Fundamental Truths of WLANs

What would I tell my past self…

Keith R. Parsons - Wednesday 17 NOV 2021 - London British Museum

wirelessLAN PROFESSIONALS

#WiFiDesignDay by Ekahau and Open Reality

Presenter

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100+ Network Certifications

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Produce #WLPC - Wireless LAN Professionals Conference

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What would I tell my younger self?

Explaining the Complex & Invisible

- 802.11/Wi-Fi is incredibly Complex
- 802.11/Wi-Fi is incredibly Resilient

- How to explain?
- Use LEGO of course!

Unorganized Information/Data

Organized

Structured

Explained with a Story…

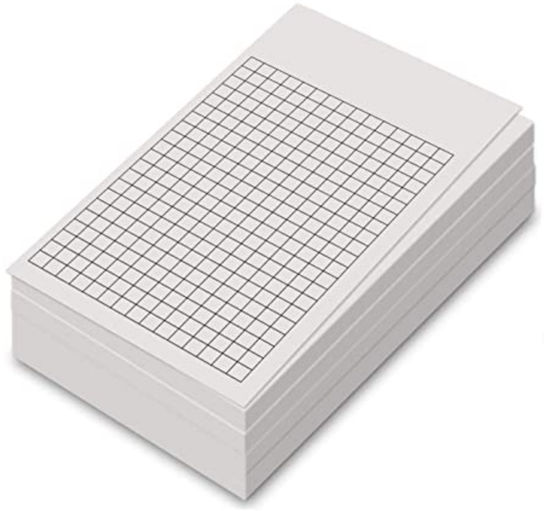
Know Yourself

Using stories… of course!

When I was younger…

BYU

MARRIOTT SCHOOL
OF MANAGEMENT



How Do YOU Learn Best?

Employment Options in Wireless LANs

Customer

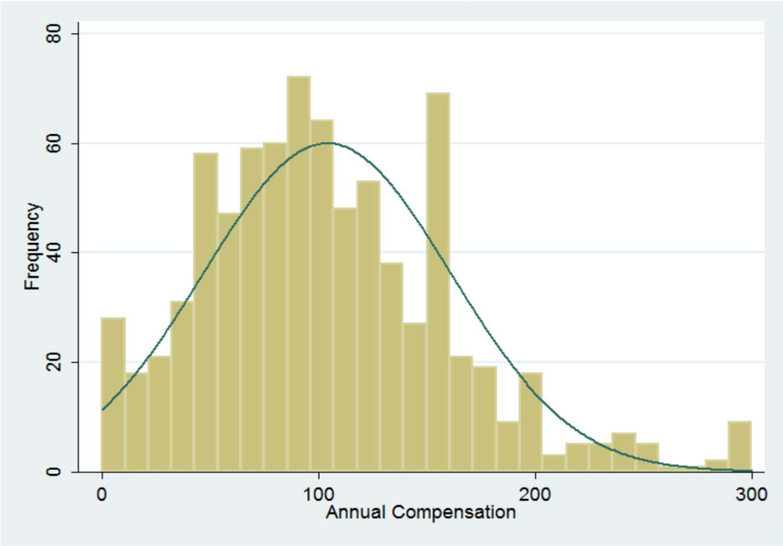
Reseller

Vendor

Consultancy

WLAN Compensation Analysis

Vendor	US	EU	RoW
Cisco	$121,000	$74,000	$72,000
Aruba	$122,000	$70,000	$79,000
Ruckus	$128,000	$89,000	$54,000
Ubiquiti	$97,000	$43,000	N/A



Region	Average	No Cert	CCIE-W	CWNE	CWNA	Any Aruba	ACMX
Overall	*$104,000*	*$99,000*	*$145,000*	*$137,000*	*$111,000*	*$112,000*	*$144,000*
US/Canada	$121,000	$107,000	$175,000	$157,000	$132,000	$128,000	$150,000
Europe	$75,000	$75,000	$82,000	$84,000	$69,000	$76,000	$100,000
Rest of World	$77,000	$88,000	$77,000	$101,000	$86,000	$92,000	$160,000

Correlation does NOT infer Causality!

Know Your Priorities

Don’t get stuck on the *WHAT*

- Focus on the **WHY** and the **HOW**
- Then when you completely understand them…
- Then move to the **WHAT**

- Three quick WISP gig stories
  - Cannabis Cameras, Marketing Numbers, Rural Internet

Tip on Scheduling Your Priorities

All about the BIG rocks!

Know the RF Fundamentals

So many protocols…

	Frequencies	Range (Single Hop)	Data Rates / Category	Authentication	Encryption	Integrity	Security Methods
802.11 - Wi-Fi	2.4 GHz, 5 GHz, and now 6 GHz	30 - 2,000 m	High LAN				
802.15.4	2.4 GHz, Sub 1 GHZ	30 - 10,000 m	Low/Medium	AES-CCM	AES-128 (DL)	MAC/Sequence Number	
LoRA/LoRaWAN	Sub 1 GHz	100 - 15,000 m	Low LPWAN	Root Session Keys	AES-128 (DL, App)	MAC/Sequence Number	
Sigfox	Sub 1 GHz	100 - 15,000 m	Low LPWAN	UL-AUTH	AES-128 (App)	CRC/Message Counter	
Bluetooth	2.4 GHz	10 - 1,500 m	Medium PAN/LAN	AES-CCM	AES-128	CRC/MIC	
BLE	2.4 GHz	10 - 1,500 m	Medium PAN/LAN	AES-CCM	AES-128	CRC/MIC	
6LoWPAN	2.4 GHz	30 - 300 m	Low/Medium PAN/LAN	AES-CCM	AES-128 (DL), IPSec (Net), TLS (Trans)	MAC/Sequence Number	
Zigbee	2.4 GHz, Sub 1 GHz	10 - 300 m (Line of Sight) 75-100 m indoors	Low PAN/LAN	Install Code	AES-128 (Net, App)	MAC/Sequence Number	Centarlized (with install codes support), Distributed
Thread	2.4 GHz	30 - 300 m	Medium PAN/LAN	PAKE	AES-128 (DL)	MAC/Sequence Number	AES-128
Z-Wave	Sub 1 GHz	10 - 300 m	Low PAN/LAN	Inclusion	AES-128 (App)	MAC/Sequence Number	
WirelessHART	2.4 GHz	30 - 300 m	Low PAN/LAN	Join Key	AES-128 (DL, Net)	MAC/Sequence Number	AES-128
ISA100.11a	2.4 GHz	30 - 300 m	Low PAN/LAN	Join Key	AES-128 (DL, Net)	MAC/Sequence Number	AES-128

Wi-Fi Spectrum

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

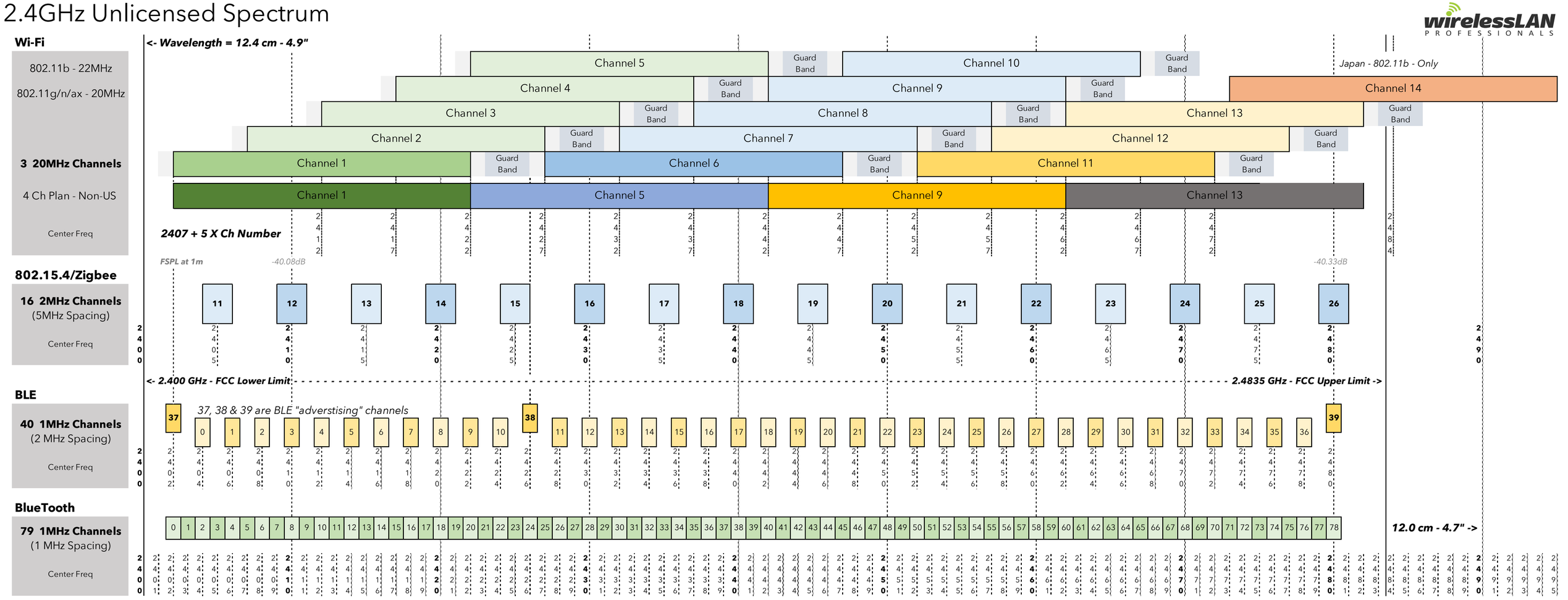
- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- METEOROLOGICAL
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED

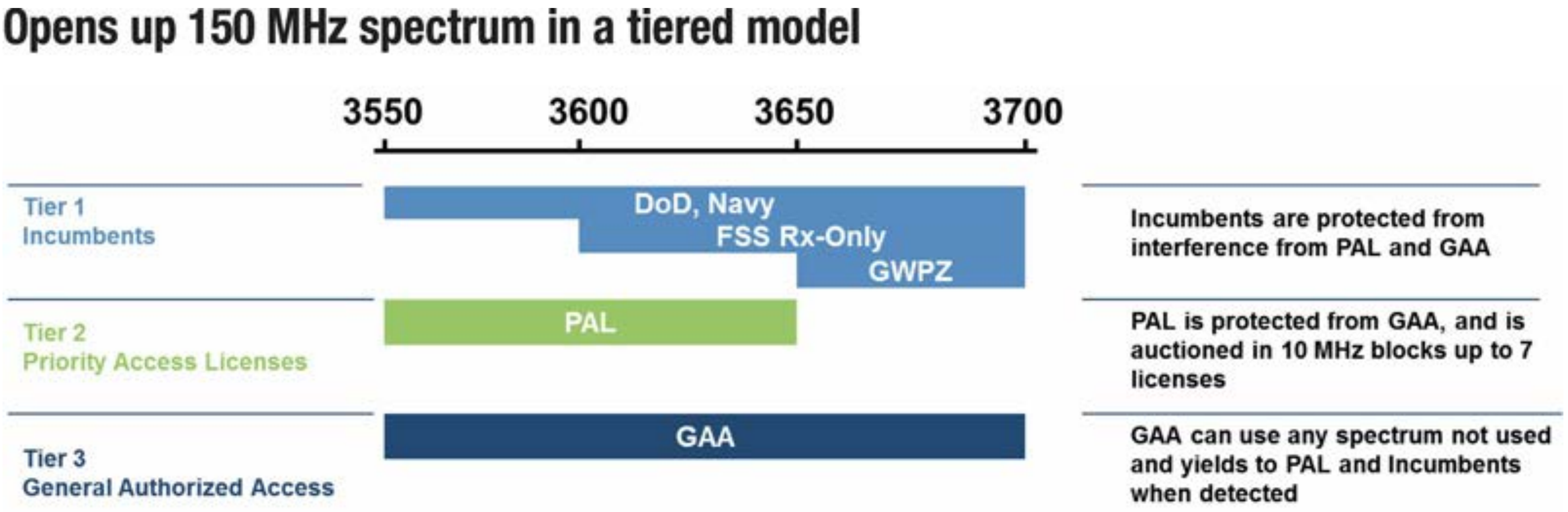
2.4 GHz Frequencies

Bluetooth, BLE, 802.15.4, 802.11



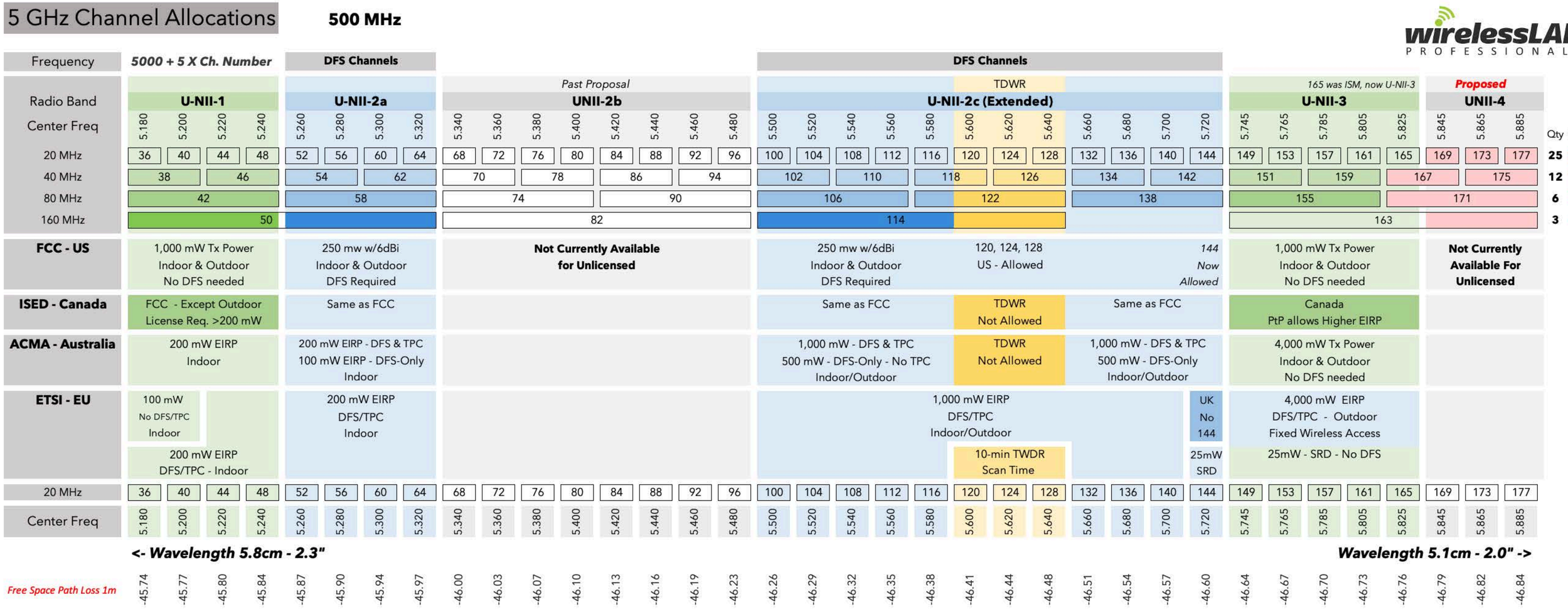
3.5 GHz Frequencies

CBRS - Private LTE



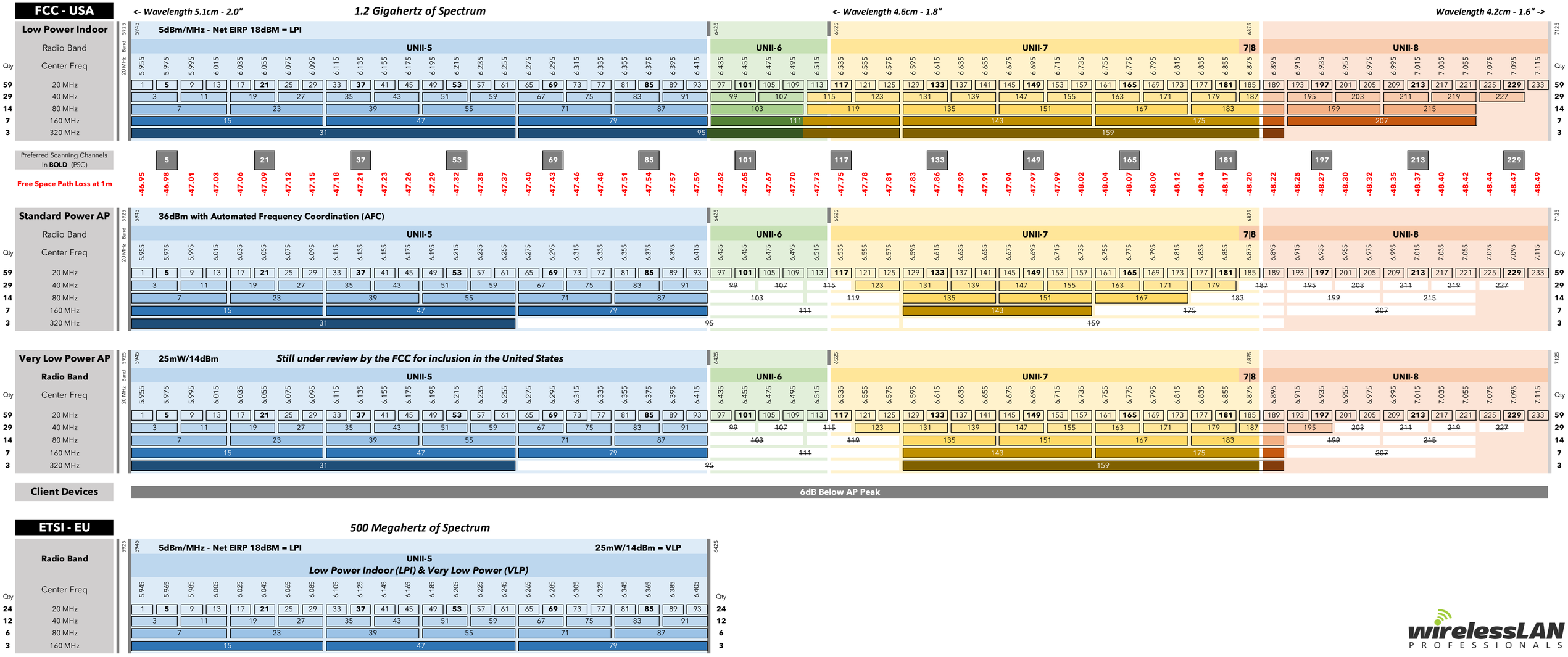
5 GHz Frequencies

802.11 n, ac, ax



6GHz

6 GHz Channel Allocations



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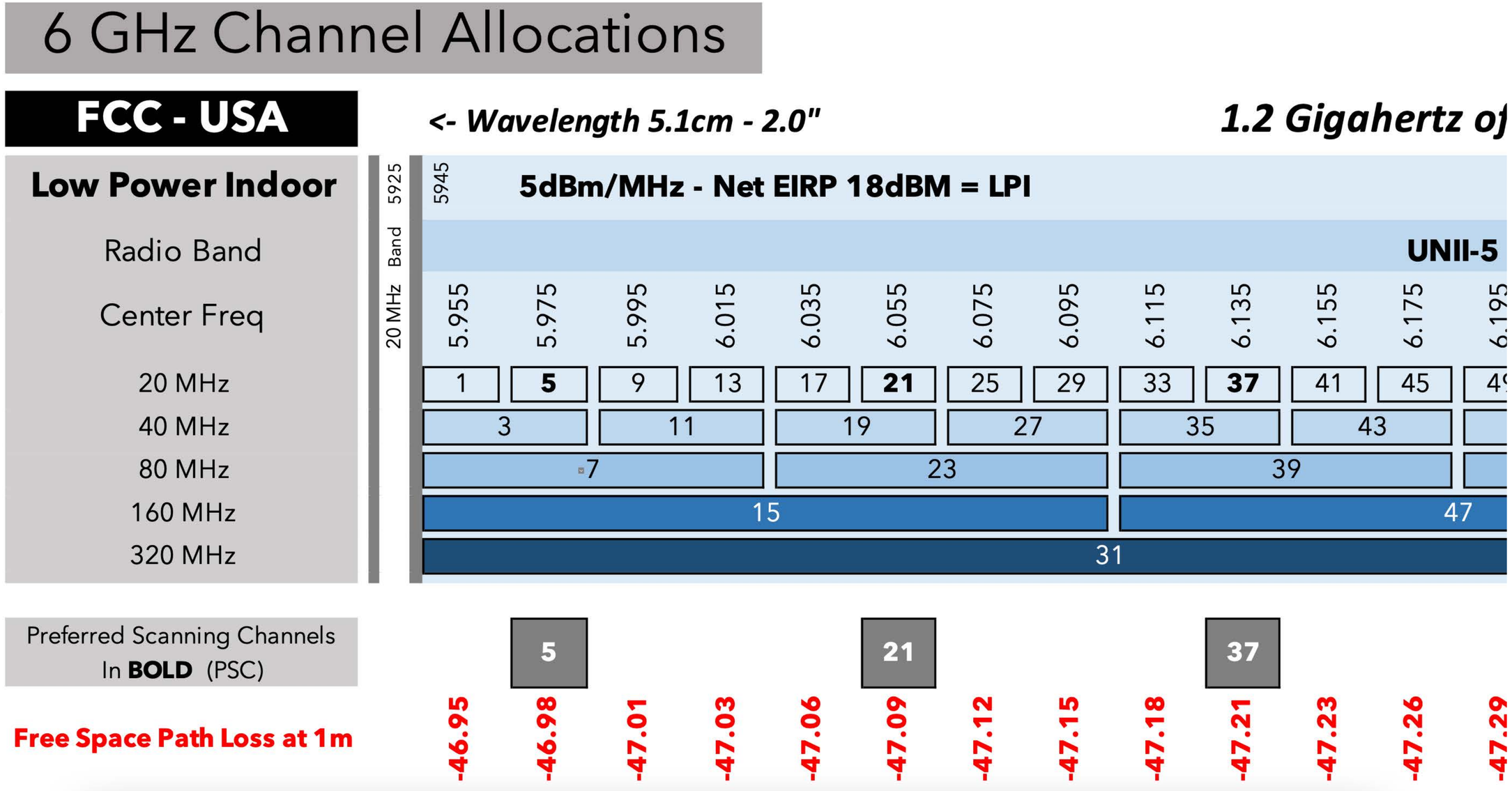
Zoom in on Details



