each data frame, 802.11n introduces the technique of confirming a burst of up to 64 frames with a single Block ACK (BA) frame
- The Block ACK even contains a bitmap to selectively acknowledge individual frames of a burst (comparable to selective acknowledges of TCP)
- The use of combined acknowledges can be requested by sending a Block ACK Request (BAR)

Block-ACK Mechanism (cont.)



Block-ACK Bitmap Analysis



Block-ACK Bitmap Analysis (cont.)

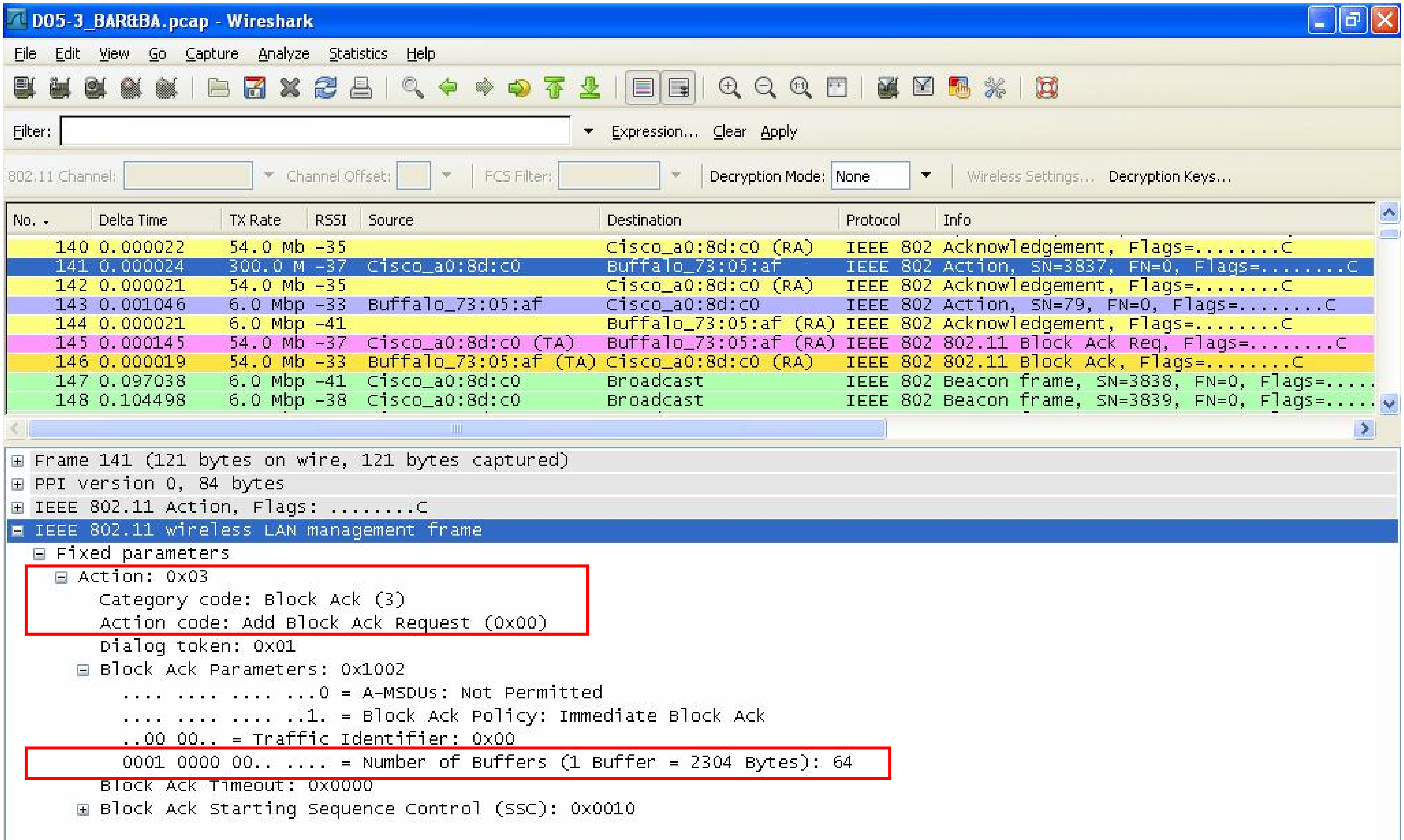
Frame #	Type	Sequence #			Bitmap (64 bits)
4579	Block ACK	Start Sequence # 1381+ 64 = 1445			**FF FF .... FF FF**
4580	MPDU #1	1445	1		
4581	MPDU #2	1446	1	**F**	
4582	MPDU #3	1447	1		
4583	MPDU #4	1448	1		
4584	MPDU #5	**1449 lost frame**	0		
4585	MPDU #6	1450	1	**E**	
4586	MPDU #7	1451	1		
4587	MPDU #8	1452	1		
4588	Block ACK	Start Sequence # 1389 + 64 = 1453			**FF FF .... FF EF**
4589	MPDU #1	**1449 retransmitted frame**			
4590	MPDU #2	1453			
4591	MPDU #3	1454			
4592	MPDU #4	1455			
4593	MPDU #5	1456			
4594	MPDU #6	1457			
4595	MPDU #7	1458			
4596	MPDU #8	1459			
4597	MPDU #9	1460			
4598	MPDU #10	1461			
4599	Block ACK	Start Sequence # 1398 + 64 = 1462			**FF FF .... FF FF**

Trace file: D05_AMPDU.pcap

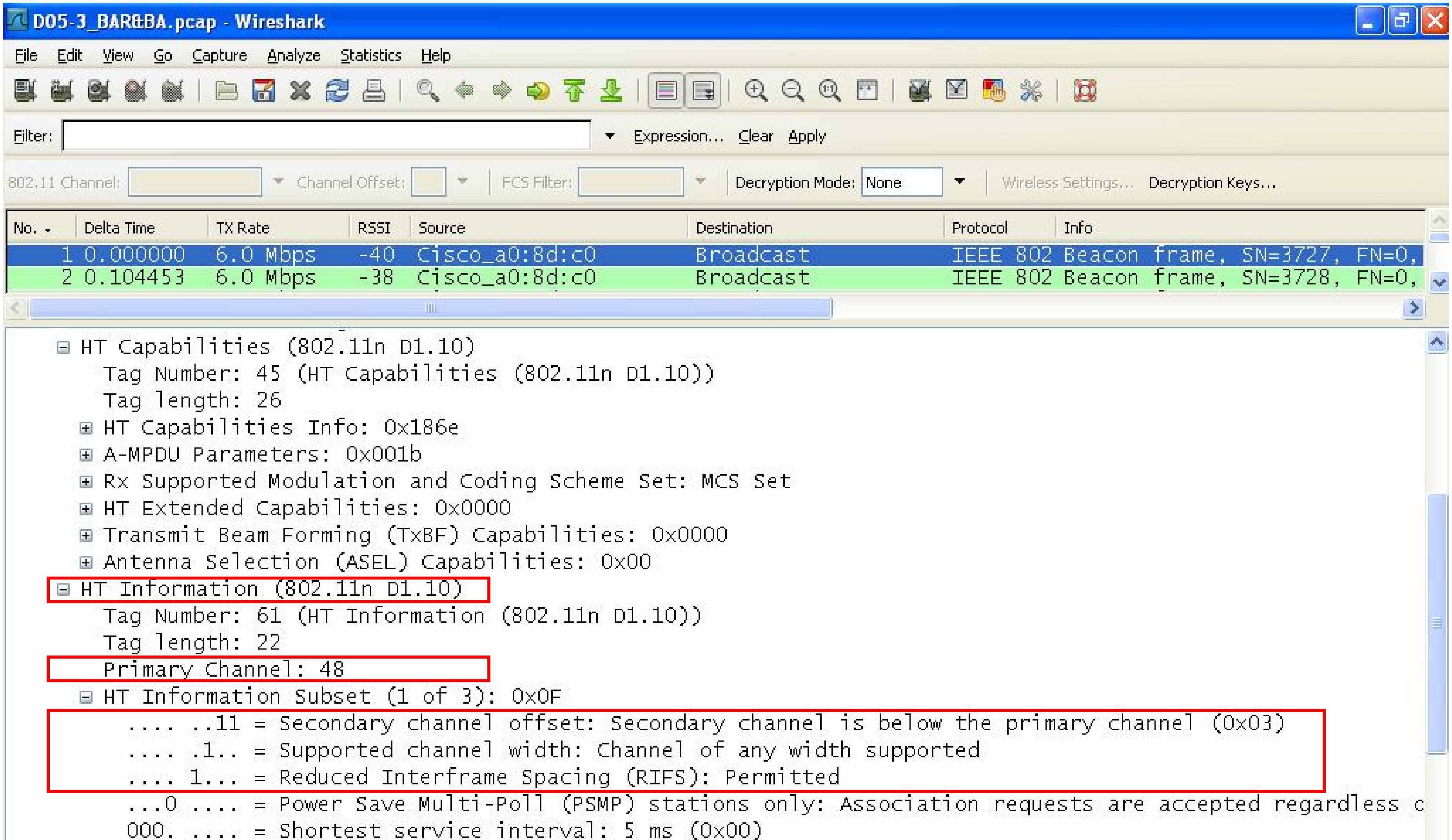
Block-ACK negotiation/activation

- The Block-ACK options are negotiated and confirmed with ‘Action’ frames defined in 802.11e (WLAN QoS)
- ‚Action‘ frames are used to negotiate other options too
  - Category Code 0 = Spectrum management
  - Category Code 1 = QoS options
  - Category Code 2 = DLS (Direct Link Setup)
  - Category Code 3 = Block Ack
- The use of combined acknowledges can be requested by sending a Block ACK Request (BAR)

Block-ACK negotiation/activation (cont.)

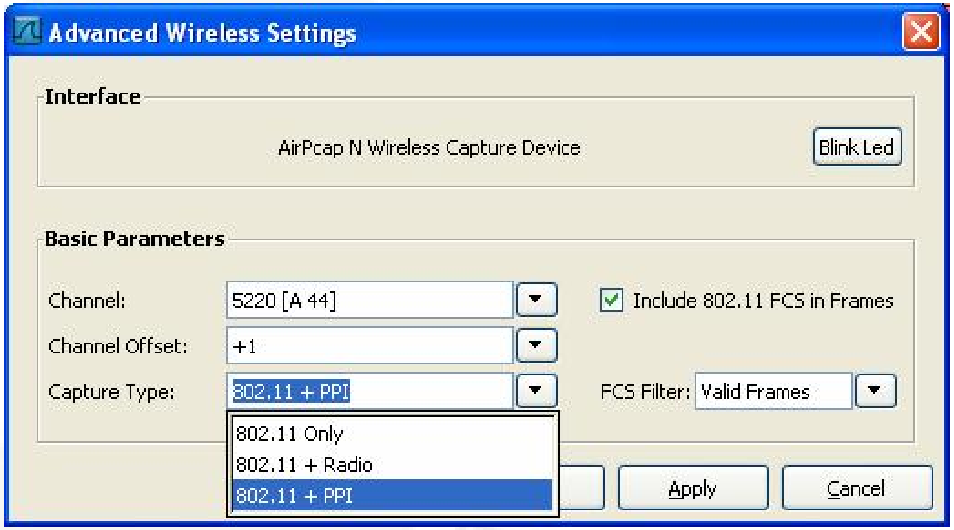


New HT Capabilities in Beacon Frame



Per-Packet Information Header (PPI)

- New PPI header replaces the radiotap header used in 802.11a/b/g with additional 802.11n radio information
- PPI adds a pseudo-header to each packet and provides Meta data about RF signal strength, timing, options etc.