Master dB math

Not merely memorize 10's and 3's… but UNDERSTAND

Easy dB Math in 5 Minutes

Rule #1

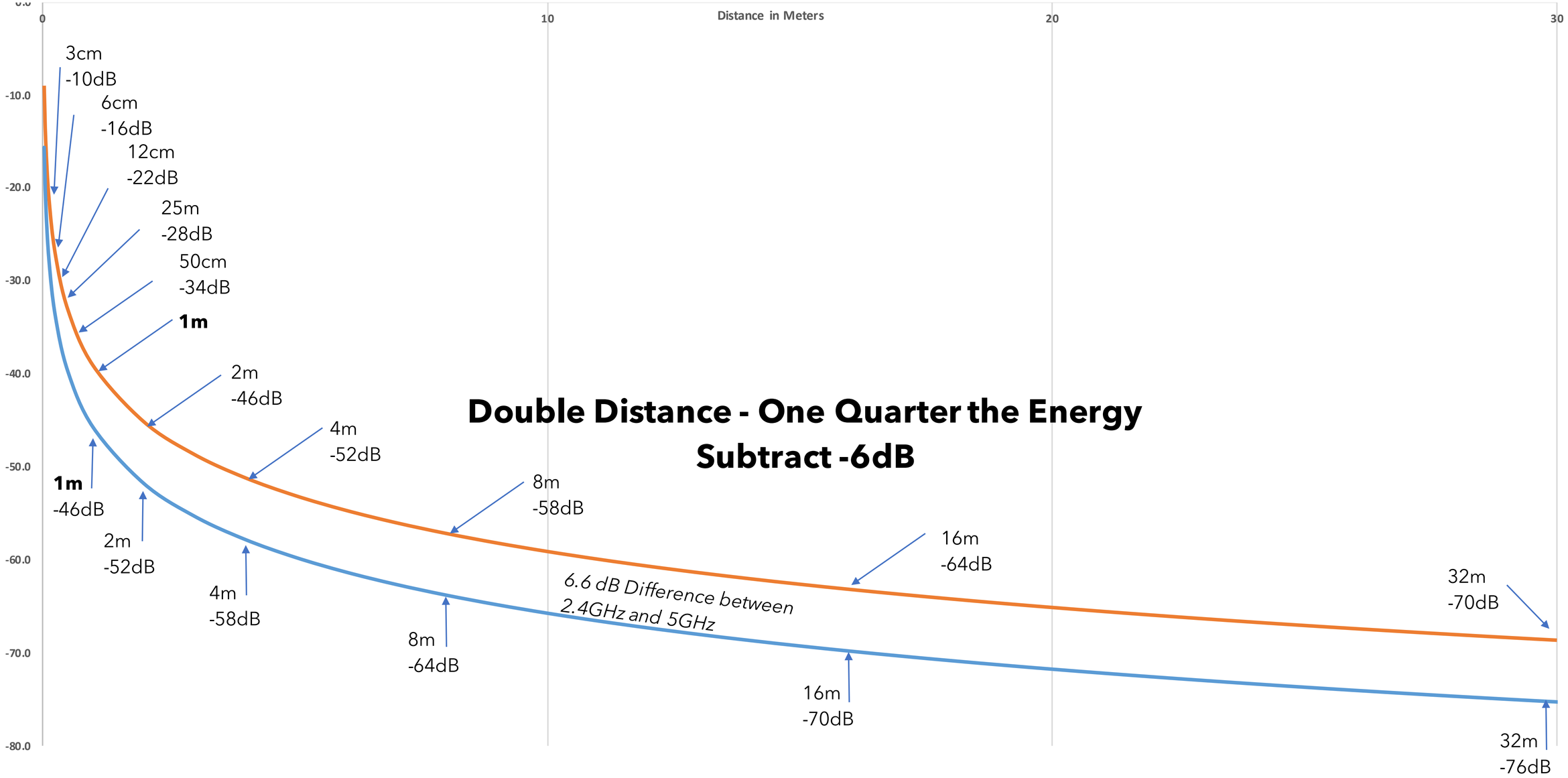
Left Side is Decibel Right Side is Normal

Rule #2

Memorize These

dB	Normal
Plus	Times
Minus	Divide
10	10
3	2

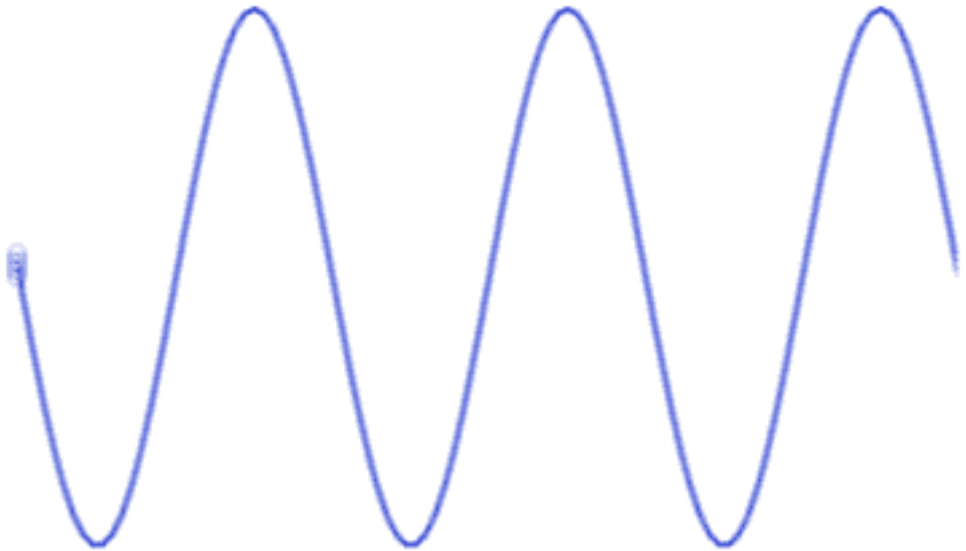
Free Space Path Loss



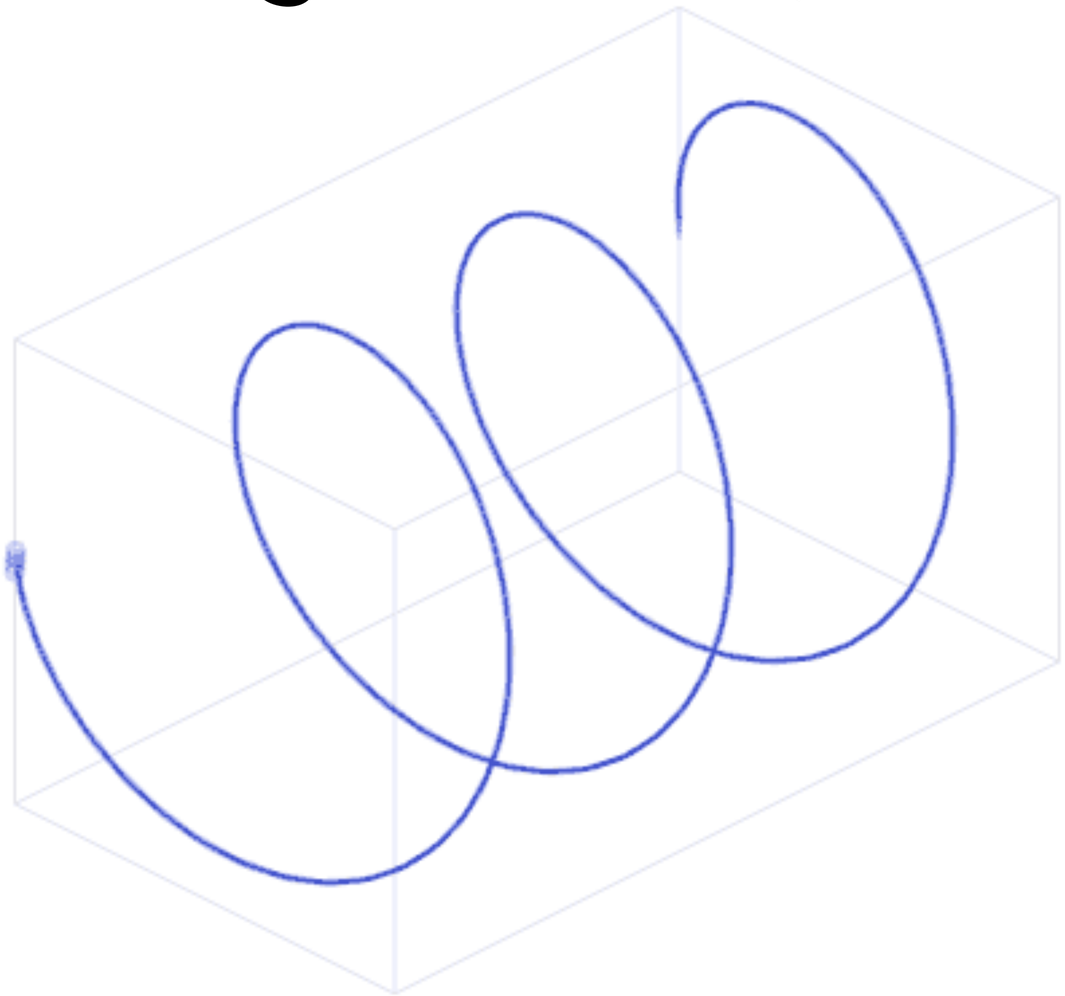
Understand RF Modulation Process

It is Core and Central to everything we do

Sine Wave (Front & Side View)



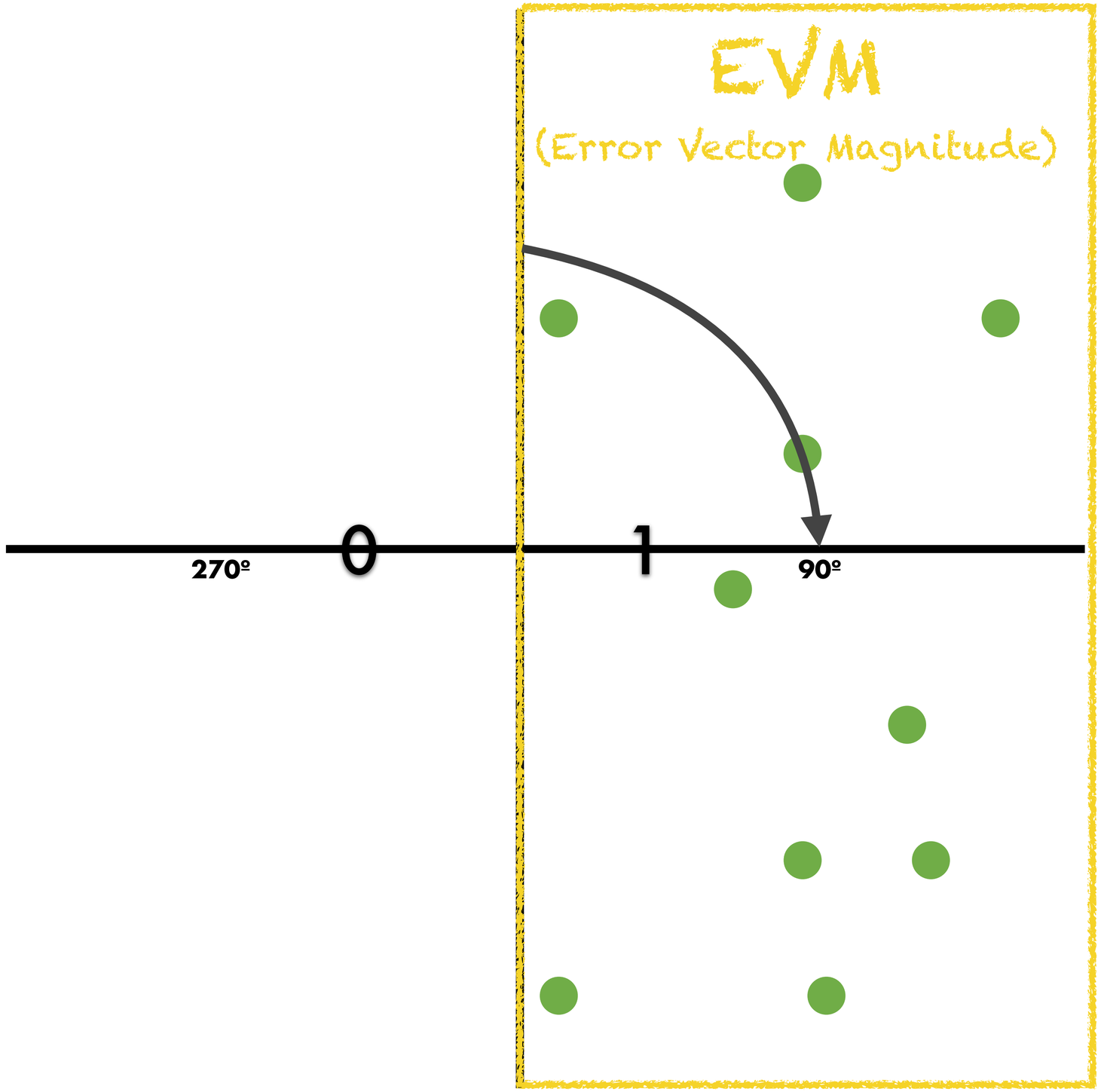
Sine Wave (Orthogonal View)



MODULATION
CONSTELLATIONS

BINARY PSK (BPSK)

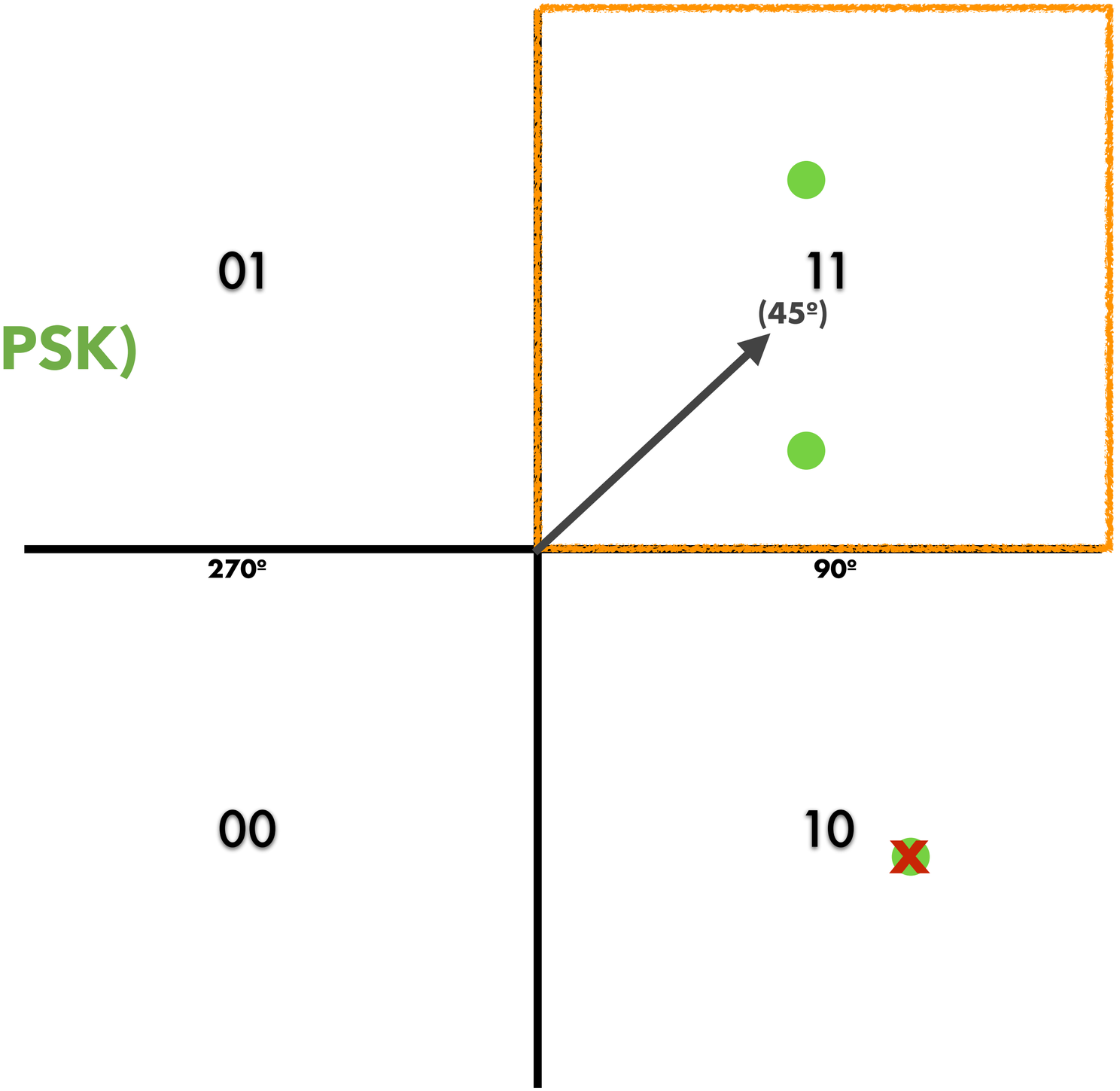
- **1** bit at a time
- Large EVM (Error Vector Magnitude)
- Very **SIMPLE**
- Very **ROBUST**
- Very **SLOW** (~6 Mbps)
- Around ~ 2-4dB SNR
- Very easy to achieve



MODULATION
CONSTELLATIONS

QUADRATURE PSK (QPSK)