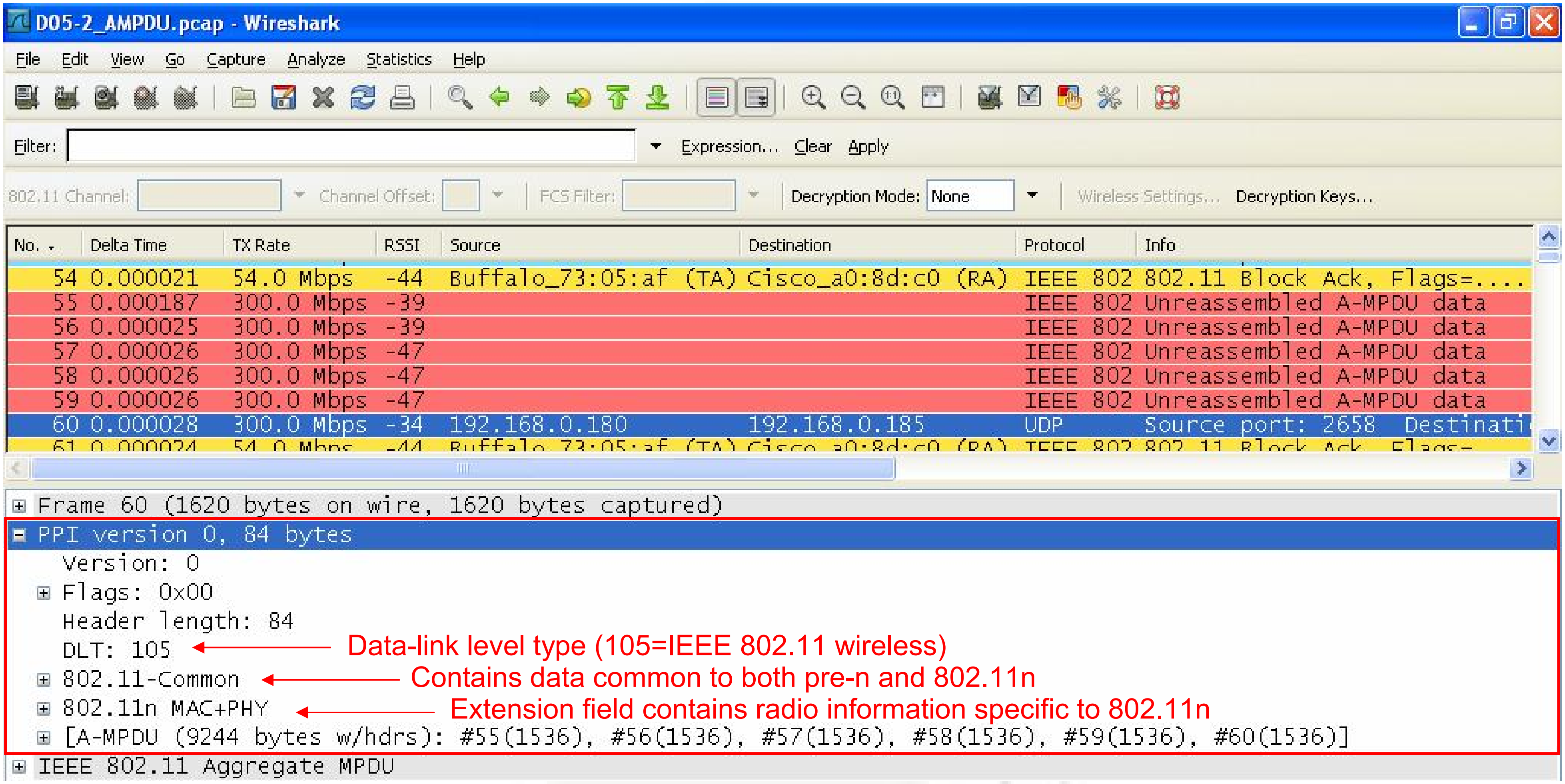


References

Radiotap manual: http://netbsd.gw.com/cgi-bin/man-cgi?ieee80211_radiotap+9+NetBSD-current

PPI manual: http://www.cacetech.com/documents/PPI_Header_format_1.0.1.pdf

Per-Packet Information Header (cont.)



Per-Packet Information Header (cont.)

```
802.11n MAC+PHY
    Field type: 802.11n MAC+PHY Extensions (4)
    Field length: 48
  MAC flags: 0x00000016
     .... .... .... .... .... .... .... ...0 = Greenfield flag: False
     .... .... .... .... .... .... .... ..1. = HT20/HT40 flag: HT40
     .... .... .... .... .... .... .... .1.. = RX Short Guard Interval (SGI) flag: True
     .... .... .... .... .... .... .... 0... = Duplicate RX flag: False
     .... .... .... .... .... .... ...1 .... = Aggregate flag: True
     .... .... .... .... .... .... ..0. .... = More aggregates flag: False
     .... .... .... .... .... .... .0.. .... = A-MPDU Delimiter CRC error after this frame flag: False
     0... .... .... .... .... .... .... .... = Debug Flag (more desc): False
    AMPDU-ID: 0x000131cd
    Num-Delimiters: 0
    MCS: 15
    Number of spatial streams: 2
    RSSI combined: 62
    Antenna 0 control RSSI: 53
    Antenna 1 control RSSI: 58
    Antenna 2 control RSSI: 58
    Antenna 3 control RSSI: 255 [invalid]
    Antenna 0 extension RSSI: 55
```

AirPcap N and Wireshark

AirPcap N and Wireshark is the perfect combination for:

- Learning about how things are functioning
- Finding out what 802.11n options and capabilities are offered and negotiated in the air
- Verifying vendor specifications (like throughput etc.)
- Investigating compatibility issues between vendors
- Training technical people

and much more…

Frame Aggregation (configuration examples)

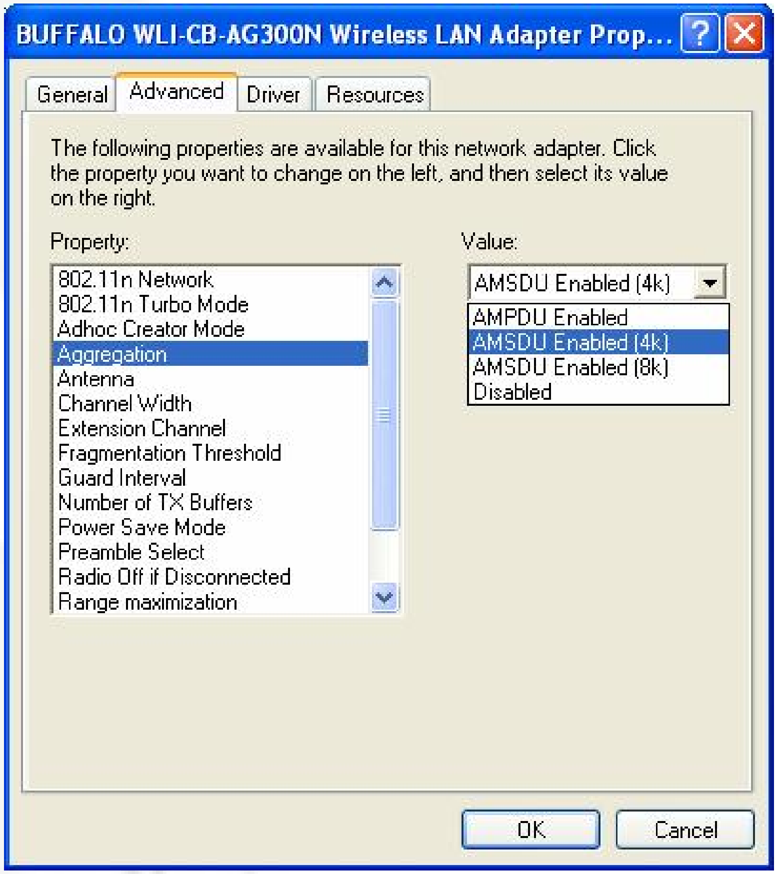
Cisco's 802.11abgn AP1250

By disabling A-MPDU with the 'no' command, the traffic associated with that priority level uses A-MSDU transmission

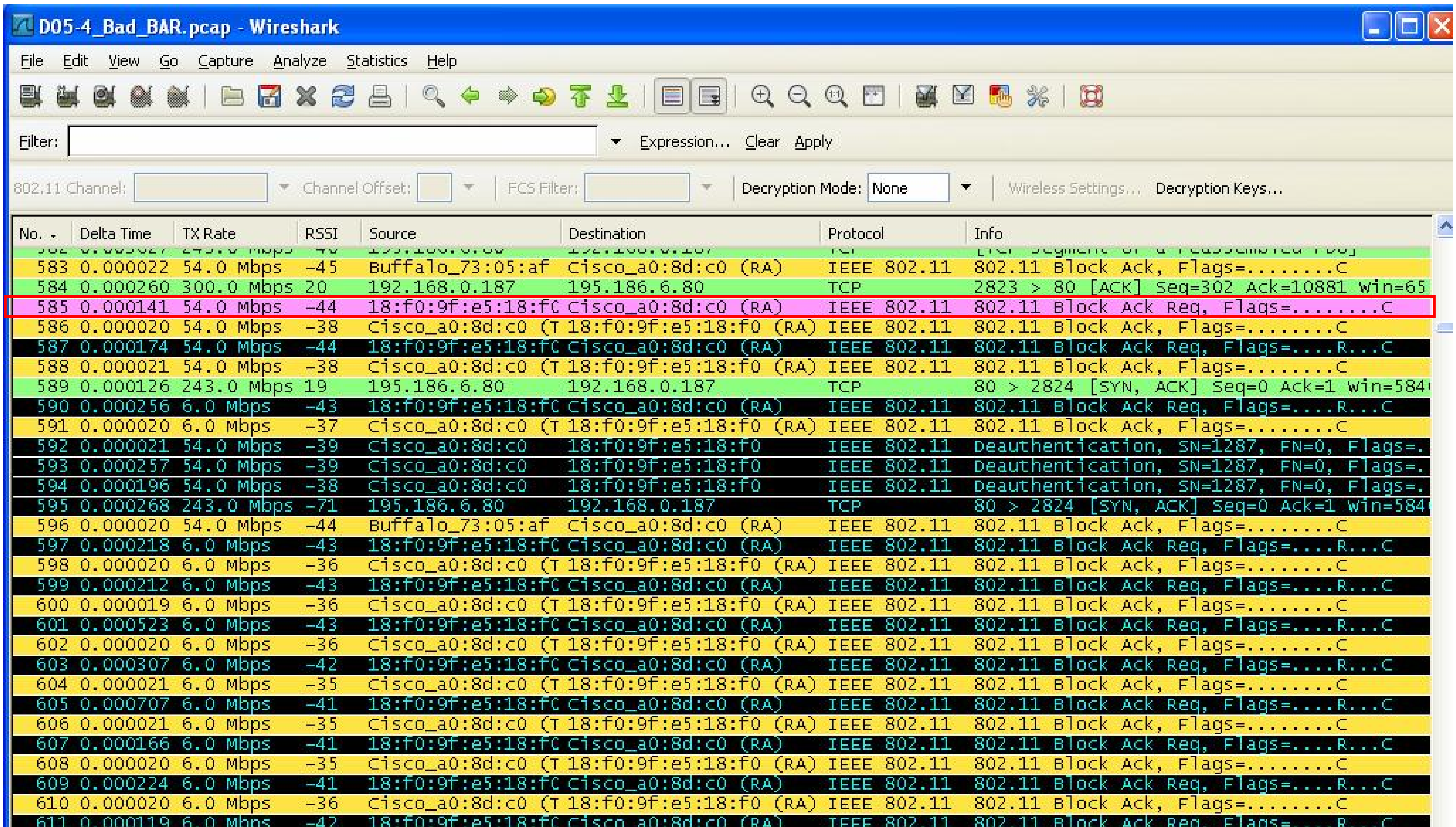
Command line interface:

```
ap1250(config)#interface dot11Radio 1
ap1250(config-if)#no ampdu transmit priority 0
```