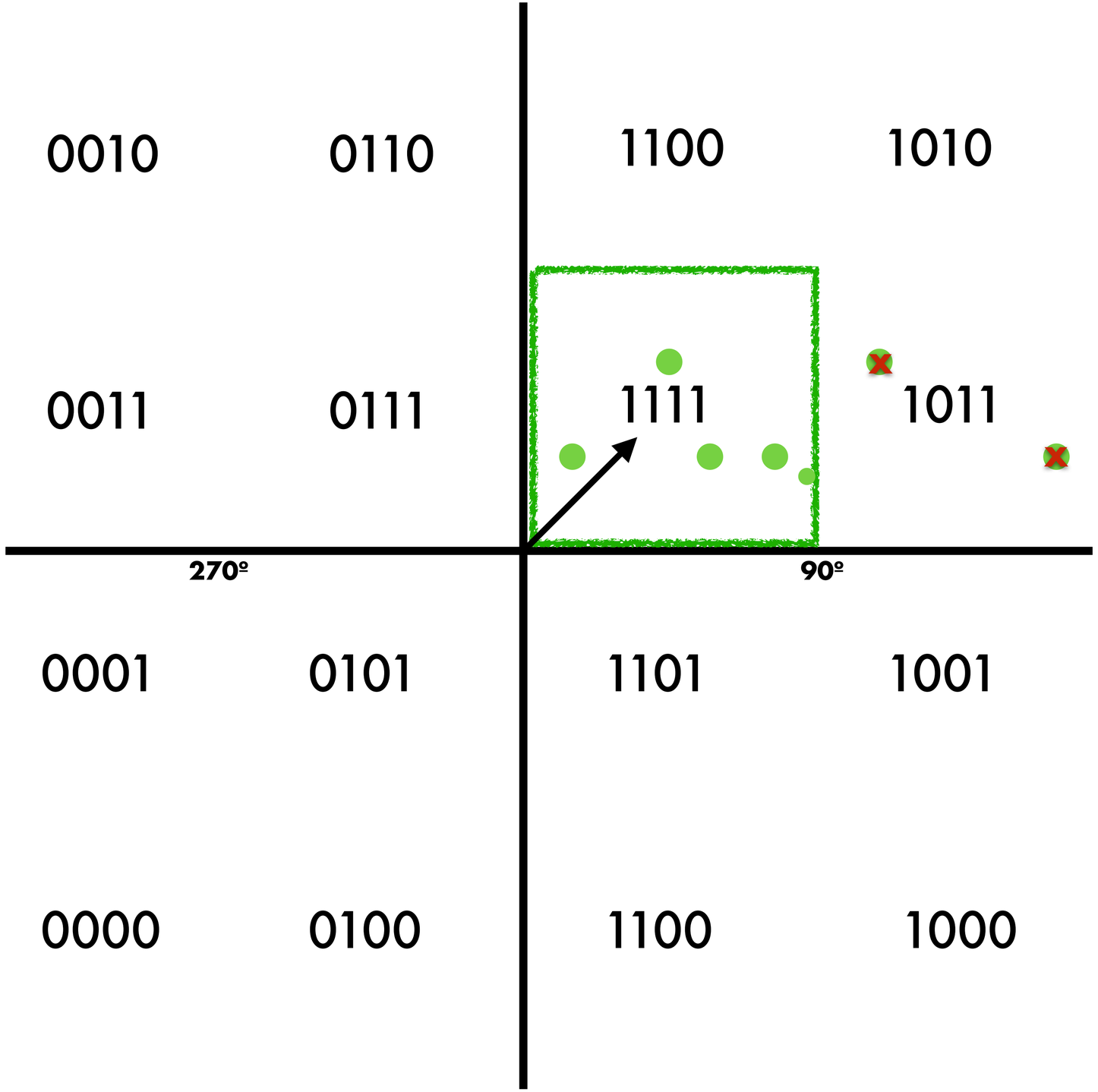
- **2** bits at a time
- 2X more throughput
- 1/2 less EVM/Robustness
- EVM gets smaller
- A bit more complex
- Still **ROBUST**



MODULATION
CONSTELLATIONS

16-QAM

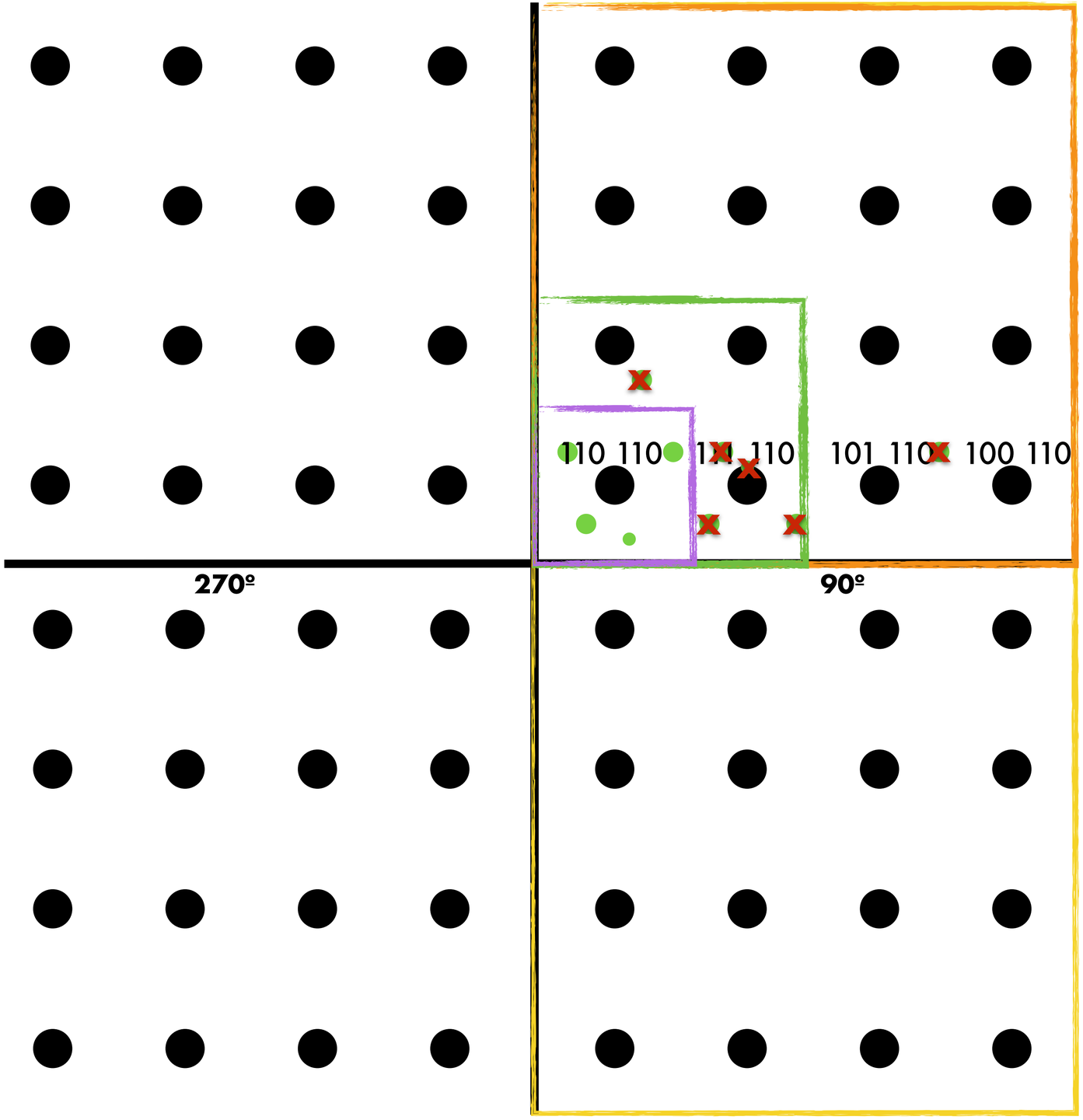
- **4** bits at a time
- EVM gets even tighter
- 2X more throughput
- 1/4 less EVM/Robustness
- Getting more **COMPLEX**
- But, still pretty **EASY** to achieve



MODULATION CONSTELLATIONS

64-QAM

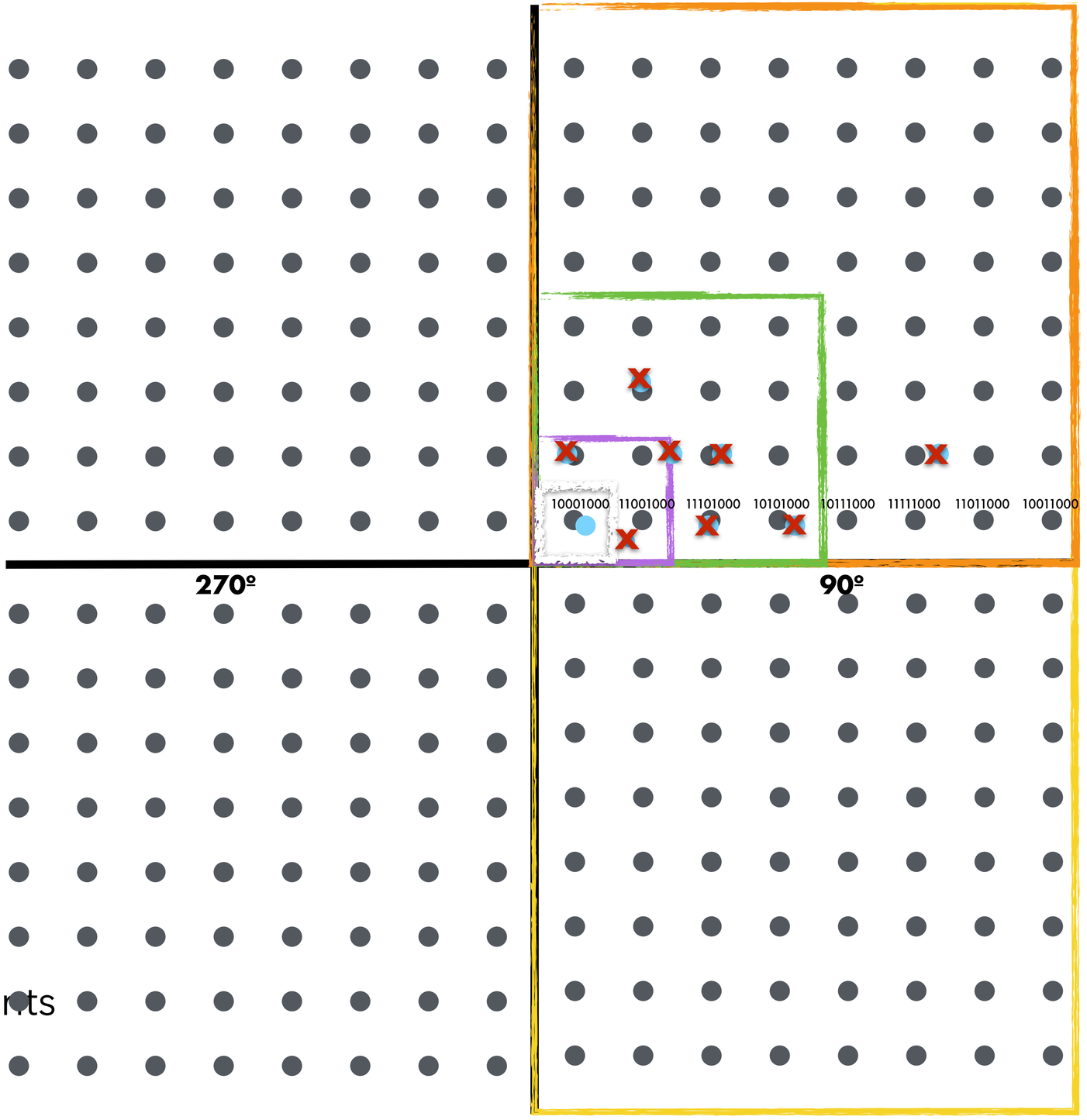
- Introduced with 802.11n
- **6** bits at a time
- 1.5 X more throughput
- 1/4 less EVM/Robustness
- **EVM** is very small.
- Very **COMPLEX**
- Very **FAST** (150, 300, 450+ Mbps)



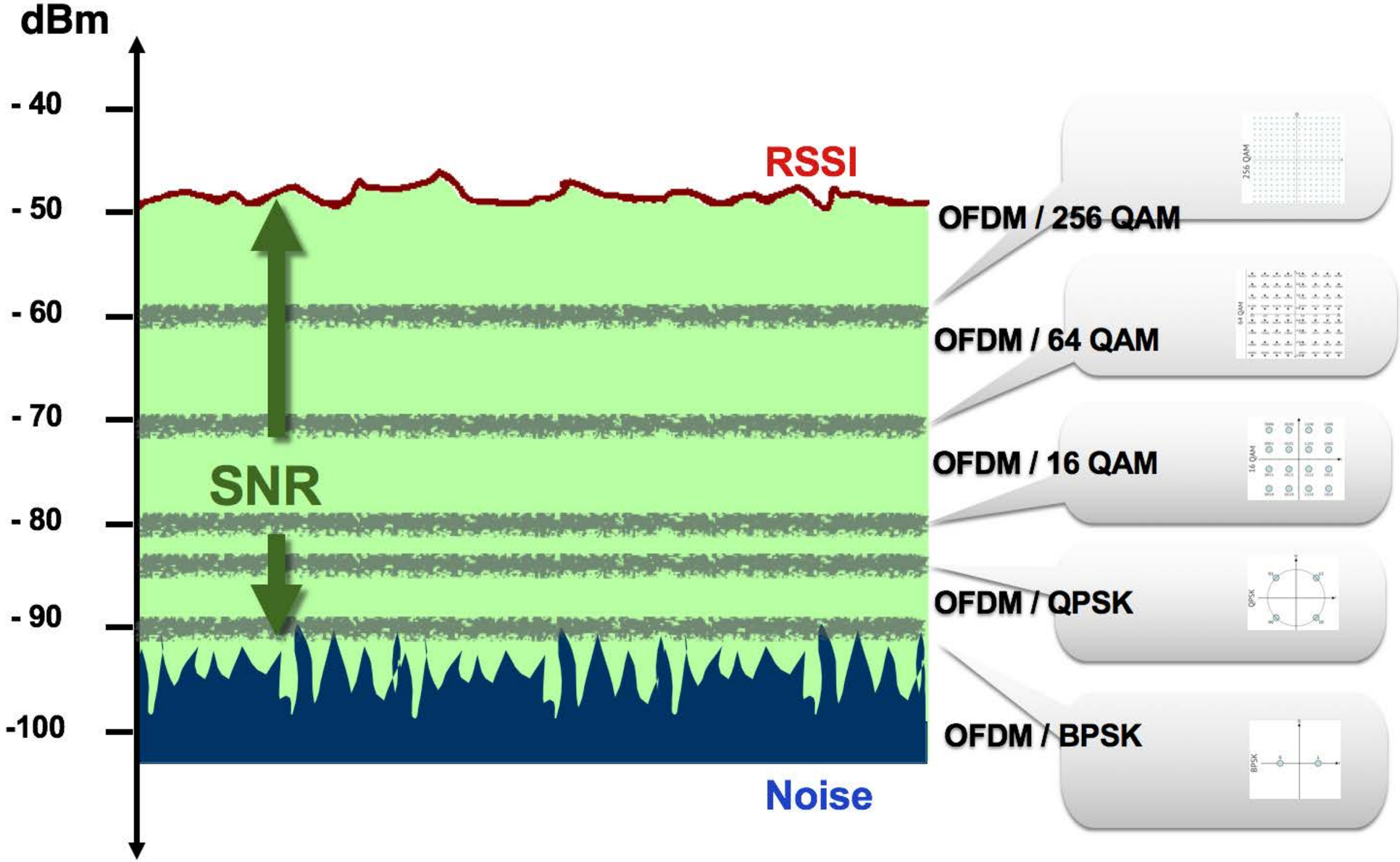
MODULATION
CONSTELLATIONS

256-QAM

- Introduced with 802.11ac
- **8** bits at a time
- 1.3 X more throughput
- 1/4 less EVM/Robustness
- EVM is even **SMALLER!**
- Extremely **COMPLEX**
- Extremely **FAST** (Up to 1.3 Gbps)
- **REQUIRES** -56, -53, -50dBm
- **SNR** of 30dB, or better
- **NOT** practical for most environments