Buffalo's 802.11abgn PC-Card

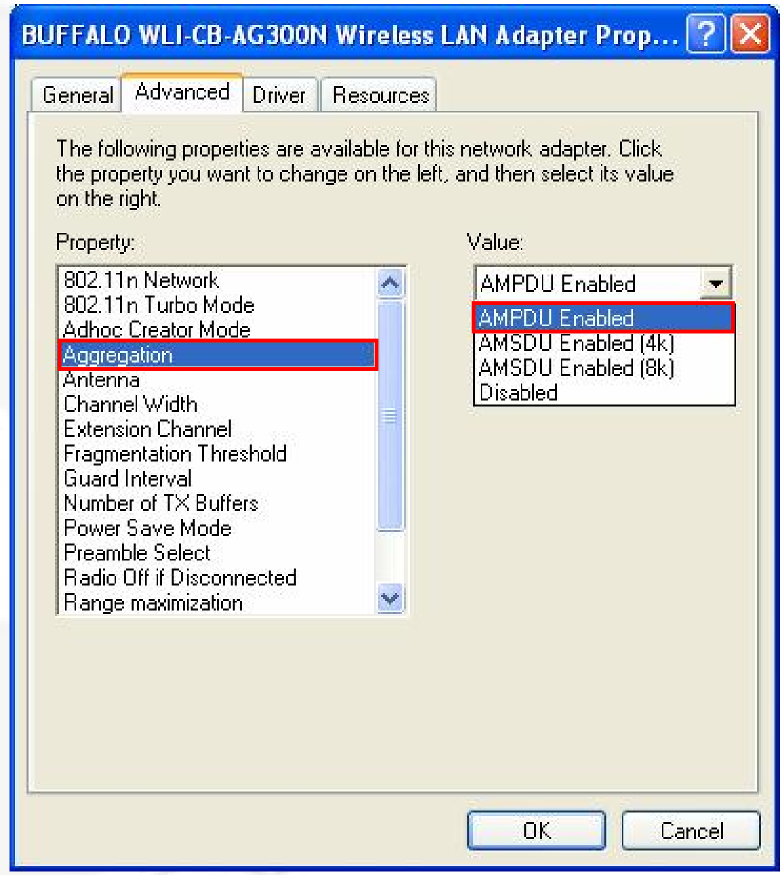


Analysing 'Bad BAR' problem

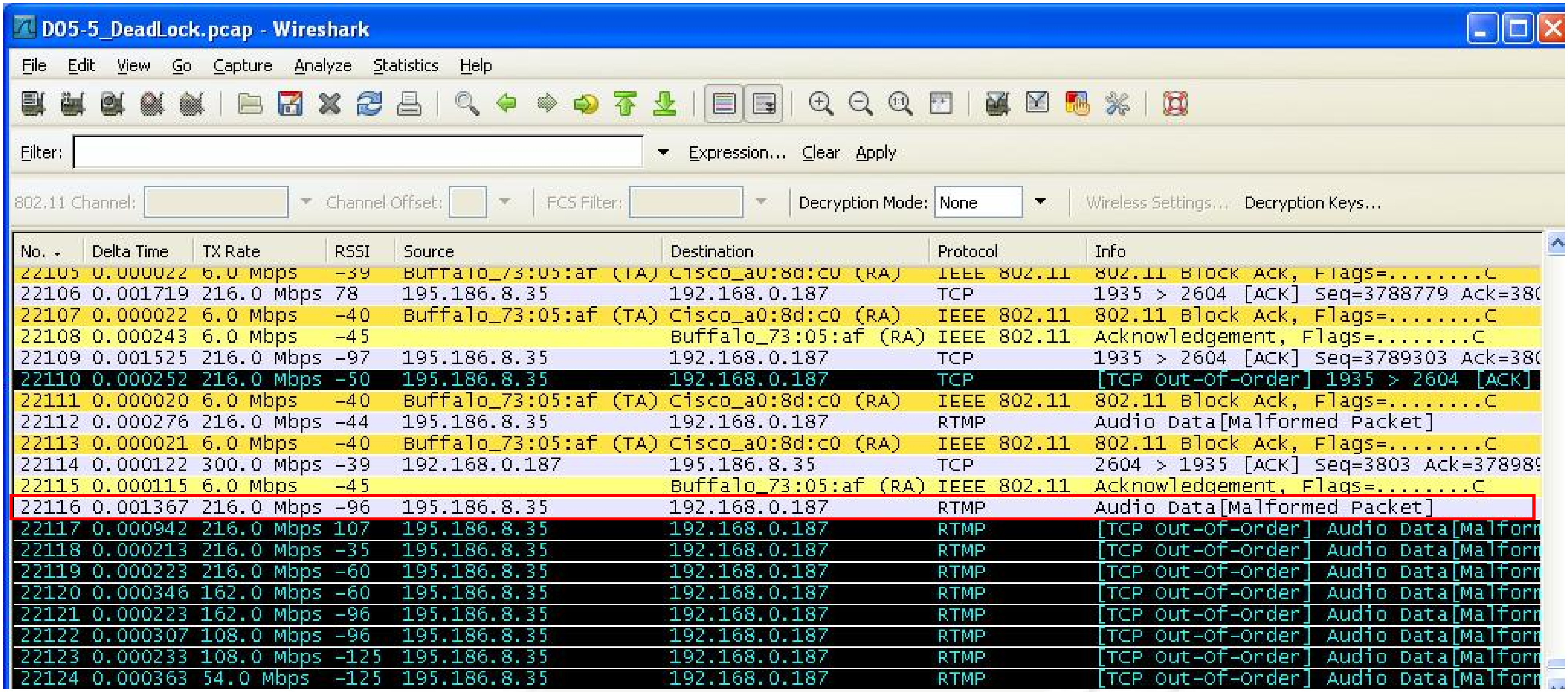


Analysing 'Bad BAR' problem (cont.)

- Buffalo WLI-CB-AG300N is using strange SRC MAC address when sending BAR
- Problem occurs only when A-MPDU is activated
- Problem seems to be related to retransmissions
- Possibly a driver issue as A-MPDU is done in soft-ware
- A-MSDU works fine