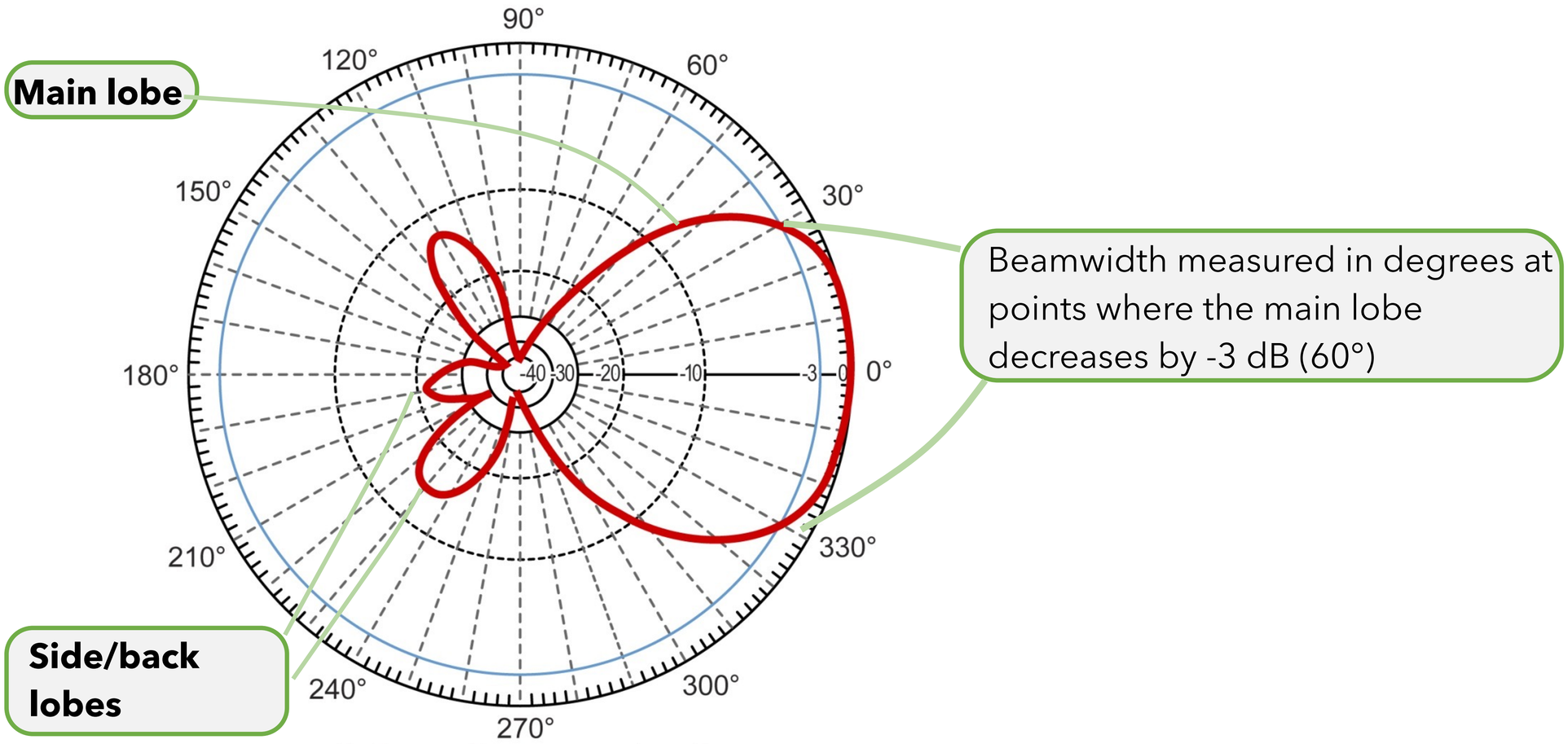


RSSI, SNR, Noise, Modulation

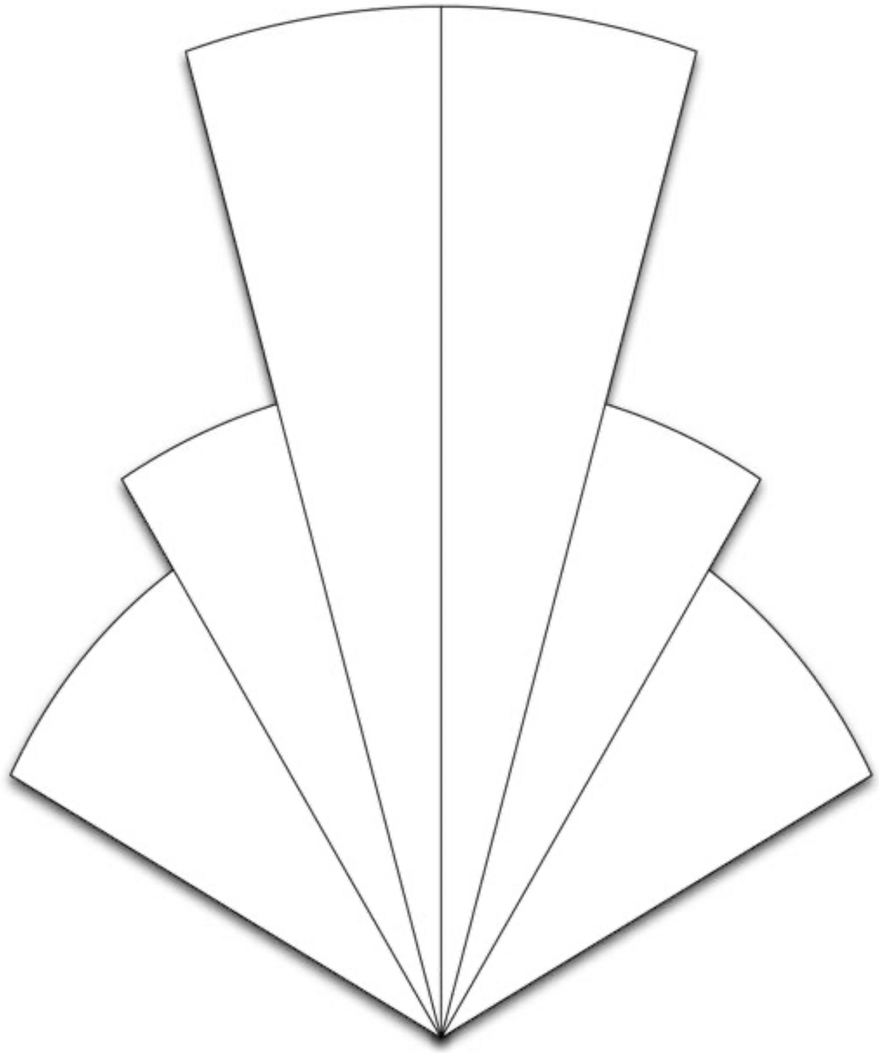


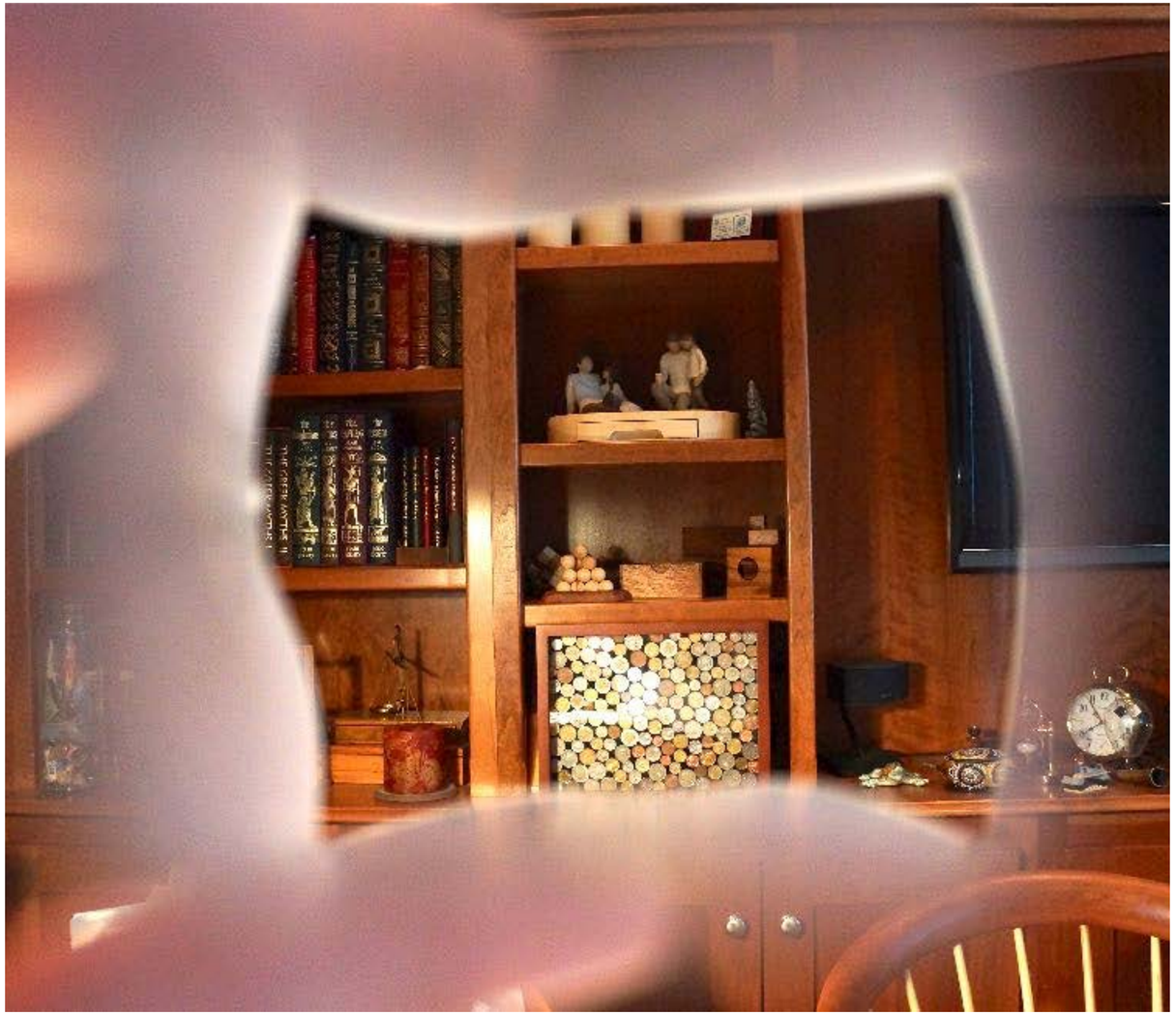
Know Antennas

Cover what you want, while not covering what you don’t want!

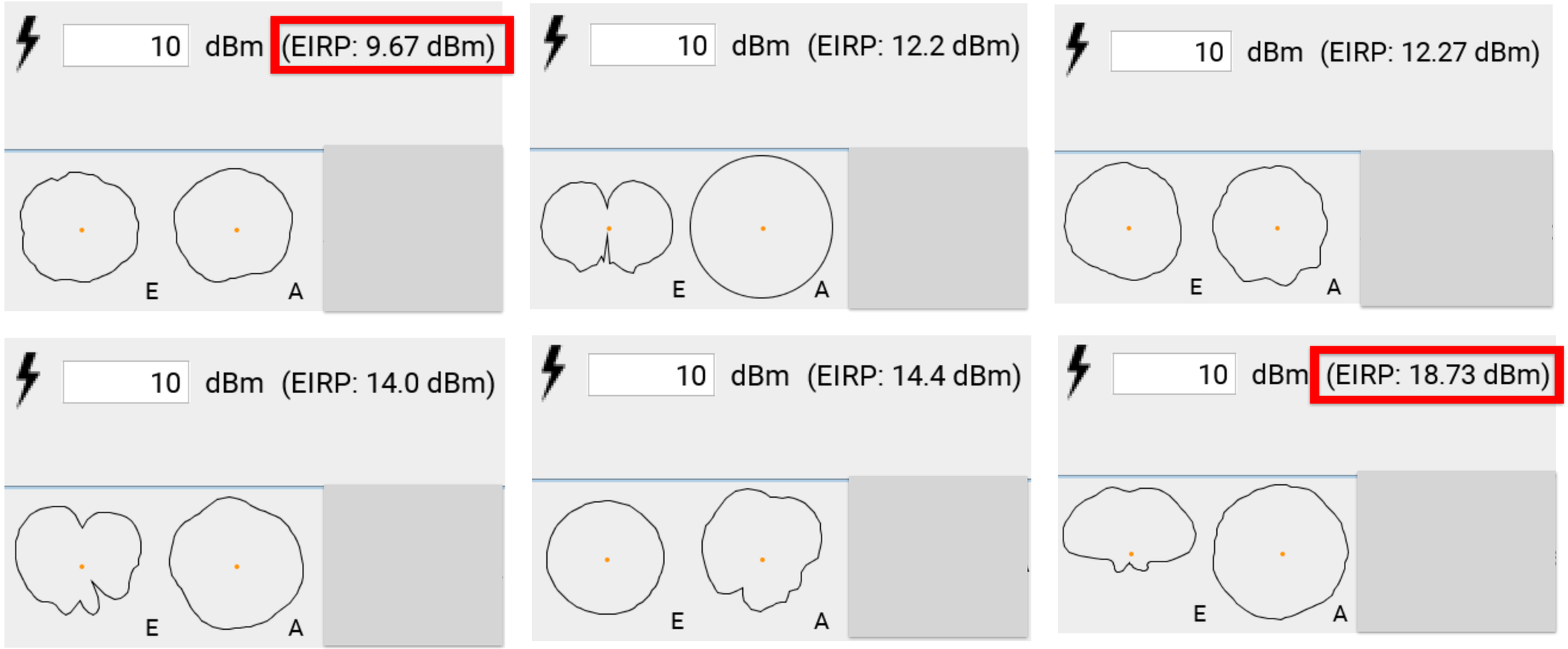


Paper Visualization Tool

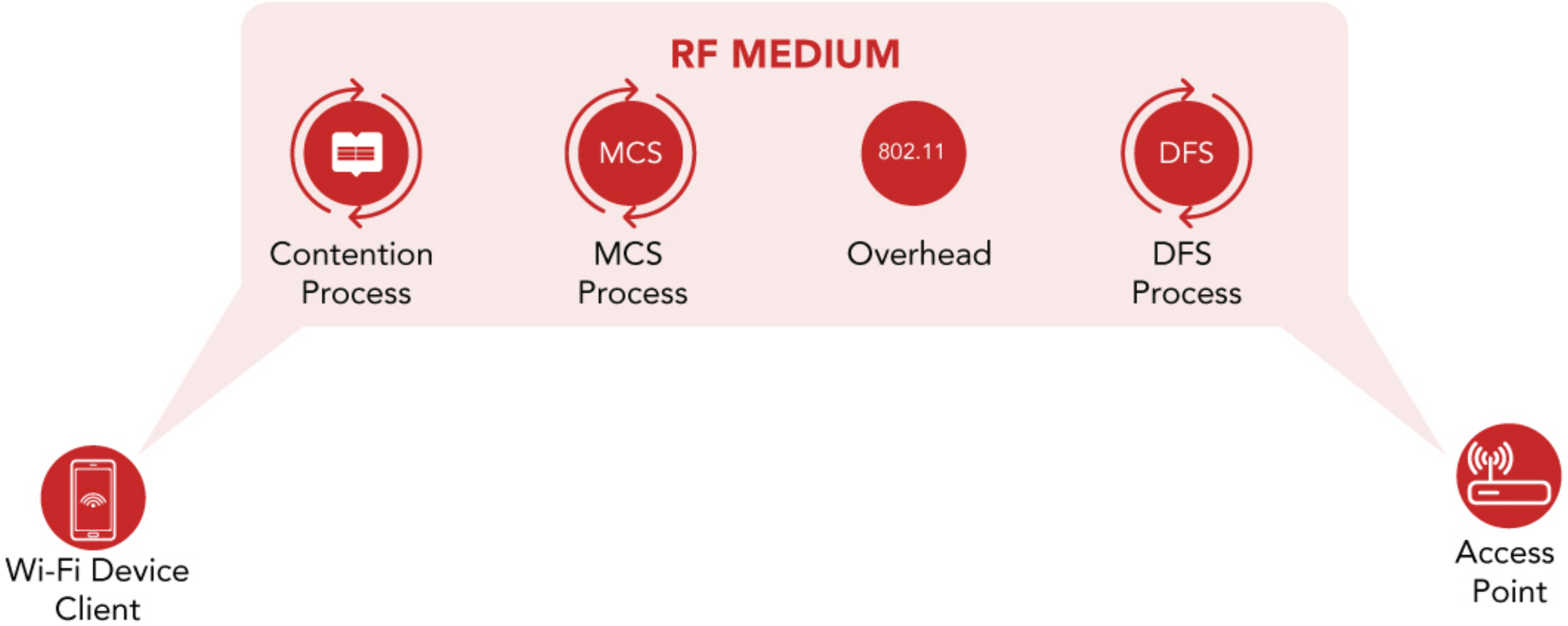




Antennas are NOT created equally

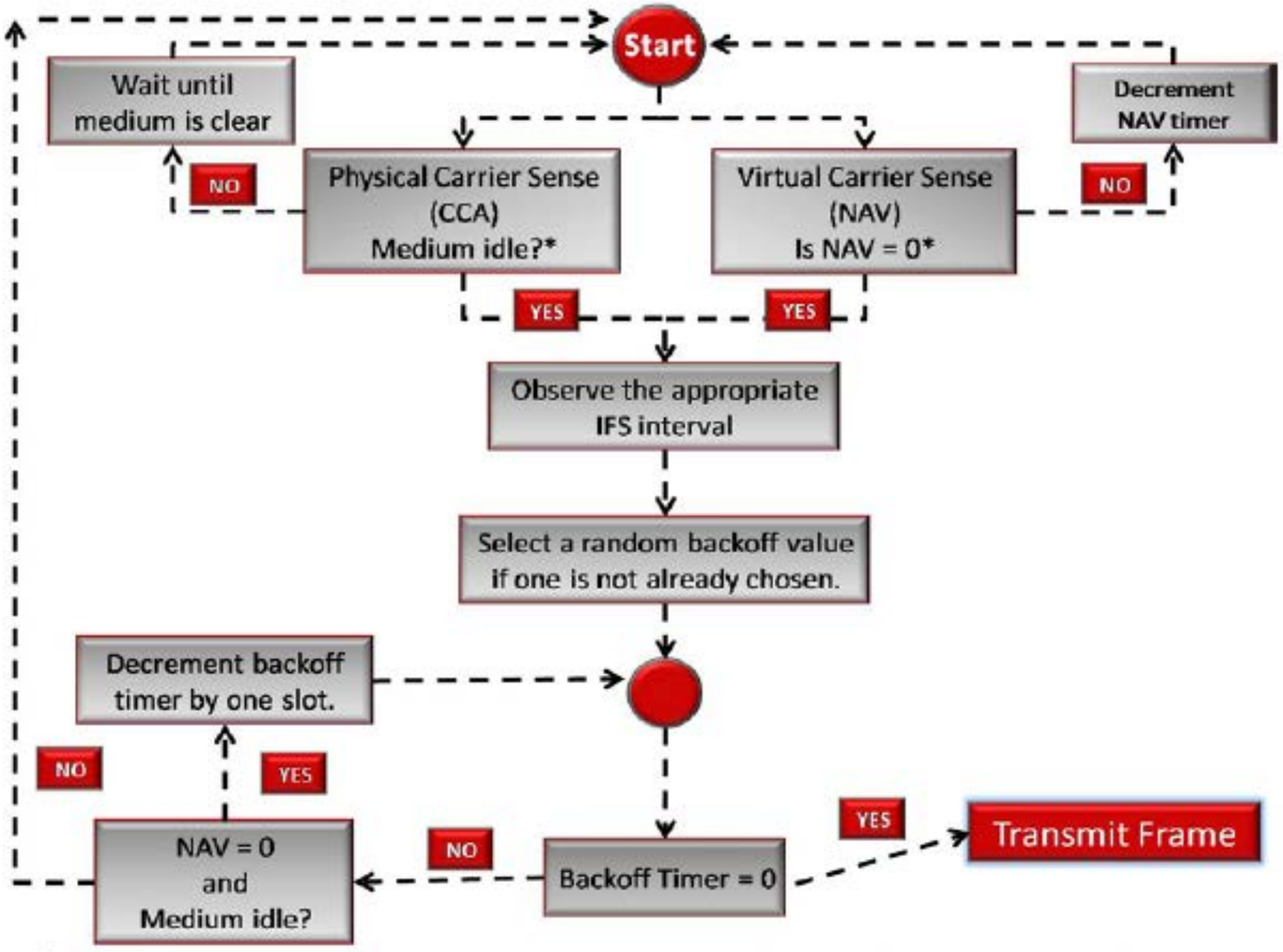


Know the PHY

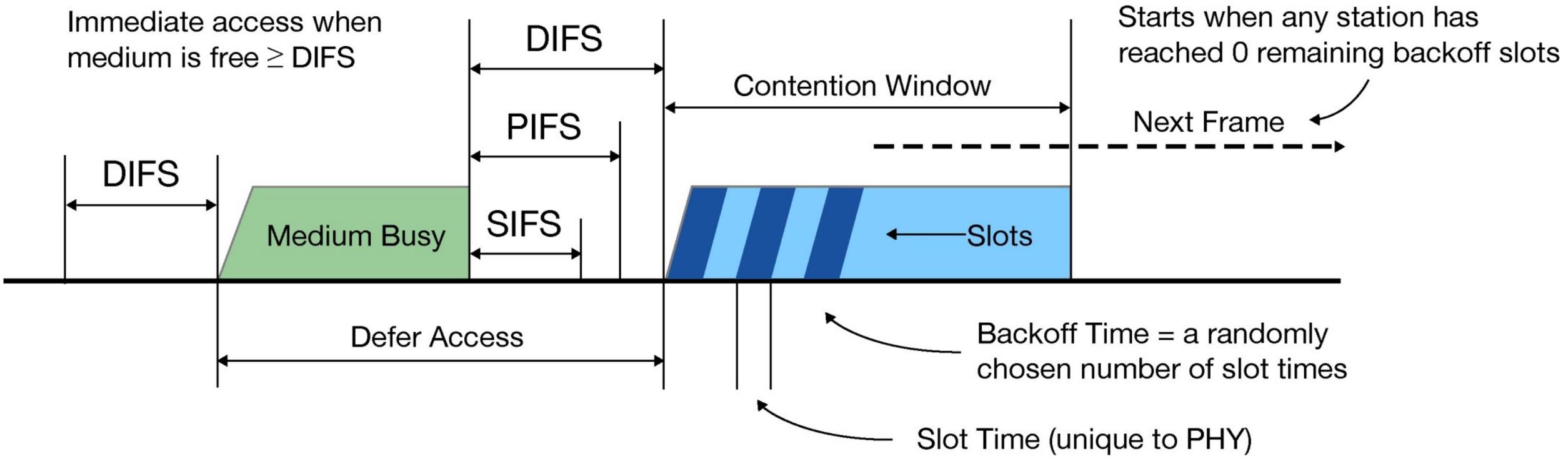

RF MEDIUM
MCS
802.11
DFS
Contention Process
MCS Process
Overhead
DFS Process
Wi-Fi Device Client
Access Point

Contention Process

- How to Access RF Medium
- AKA - “The Game”
- Preamble Detect
- Energy Detect
- Transmit Opportunity TxOp
- Wait Time
- Random Slots (CW)
- QoS
- Duration ID



The “Game”


Immediate access when
medium is free ≥ DIFS
DIFS
PIFS
SIFS
DIFS
Medium Busy
Contention Window
Starts when any station has
reached 0 remaining backoff slots
Next Frame
Slots
Defer Access
Backoff Time = a randomly
chosen number of slot times
Slot Time (unique to PHY)

MCS Process

802.11n and 802.11ac MCS, SNR and RSSI

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HT MCS	VHT MCS	Modulation	Coding	20MHz				40MHz				80MHz				160MHz			
				Data Rate		Min. SNR	RSSI	Data Rate		Min. SNR	RSSI	Data Rate		Min. SNR	RSSI	Data Rate		Min. SNR	RSSI
				800ns	400ns			800ns	400ns			800ns	400ns			800ns	400ns		
1 Spatial Stream																			
0	0	BPSK	1/2	6.5	7.2	2	-82	13.5	15	5	-79	29.3	32.5	8	-76	58.5	65	11	-73
1	1	QPSK	1/2	13	14.4	5	-79	27	30	8	-76	58.5	65	11	-73	117	130	14	-70
2	2	QPSK	3/4	19.5	21.7	9	-77	40.5	45	12	-74	87.8	97.5	15	-71	175.5	195	18	-68
3	3	16-QAM	1/2	26	28.9	11	-74	54	60	14	-71	117	130	17	-68	234	260	20	-65
4	4	16-QAM	3/4	39	43.3	15	-70	81	90	18	-67	175.5	195	21	-64	351	390	24	-61
5	5	64-QAM	2/3	52	57.8	18	-66	108	120	21	-63	234	260	24	-60	468	520	27	-57
6	6	64-QAM	3/4	58.5	65	20	-65	121.5	135	23	-62	263.3	292.5	26	-59	526.5	585	29	-56
7	7	64-QAM	5/6	65	72.2	25	-64	135	150	28	-61	292.5	325	31	-58	585	650	34	-55
	8	256-QAM	3/4	78	86.7	29	-59	162	180	32	-56	351	390	35	-53	702	780	38	-50
	9	256-QAM	5/6			31	-57	180	200	34	-54	390	433.3	37	-51	780	866.7	40	-48
2 Spatial Streams																			
8	0	BPSK	1/2	13	14.4	2	-82	27	30	5	-79	58.5	65	8	-76	117	130	11	-73
9	1	QPSK	1/2	26	28.9	5	-79	54	60	8	-76	117	130	11	-73	234	260	14	-70
10	2	QPSK	3/4	39	43.3	9	-77	81	90	12	-74	175.5	195	15	-71	351	390	18	-68
11	3	16-QAM	1/2	52	57.8	11	-74	108	120	14	-71	234	260	17	-68	468	520	20	-65
12	4	16-QAM	3/4	78	86.7	15	-70	162	180	18	-67	351	390	21	-64	702	780	24	-61
13	5	64-QAM	2/3	104	115.6	18	-66	216	240	21	-63	468	520	24	-60	936	1040	27	-57
14	6	64-QAM	3/4	117	130.3	20	-65	243	270	23	-62	526.5	585	26	-59	1053	1170	29	-56
15	7	64-QAM	5/6	130	144.4	25	-64	270	300	28	-61	585	650	31	-58	1170	1300	34	-55
	8	256-QAM	3/4	156	173.3	29	-59	324	360	32	-56	702	780	35	-53	1404	1560	38	-50
	9	256-QAM	5/6			31	-57	360	400	34	-54	780	866.7	37	-51	1560	1733	40	-48

802.11n, 802.11ac, and 802.11ax MCS Index

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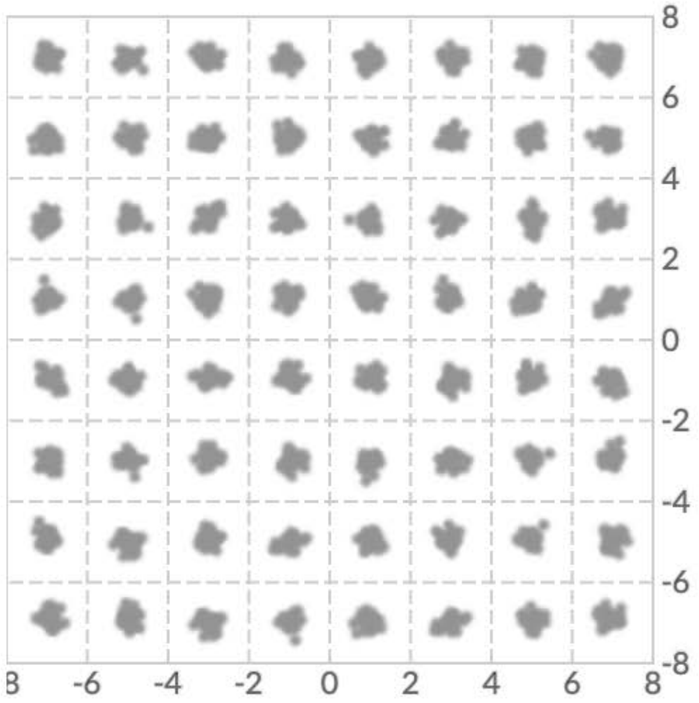
MCS Index						OFDM (Prior 11ax)								OFDM (802.11ax)											
						20MHz		40MHz		80MHz		160MHz		20MHz			40MHz			80MHz			160MHz		
HT	VHT	HE	Spatial Streams	Modulation	Coding	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI	0.8µs GI	1.6µs GI	3.2µs GI
0	0	0	1	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65	8.6	8.1	7.3	17.2	16.3	14.6	36	34	30.6	72.1	68.1	61.3
1	1	1		QPSK	1/2	13	14.4	27	30	58.5	65	117	130	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
2	2	2		QPSK	3/4	19.5	21.7	40.5	45	87.8	97.5	175.5	195	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
3	3	3		16-QAM	1/2	26	28.9	54	60	117	130	234	260	34.4	32.5	29.3	68.8	65	58.5	144.1	136.1	122.5	288.2	272.2	245
4	4	4		16-QAM	3/4	39	43.3	81	90	175.5	195	351	390	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
5	5	5		64-QAM	2/3	52	57.8	108	120	234	260	468	520	68.8	65	58.5	137.6	130	117	288.2	272.2	245	576.5	544.4	490
6	6	6		64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
7	7	7		64-QAM	5/6	65	72.2	135	150	292.5	325	585	650	86	81.3	73.1	172.1	162.5	146.3	360.3	340.3	306.3	720.6	680.6	612.5
	8	8		256-QAM	3/4	78	86.7	162	180	351	390	702	780	103.2	97.5	87.8	206.5	195	175.5	432.4	408.3	367.5	864.7	816.7	735
	9	9		256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7	114.7	108.3	97.5	229.4	216.7	195	480.4	453.7	408.3	960.8	907.4	816.7
		10		1024-QAM	3/4									129	121.9	109.7	258.1	243.8	219.4	540.4	510.4	459.4	1080.9	1020.8	918.8
		11		1024-QAM	5/6									143.4	135.4	121.9	286.8	270.8	243.8	600.5	567.1	510.4	1201	1134.3	1020.8
8	0	0	2	BPSK	1/2	13	14.4	27	30	58.5	65	117	130	17.2	16.3	14.6	34.4	32.5	29.3	72.1	68.1	61.3	144.1	136.1	122.5
9	1	1		QPSK	1/2	26	28.9	54	60	117	130	234	260	34.4	32.5	29.3	68.8	65	58.5	144.1	136.1	122.5	288.2	272.2	245
10	2	2		QPSK	3/4	39	43.3	81	90	175.5	195	351	390	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
11	3	3		16-QAM	1/2	52	57.8	108	120	234	260	468	520	68.8	65	58.5	137.6	130	117	288.2	272.2	245	576.5	544.4	490
12	4	4		16-QAM	3/4	78	86.7	162	180	351	390	702	780	103.2	97.5	87.8	206.5	195	175.5	432.4	408.3	367.5	864.7	816.7	735
13	5	5		64-QAM	2/3	104	115.6	216	240	468	520	936	1040	137.6	130	117	275.3	260	234	576.5	544.4	490	1152.9	1088.9	980
14	6	6		64-QAM	3/4	117	130	243	270	526.5	585	1053	1170	154.9	146.3	131.6	309.7	292.5	263.3	648.5	612.5	551.3	1297.1	1225	1102.5
15	7	7		64-QAM	5/6	130	144.4	270	300	585	650	1170	1300	172.1	162.5	146.3	344.1	325	292.5	720.6	680.6	612.5	1441.2	1361.1	1225
	8	8		256-QAM	3/4	156	173.3	324	360	702	780	1404	1560	206.5	195	175.5	412.9	390	351	864.7	816.7	735	1729.4	1633.3	1470
	9	9		256-QAM	5/6	N/A	N/A	360	400	780	866.7	1560	1733.3	229.4	216.7	195	458.8	433.3	390	960.8	907.4	816.7	1921.6	1814.8	1633.3
		10		1024-QAM	3/4									258.1	243.8	219.4	516.2	487.5	438.8	1080.9	1020.8	918.8	2161.8	2041.7	1837.5
		11		1024-QAM	5/6									286.8	270.8	243.8	573.5	541.7	487.5	1201	1134.3	1020.8	2402	2268.5	2041.7
16	0	0	3	BPSK	1/2	19.5	21.7	40.5	45	87.8	97.5	175.5	195	25.8	24.4	21.9	51.6	48.8	43.9	108.1	102.1	91.9	216.2	204.2	183.8
17	1	1		QPSK	1/2	39	43.3	81	90	175.5	195	351	390	51.6	48.8	43.9	103.2	97.5	87.8	216.2	204.2	183.8	432.4	408.3	367.5
18	2	2		QPSK	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585	77.4	73.1	65.8	154.9	146.3	131.6	324.3	306.3	275.6	648.5	612.5	551.3
19	3	3		16-QAM	1/2	78	86.7	162	180	351	390	702	780	103.2	97.5	87.8	206.5	195	175.5	432.4	408.3	367.5	864.7	816.7	735
20	4	4		16-QAM	3/4	117	130	243	270	526.5	585	1053	1170	154.9	146.3	131.6	309.7	292.5	263.3	648.5	612.5	551.3	1297.1	1225	1102.5
21	5	5		64-QAM	2/3	156	173.3	324	360	702	780	1404	1560	206.5	195	175.5	412.9	390	351	864.7	816.7	735	1729.4	1633.3	1470
22	6	6		64-QAM	3/4	175.5	195	364.5	405	N/A	N/A	1579.5	1755	232.3	219.4	197.4	464.6	438.8	394.9	972.8	918.8	826.9	1945.6	1837.5	1653.8
23	7	7		64-QAM	5/6	195	216.7	405	450	877.5	975	1755	1950	258.1	243.8	219.4	516.2	487.5	438.8	1080.9	1020.8	918.8	2161.8	2041.7	1837.5
	8	8		256-QAM	3/4	234	260	486	540	1053	1170	2106	2340	309.7	292.5	263.3	619.4	585	526.5	1297.1	1225	1102.5	2594.1	2450	2205
	9	9		256-QAM	5/6	260	288.9	540	600	1170	1300	N/A	N/A	344.1	325	292.5	688.2	650	585	1441.2	1361.1	1225	2882.4	2722.2	2450
		10		1024-QAM	3/4									387.1	365.6	329.1	774.3	731.3	658.1	1621.3	1531.3	1378.1	3242.6	3062.5	2756.3
		11		1024-QAM	5/6									430.1	406.3	365.6	860.3	812.5	731.3	1801.5	1701.4	1531.3	3602.9	3402.8	3062.5

MCS Demo - Constellation Diagrams

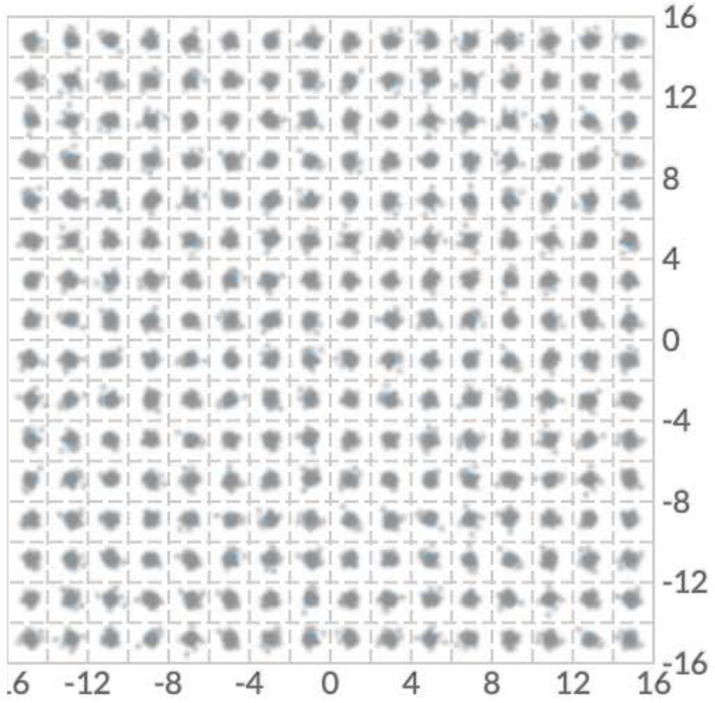
LOCAL RX

DEVICE NAME	Bridge Demo Station
CINR	31 dB
POWER	-60 dBm

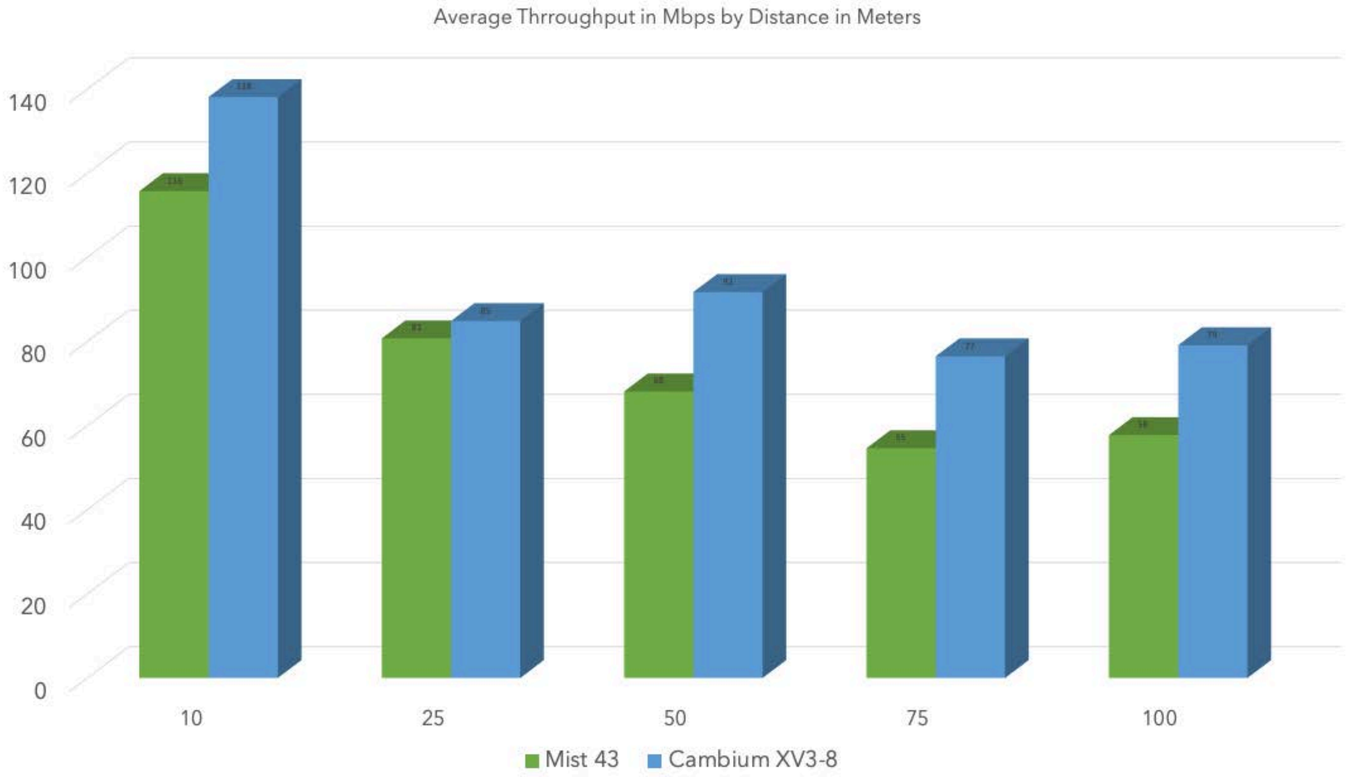


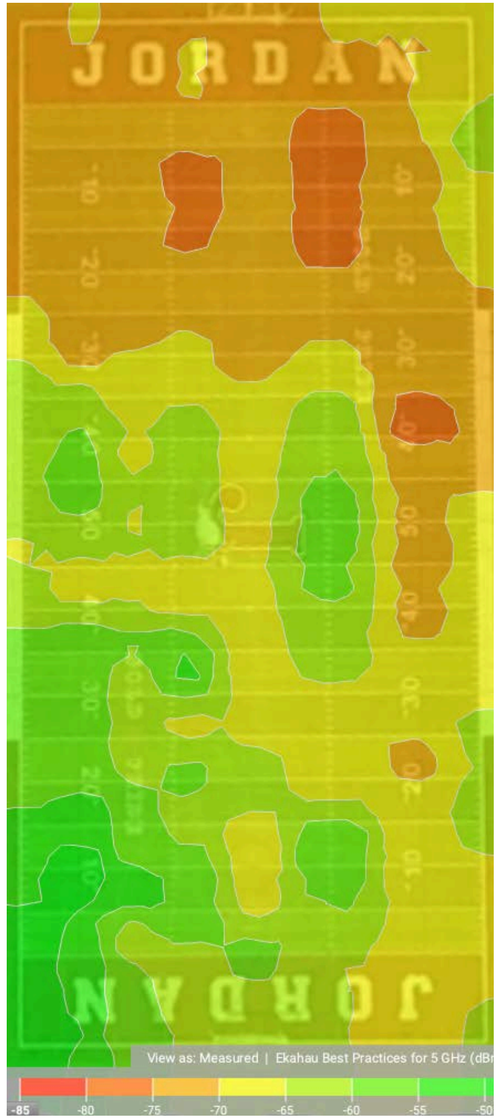
REMOTE RX

DEVICE NAME	Bridge Demo AP
CINR	33 dB
POWER	-58 dBm

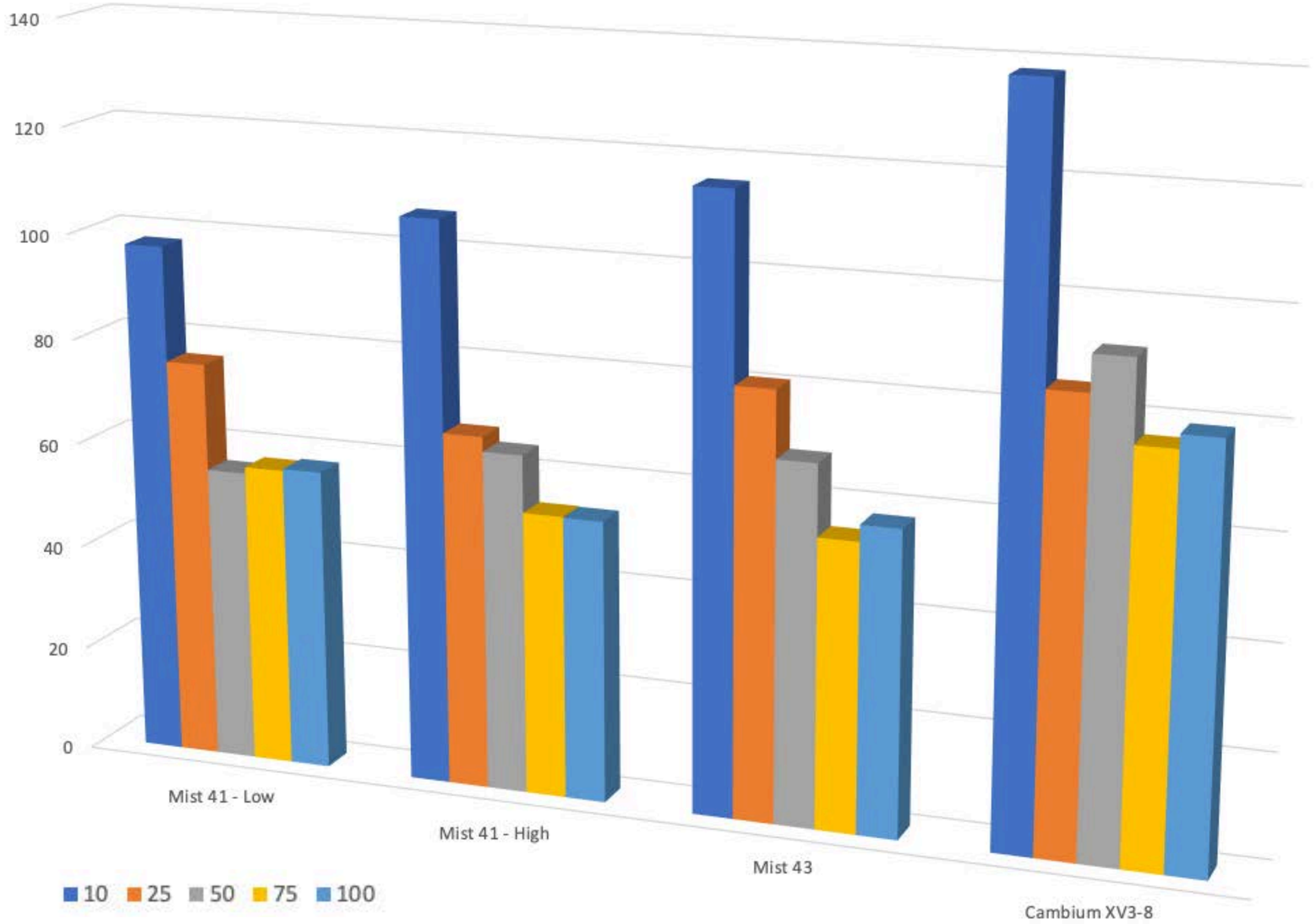


Not ONLY about the GREEN!