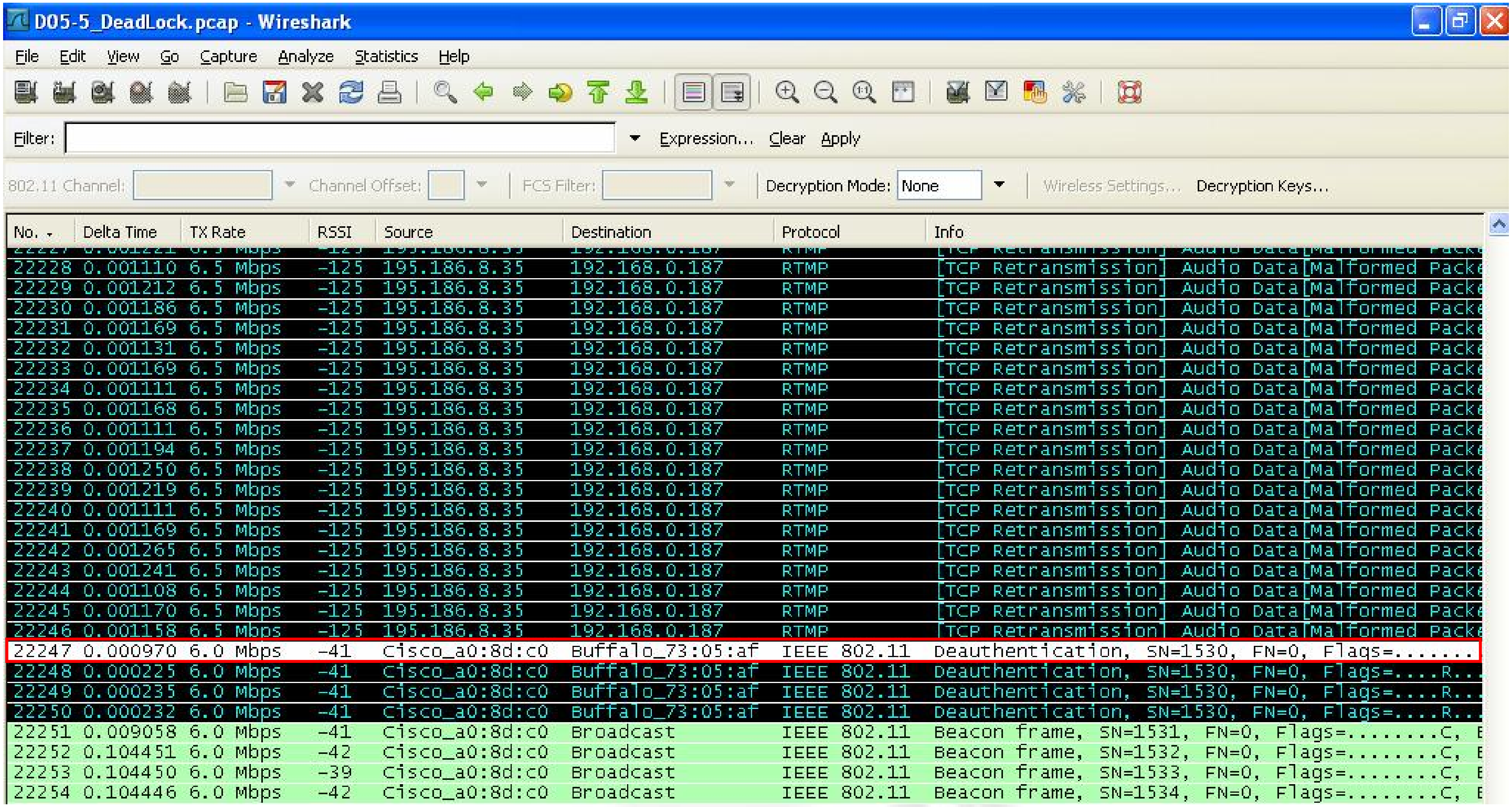
Analysing 'Deadlock' problem



No.	Delta Time	TX Rate	RSSI	Source	Destination	Protocol	Info
22105	0.000022	6.0 Mbps	-39	Buffalo_73:05:af (TA)	Cisco_a0:8d:c0 (RA)	IEEE 802.11	802.11 Block Ack, Flags=........C
22106	0.001719	216.0 Mbps	78	195.186.8.35	192.168.0.187	TCP	1935 > 2604 [ACK] Seq=3788779 Ack=380
22107	0.000022	6.0 Mbps	-40	Buffalo_73:05:af (TA)	Cisco_a0:8d:c0 (RA)	IEEE 802.11	802.11 Block Ack, Flags=........C
22108	0.000243	6.0 Mbps	-45		Buffalo_73:05:af (RA)	IEEE 802.11	Acknowledgement, Flags=........C
22109	0.001525	216.0 Mbps	-97	195.186.8.35	192.168.0.187	TCP	1935 > 2604 [ACK] Seq=3789303 Ack=380
22110	0.000252	216.0 Mbps	-50	195.186.8.35	192.168.0.187	TCP	[TCP Out-Of-Order] 1935 > 2604 [ACK]
22111	0.000020	6.0 Mbps	-40	Buffalo_73:05:af (TA)	Cisco_a0:8d:c0 (RA)	IEEE 802.11	802.11 Block Ack, Flags=........C
22112	0.000276	216.0 Mbps	-44	195.186.8.35	192.168.0.187	RTMP	Audio Data[Malformed Packet]
22113	0.000021	6.0 Mbps	-40	Buffalo_73:05:af (TA)	Cisco_a0:8d:c0 (RA)	IEEE 802.11	802.11 Block Ack, Flags=........C
22114	0.000122	300.0 Mbps	-39	192.168.0.187	195.186.8.35	TCP	2604 > 1935 [ACK] Seq=3803 Ack=378989
22115	0.000115	6.0 Mbps	-45		Buffalo_73:05:af (RA)	IEEE 802.11	Acknowledgement, Flags=........C
22116	0.001367	216.0 Mbps	-96	195.186.8.35	192.168.0.187	RTMP	Audio Data[Malformed Packet]
22117	0.000942	216.0 Mbps	107	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22118	0.000213	216.0 Mbps	-35	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22119	0.000223	216.0 Mbps	-60	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22120	0.000346	162.0 Mbps	-60	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22121	0.000223	162.0 Mbps	-96	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22122	0.000307	108.0 Mbps	-96	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22123	0.000233	108.0 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform
22124	0.000363	54.0 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Out-Of-Order] Audio Data[Malform

Problem starts at frame # 22116 which is not acknowledged by receiver

Analysing 'Deadlock' problem (cont.)

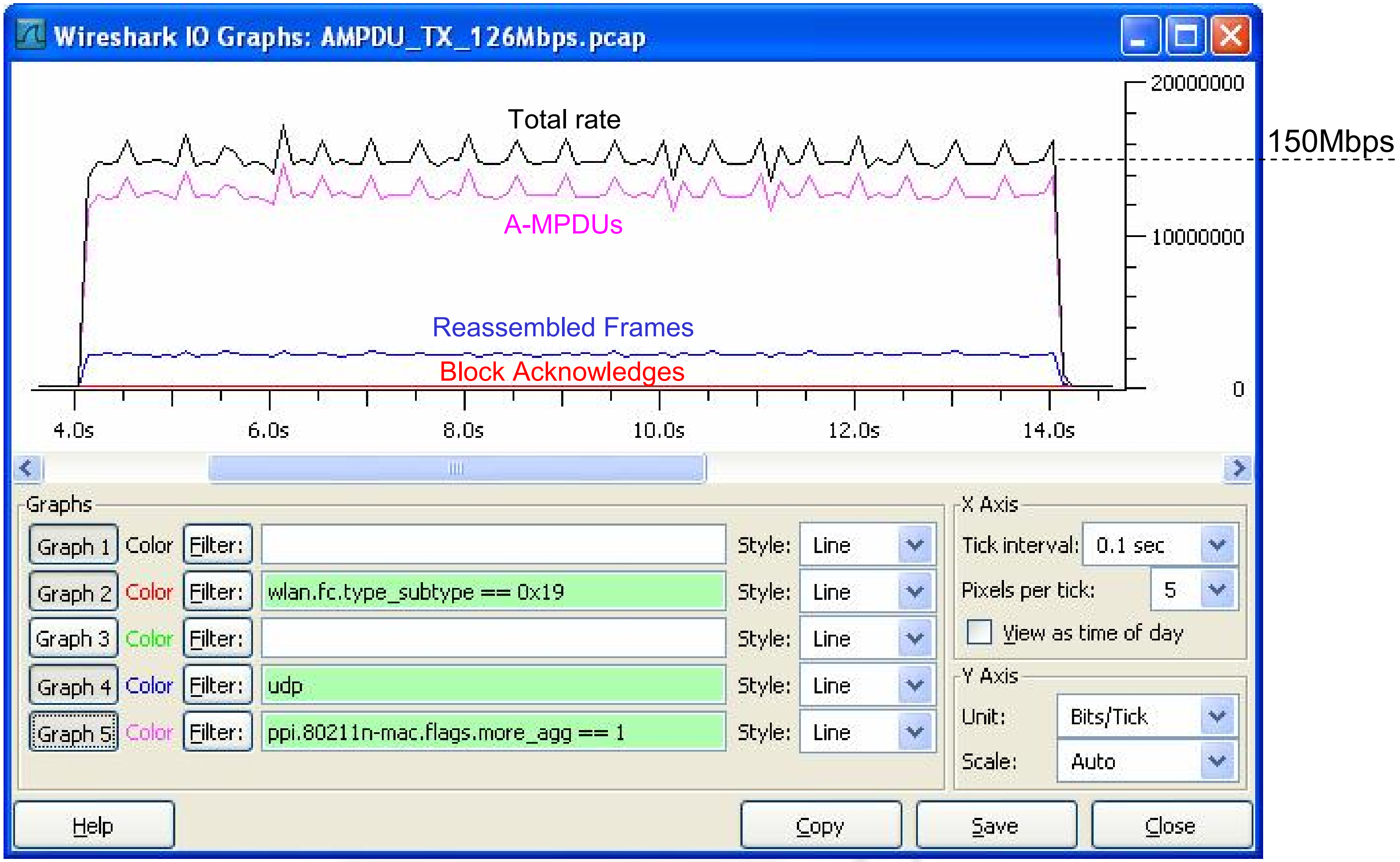


No.	Delta Time	TX Rate	RSSI	Source	Destination	Protocol	Info
22228	0.001110	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22229	0.001212	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22230	0.001186	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22231	0.001169	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22232	0.001131	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22233	0.001169	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22234	0.001111	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22235	0.001168	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22236	0.001111	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22237	0.001194	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22238	0.001250	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22239	0.001219	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22240	0.001111	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22241	0.001169	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22242	0.001265	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22243	0.001241	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22244	0.001108	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22245	0.001170	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22246	0.001158	6.5 Mbps	-125	195.186.8.35	192.168.0.187	RTMP	[TCP Retransmission] Audio Data[Malformed Packe
22247	0.000970	6.0 Mbps	-41	Cisco_a0:8d:c0	Buffalo_73:05:af	IEEE 802.11	Deauthentication, SN=1530, FN=0, Flags=.......
22248	0.000225	6.0 Mbps	-41	Cisco_a0:8d:c0	Buffalo_73:05:af	IEEE 802.11	Deauthentication, SN=1530, FN=0, Flags=....R..
22249	0.000235	6.0 Mbps	-41	Cisco_a0:8d:c0	Buffalo_73:05:af	IEEE 802.11	Deauthentication, SN=1530, FN=0, Flags=....R..
22250	0.000232	6.0 Mbps	-41	Cisco_a0:8d:c0	Buffalo_73:05:af	IEEE 802.11	Deauthentication, SN=1530, FN=0, Flags=....R..
22251	0.009058	6.0 Mbps	-41	Cisco_a0:8d:c0	Broadcast	IEEE 802.11	Beacon frame, SN=1531, FN=0, Flags=........C, E
22252	0.104451	6.0 Mbps	-42	Cisco_a0:8d:c0	Broadcast	IEEE 802.11	Beacon frame, SN=1532, FN=0, Flags=........C, E
22253	0.104450	6.0 Mbps	-39	Cisco_a0:8d:c0	Broadcast	IEEE 802.11	Beacon frame, SN=1533, FN=0, Flags=........C, E
22254	0.104446	6.0 Mbps	-42	Cisco_a0:8d:c0	Broadcast	IEEE 802.11	Beacon frame, SN=1534, FN=0, Flags=........C, E

Analysing ‘Deadlock’ problem (cont.)

- Access point retransmits frame 128 times up to frame # 22246 (value of Max. Data Retries counter)
- As the mobile station does not acknowledge, access point sends ‘Deauthentication’ in frame # 22247 and removes station from association list
- As mobile station does not acknowledge again, access point retransmits in frames # 22248 to 22250
- Mobile station does not acknowledge, assumes to be still associated with access point and keeps sending frames (# 22298, 22315 etc.) → Deadlock situation