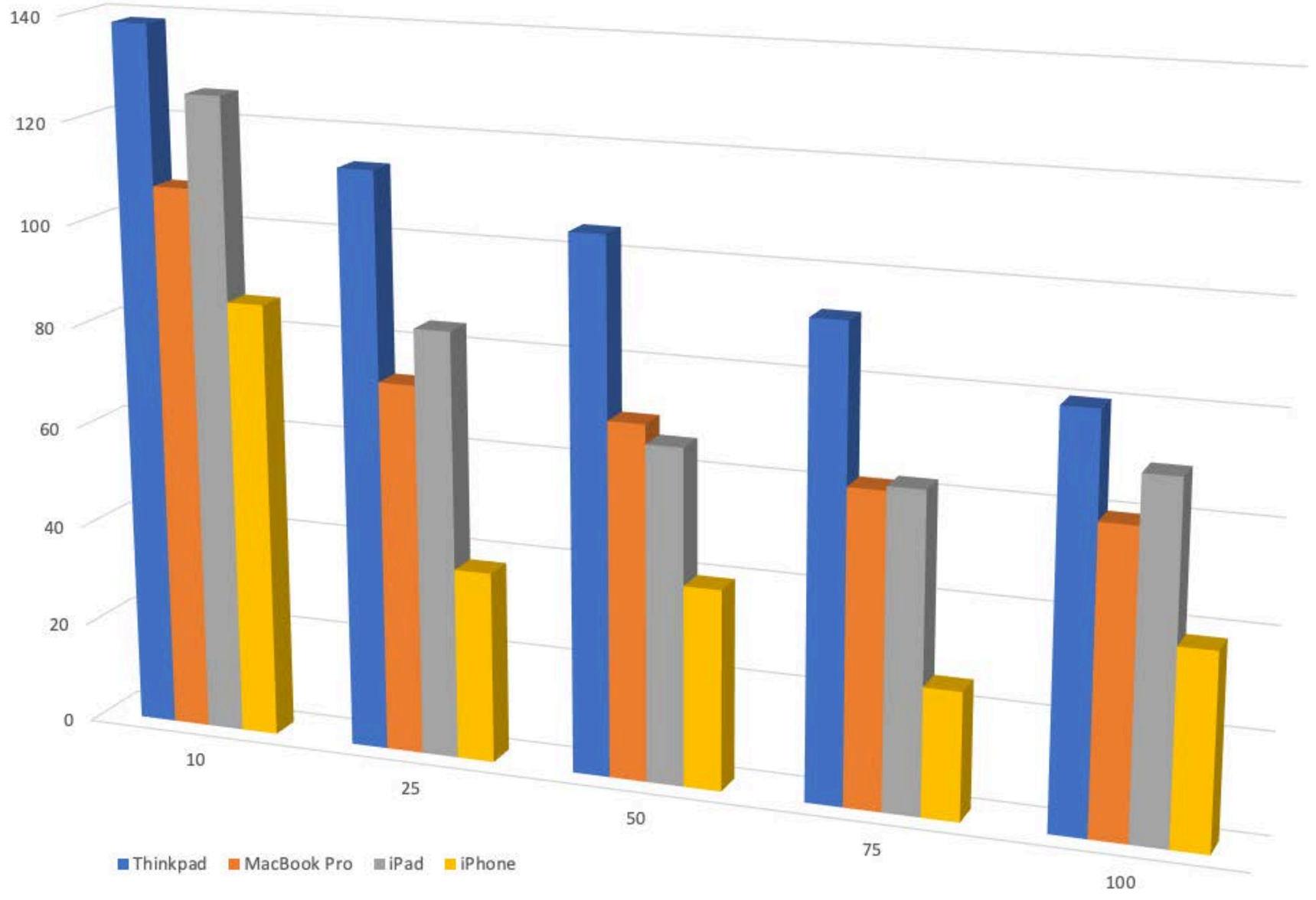




Spatial Streams

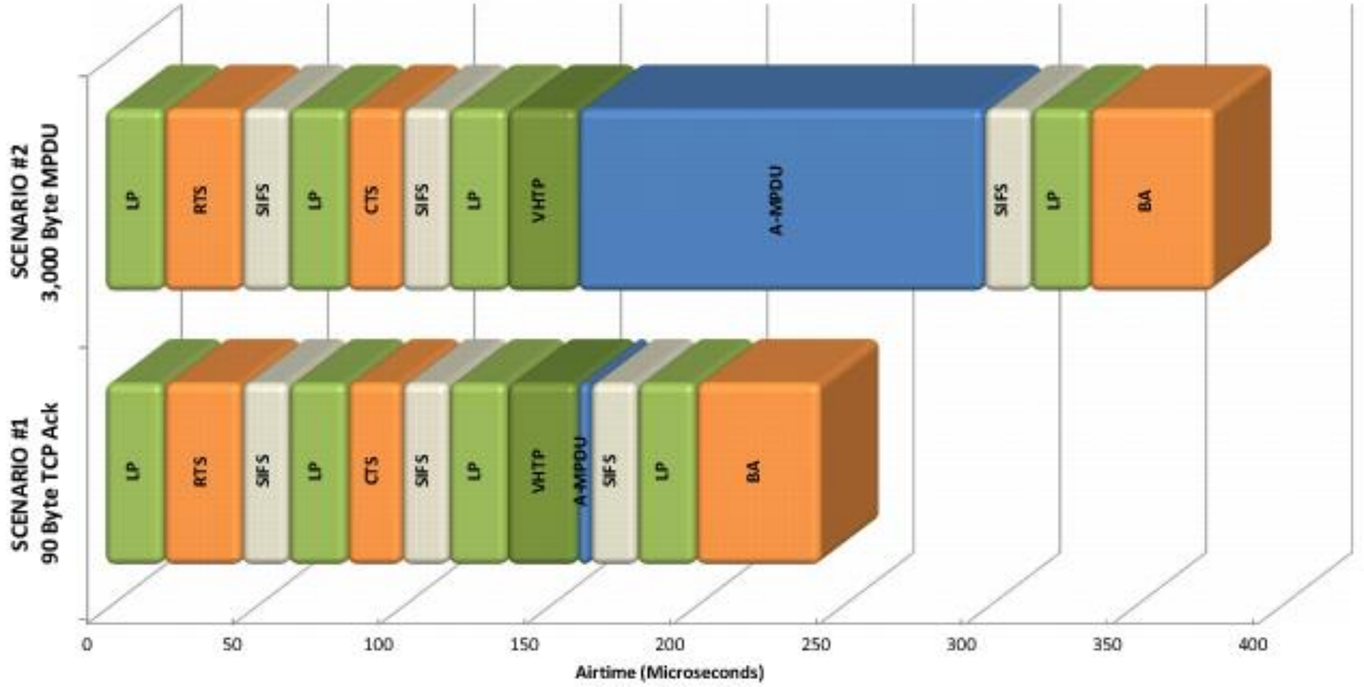


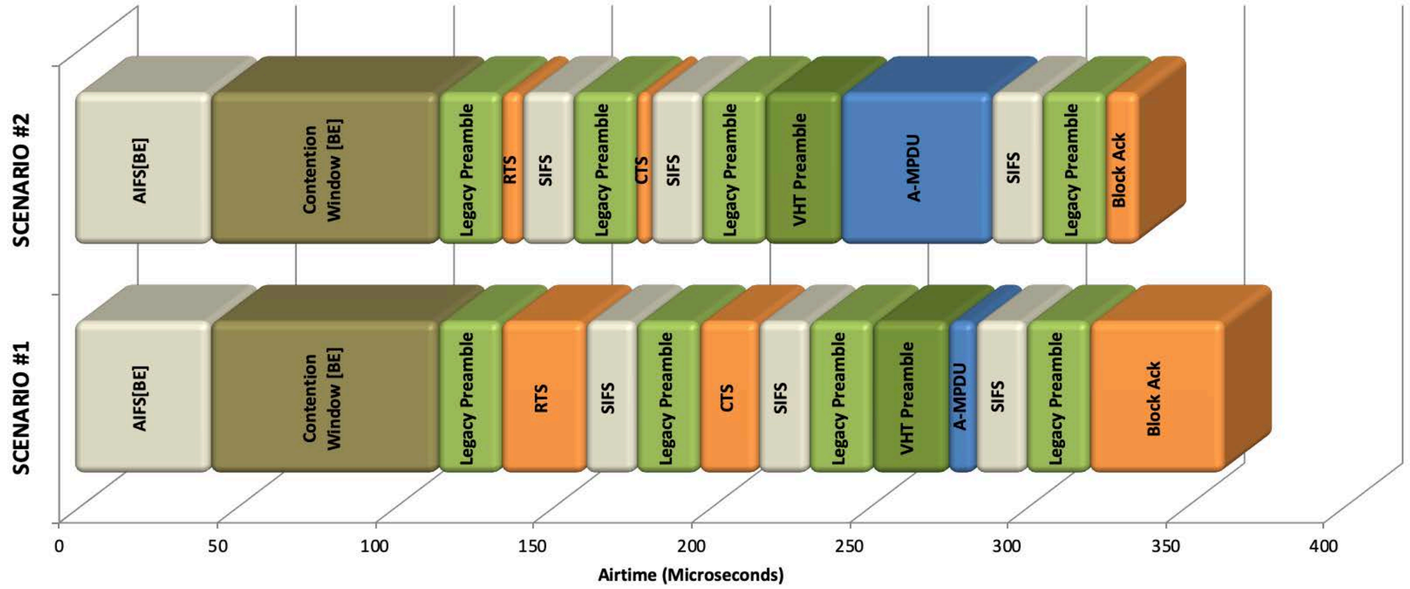
Wi-Fi 6 vs Wi-Fi 5



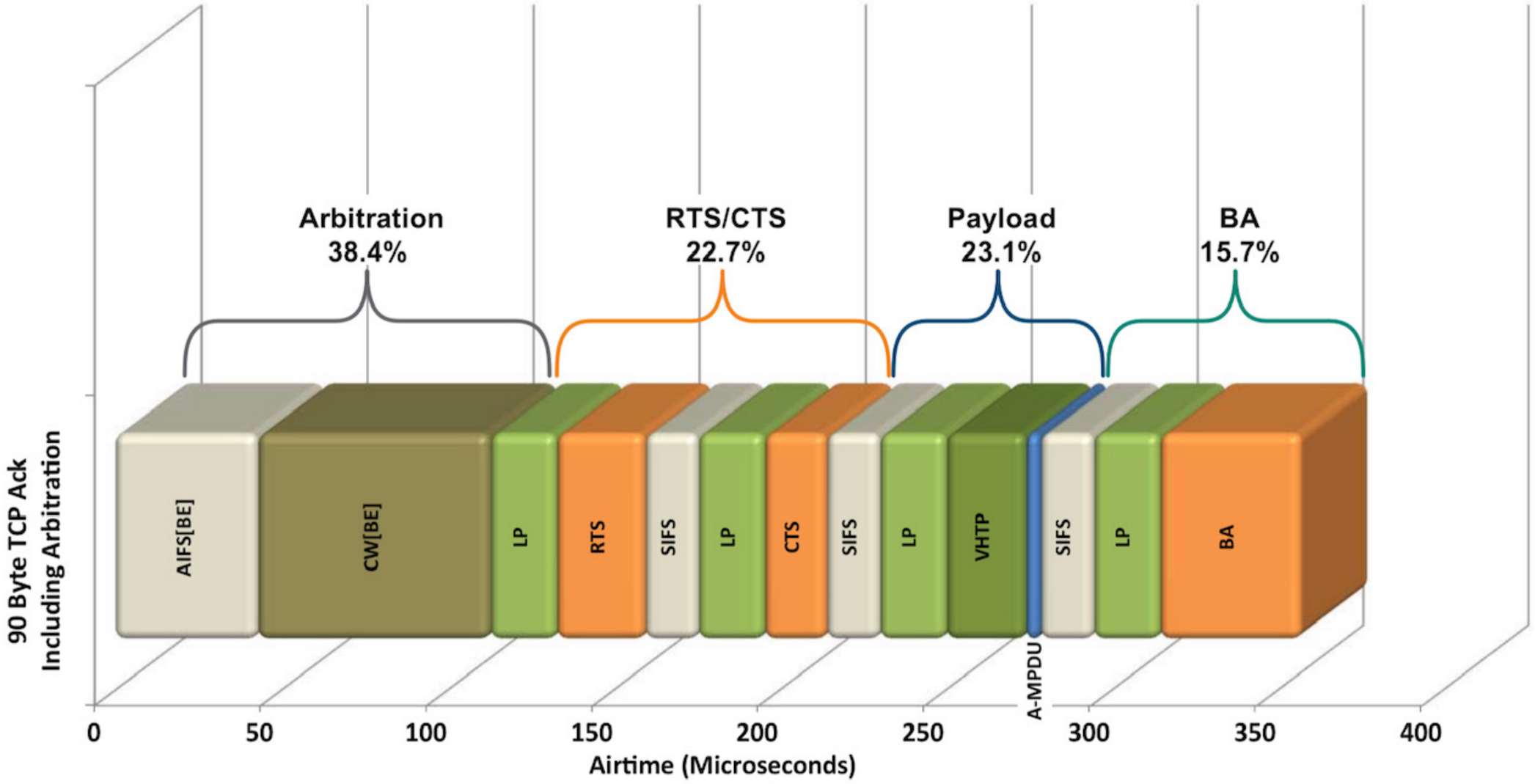
PHY Overhead

- ☑ AIFS - Arbitration Inter-frame Space
- ☑ Contention Window (*CW*)
- ☑ Preamble - *BPSK*
- ☑ RTS - *MBR*
- ☑ SIFS - *Fixed Tme*
- ☑ Preamble - *BPSK*
- ☑ CTS - *MBR*
- ☑ SIFS - *Fixed Tme*
- ☑ Preamble - *BPSK*
- ☑ Preamble - *VHT*
- ☑ Header - *MBR*
- ☑ **Payload - *PHY Rate***
- ☑ CRC
- ☑ SIFS - *Fixed Tme*
- ☑ Preamble - *BPSK*
- ☑ ACK - *MBR*

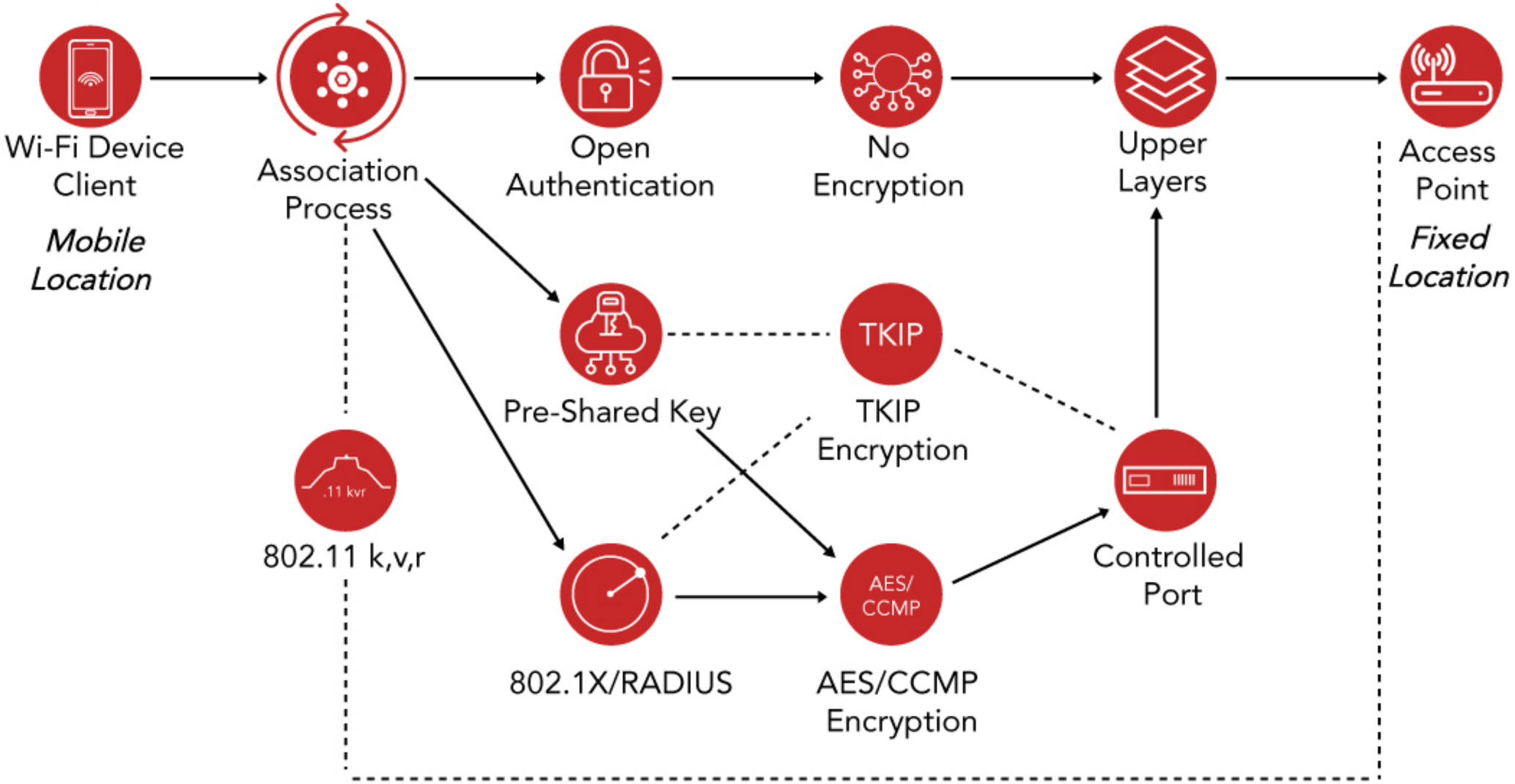




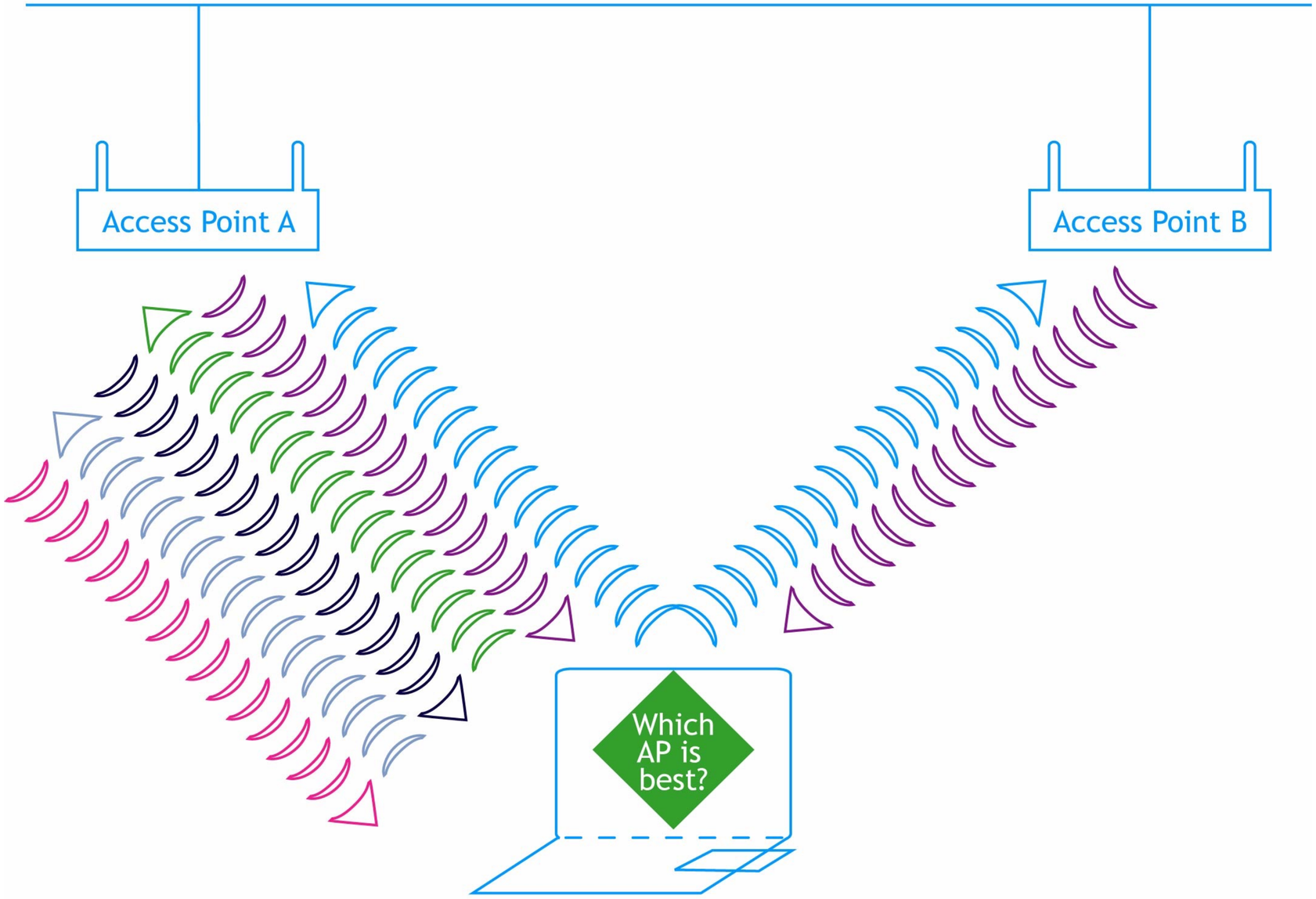
Only Blue is the Payload



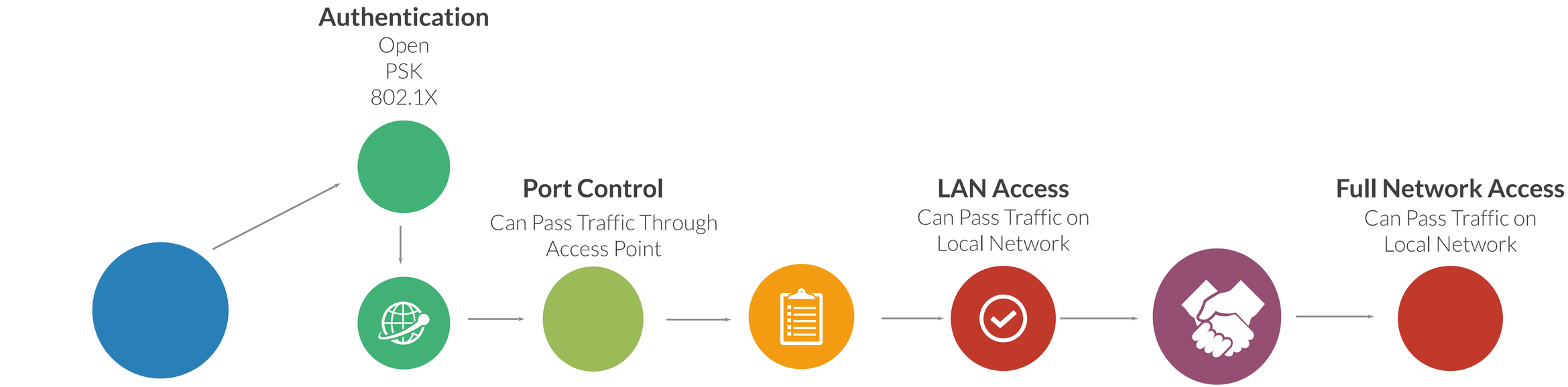
Know the MAC


Wi-Fi Device Client
Mobile Location
Association Process
Open Authentication
No Encryption
Upper Layers
Access Point
Fixed Location
Pre-Shared Key
TKIP
TKIP Encryption
.11 kvr
802.11 k,v,r
802.1X/RADIUS
AES/ CCMP
AES/CCMP Encryption
Controlled Port

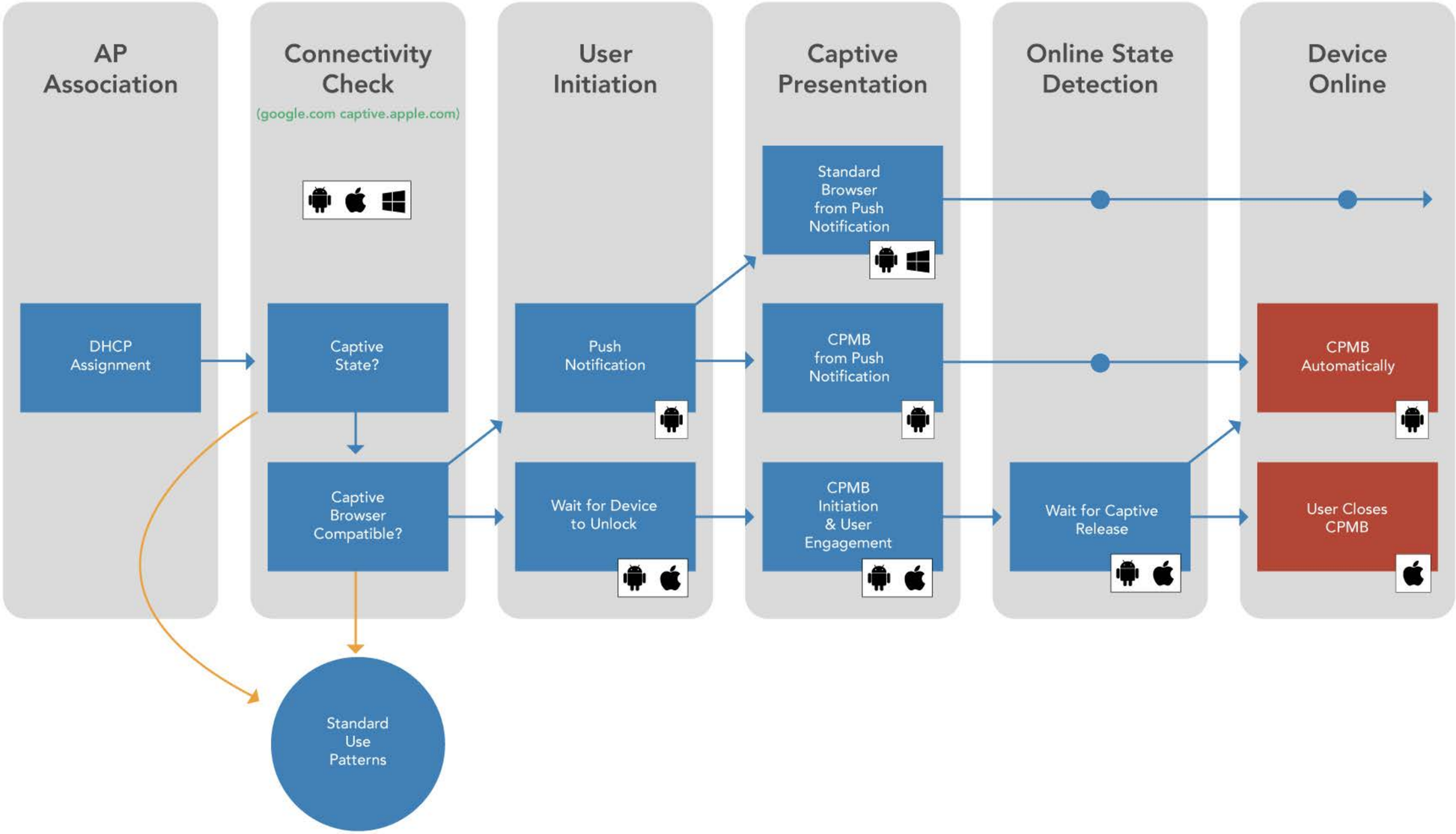
Association Process



Client Joining a WLAN Process

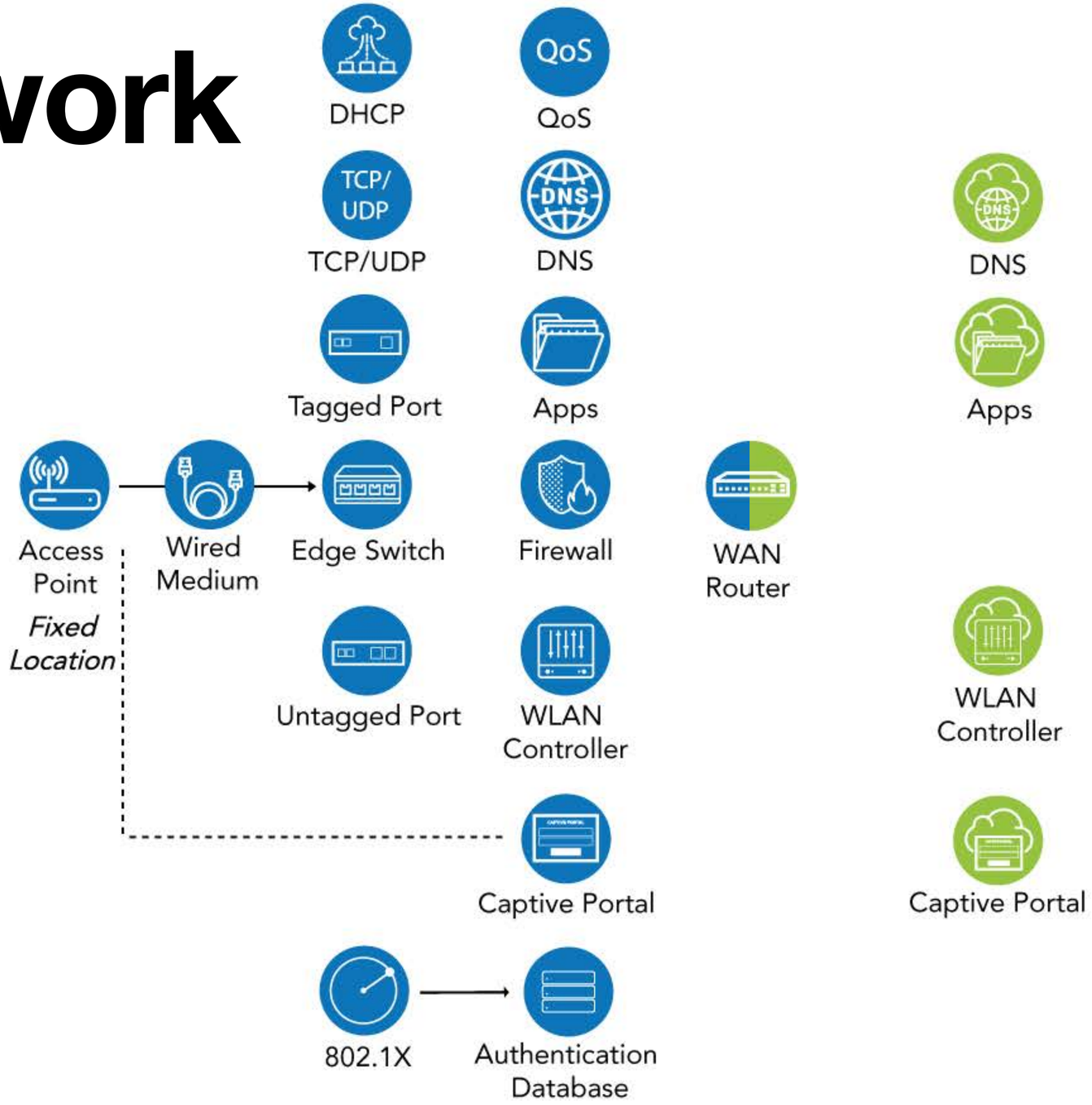


Captive Portal Processes

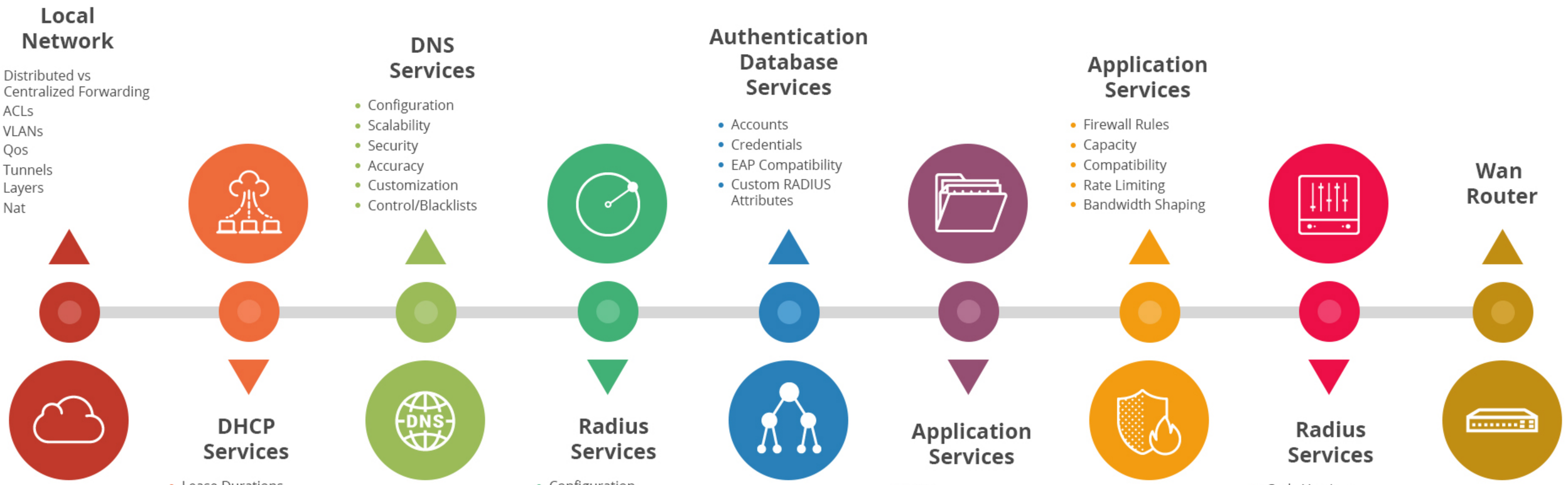


Know the Network

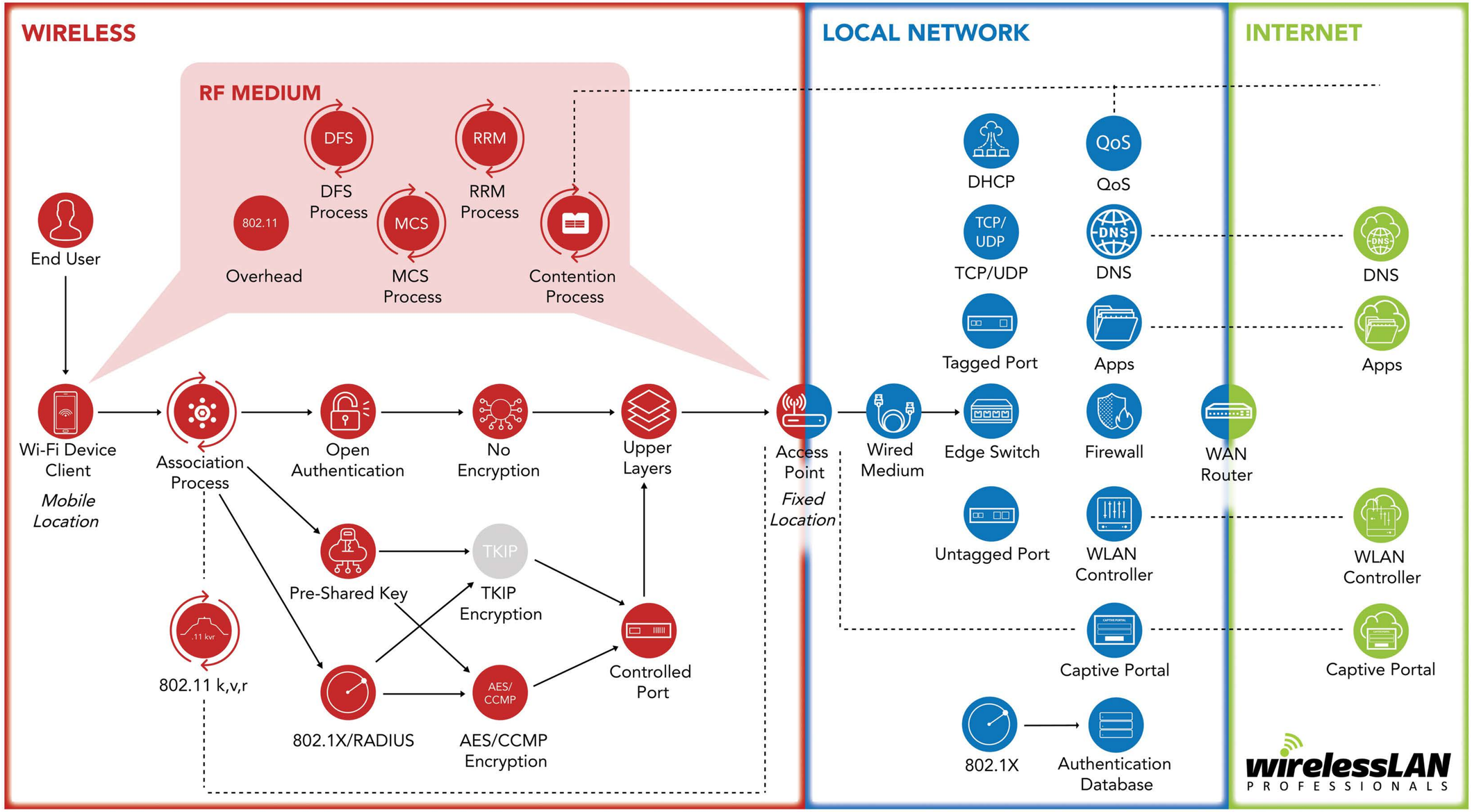
- Local Network
- Network Services
- Internet/WAN