Bandwidth Measurement



UDP bandwidth measurement with **IPerf** indicates throughput of 126Mbps

Backwards compatibility to a/b/g

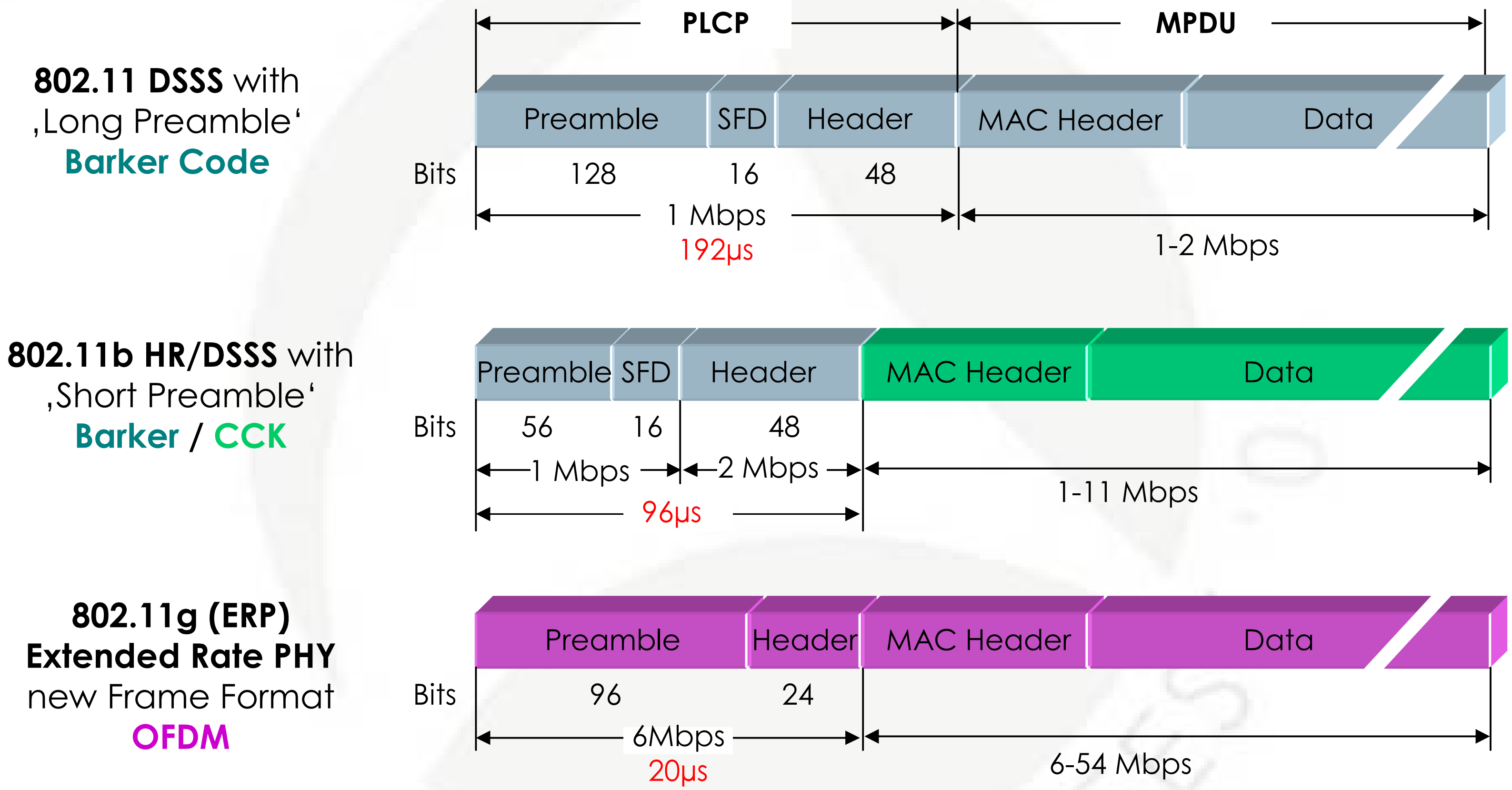
Present situation

Mbps	Coding	Description	
1 2	Barker Code Barker Code	**802.11** **DSSS (Clause 15)** with ‚Long Preamble‘	
5.5 11	CCK CCK	**802.11b** **HR/DSSS (Clause 18)** with ‚Short Preamble‘	
6 9 12 18 24 36 48 54	OFDM OFDM OFDM OFDM OFDM OFDM OFDM OFDM	**802.11g** **Extended Rate PHY** **(ERP)** new Frame Format	**802.11a**

CCK = Complementary Code Keying
OFDM = Orthogonal Frequency Division Multiplexing

Backwards compatibility to a/b/g (cont.)

Present situation



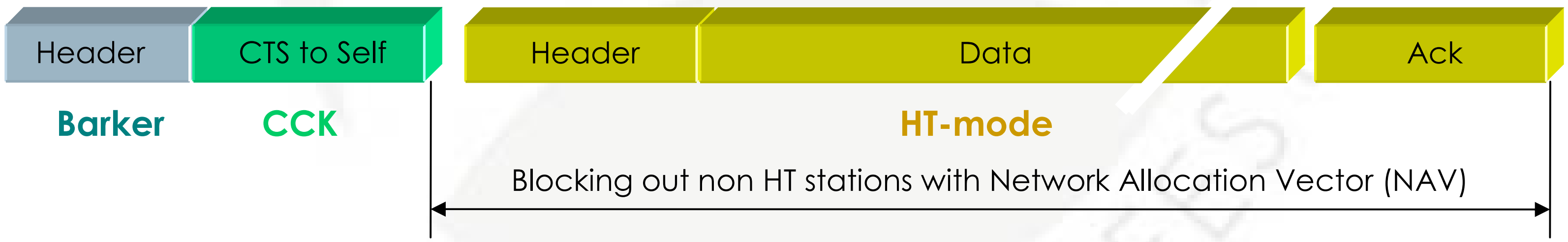
PLCP = Physical Layer Convergence Protocol
MPDU = MAC Layer Protocol Data Unit (decoded by Wireshark)

Backwards compatibility to a/b/g (cont.)

- 802.11n supports three compatibility modes
  - Legacy mode
  - Mixed mode
  - Greenfield mode

- Legacy mode

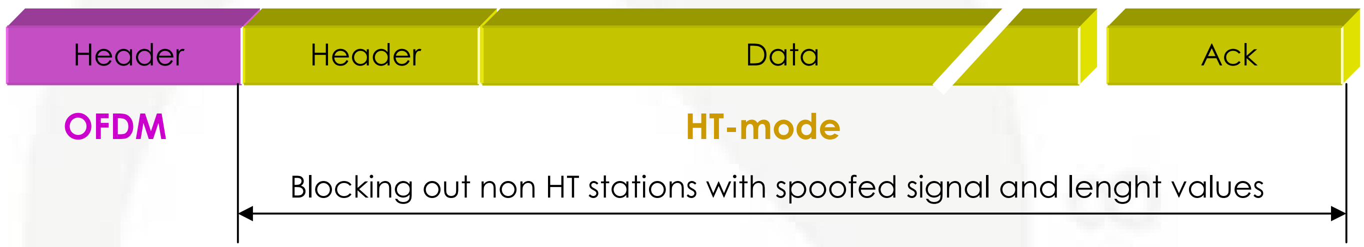
  802.11n to b/g compatibility with Clear-to-send to self



Backwards compatibility to a/b/g (cont.)

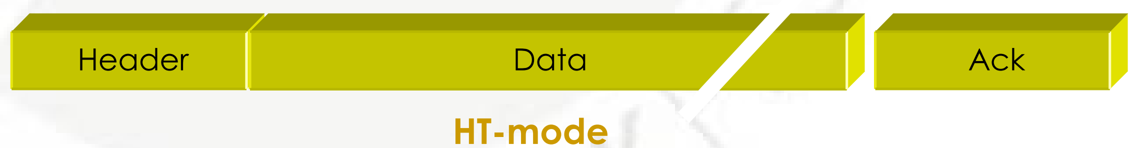
Mixed mode

802.11n to a/g compatibility with Legacy header



Greenfield mode

No backwards compatibility to a/b/g



Future of 802.11n

- Standard ratification not expected before June 2009
- The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) holds OFDM patent (#5487069) and may delay ratification of 802.11n
- Interoperability remains a question mark for pre-N products
- New products supporting technical features like:
  - Up to four spatial streams
  - Transmit Beamforming
  - Direct Link Setup … and many more

Thank you for your attention