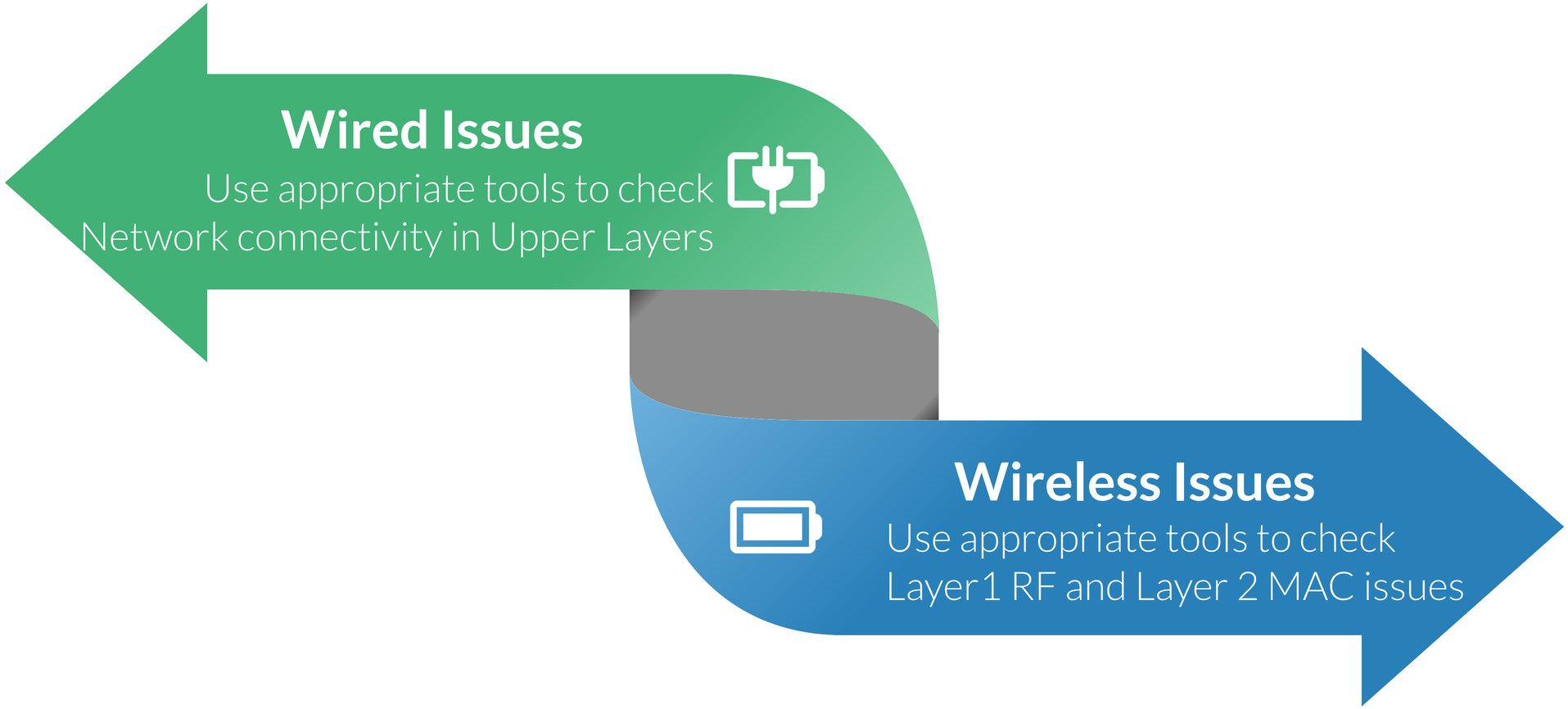
Network Services



Know the Big Picture



Understand Wired vs Wireless



How to Determine if Wired or Wireless

IP Address

Does target Wi-Fi Client Devices have an IP Address?

Ping Wi-Fi Client

Can you Ping your Wi-Fi Client Device from the Wired Network?

MCS of Wi-Fi Client

Is the MCS of Wi-Fi client showing stress

MCS 5-9 means 64-QAM or Better

MCS of <5 means difficulty over RF

Compare Throughputs

Compare Wi-Fi connection data rate to Internet Speed Test

Check RSSI & SNR

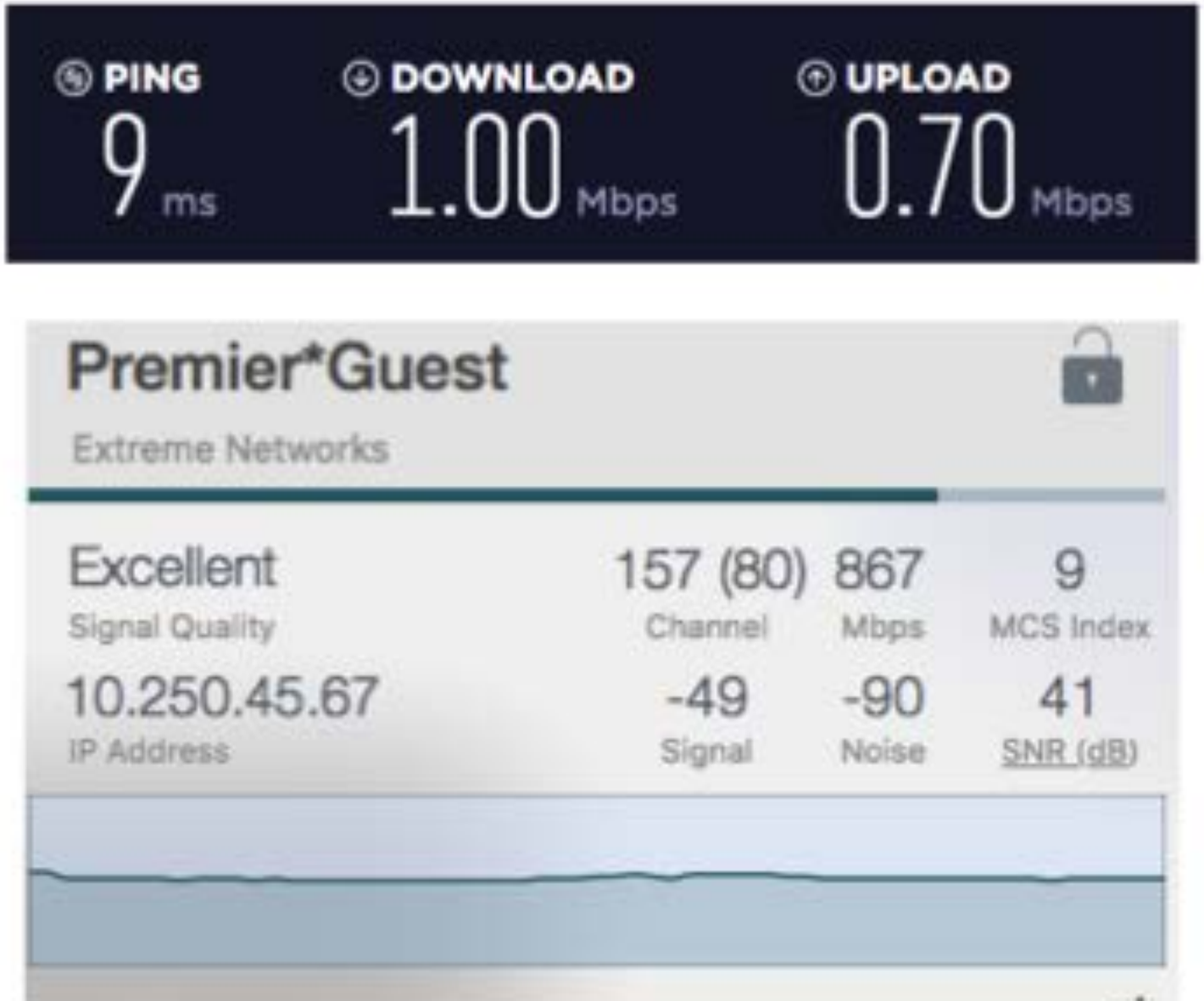
Both from the Client's point of view as well as from the Access Points'

Isolated?

Are the issues isolated to only Wi-Fi devices or across network

Especially check network services

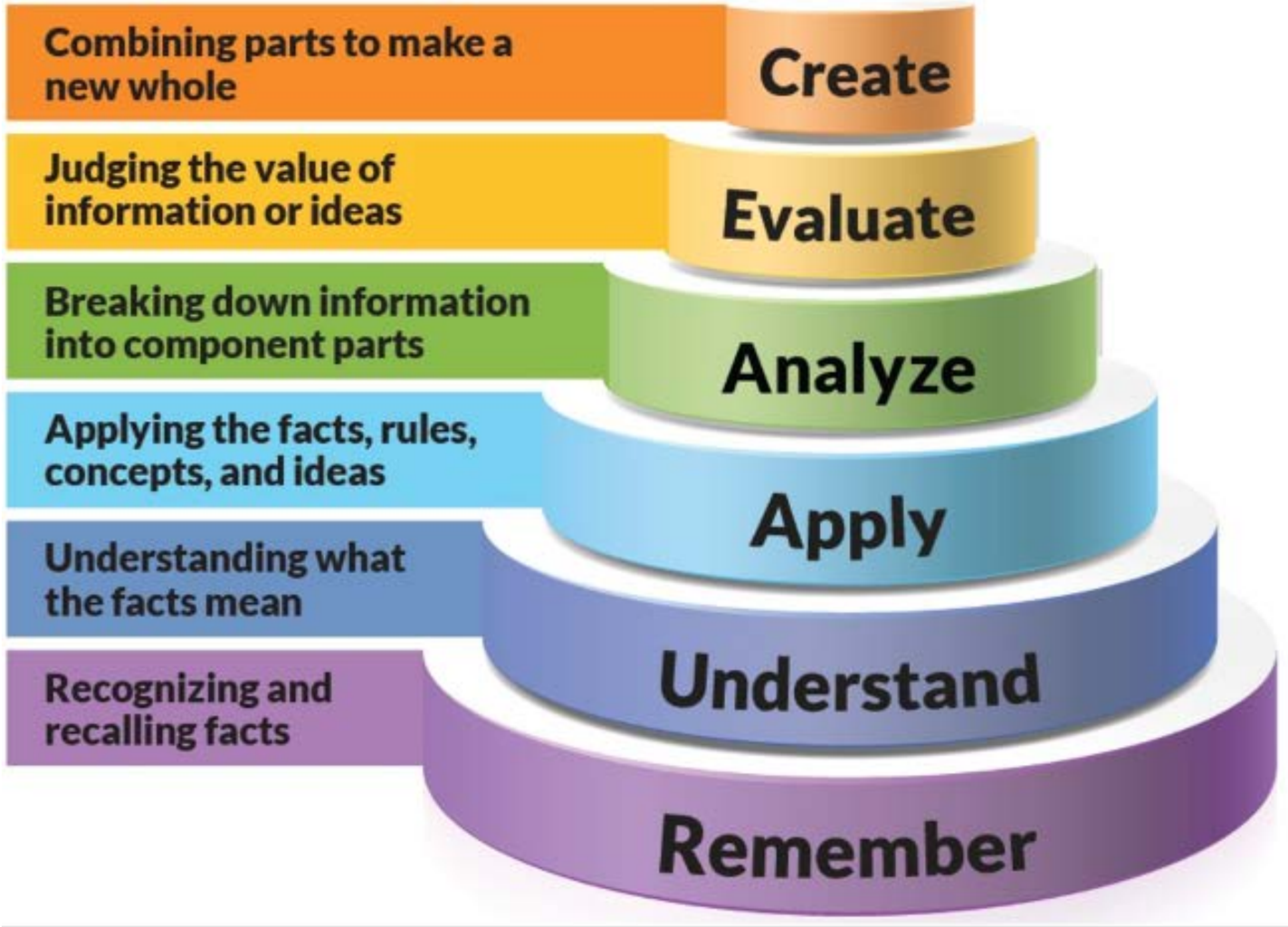
WiFi Signal vs Throughput



Business Requirements

- Where you fit in the grand scheme
- Who you report to
- What is your responsibility
- Use Bloom’s Taxonomy & Business Vocabulary
  - What do YOU want to do?

Bloom's Taxonomy



Use Appropriate Vocabulary

for The Job You WANT

Know the Rules

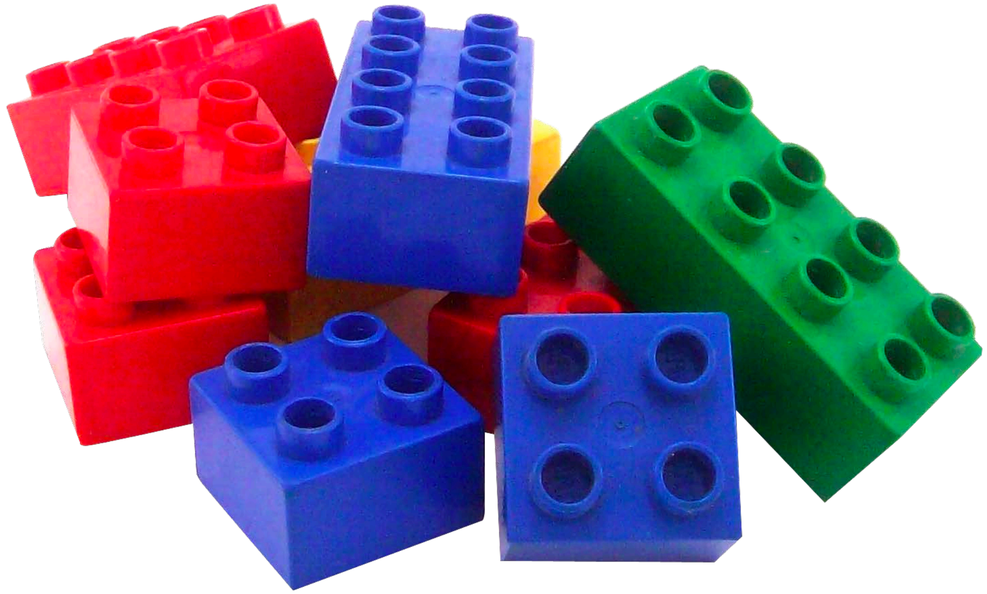
And when to break them!

- #1 Rule - 802.11/Wi-Fi is EXTREMELY Resilient
- What does the above statement imply?

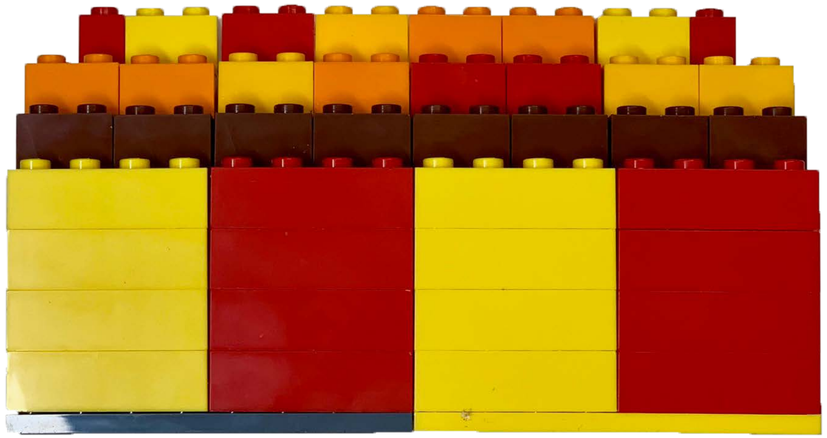
- LEGO House Requirements Example
  - Robust vs Brittle

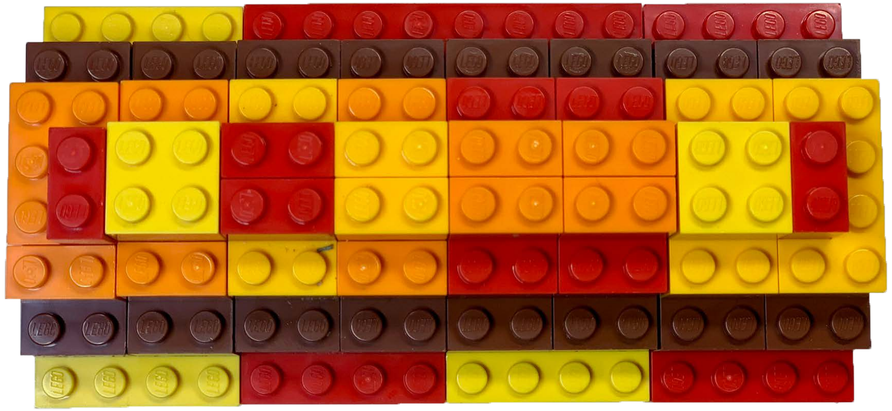
Building Requirements

8 x 16 ‘House’
7 Bricks High
Sloped Roof
Fixed set of Bricks

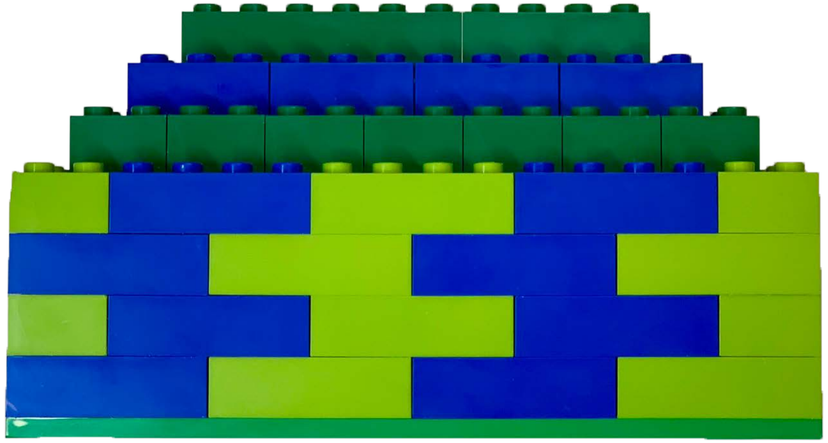


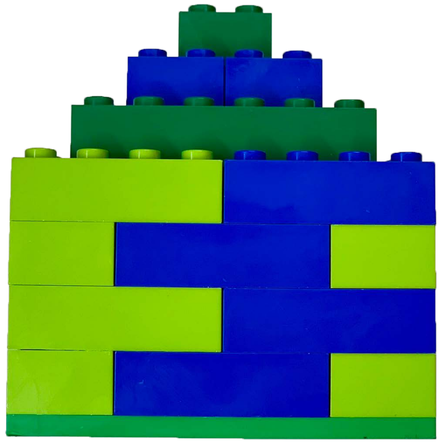
One way of meeting the requirements

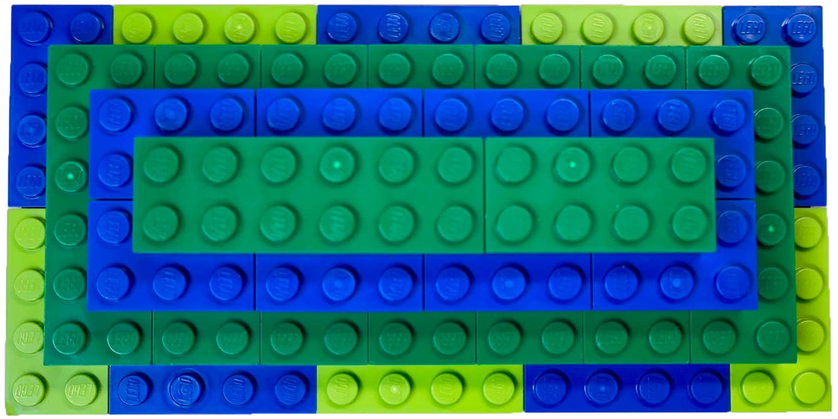




Same Bricks - Different Engineering

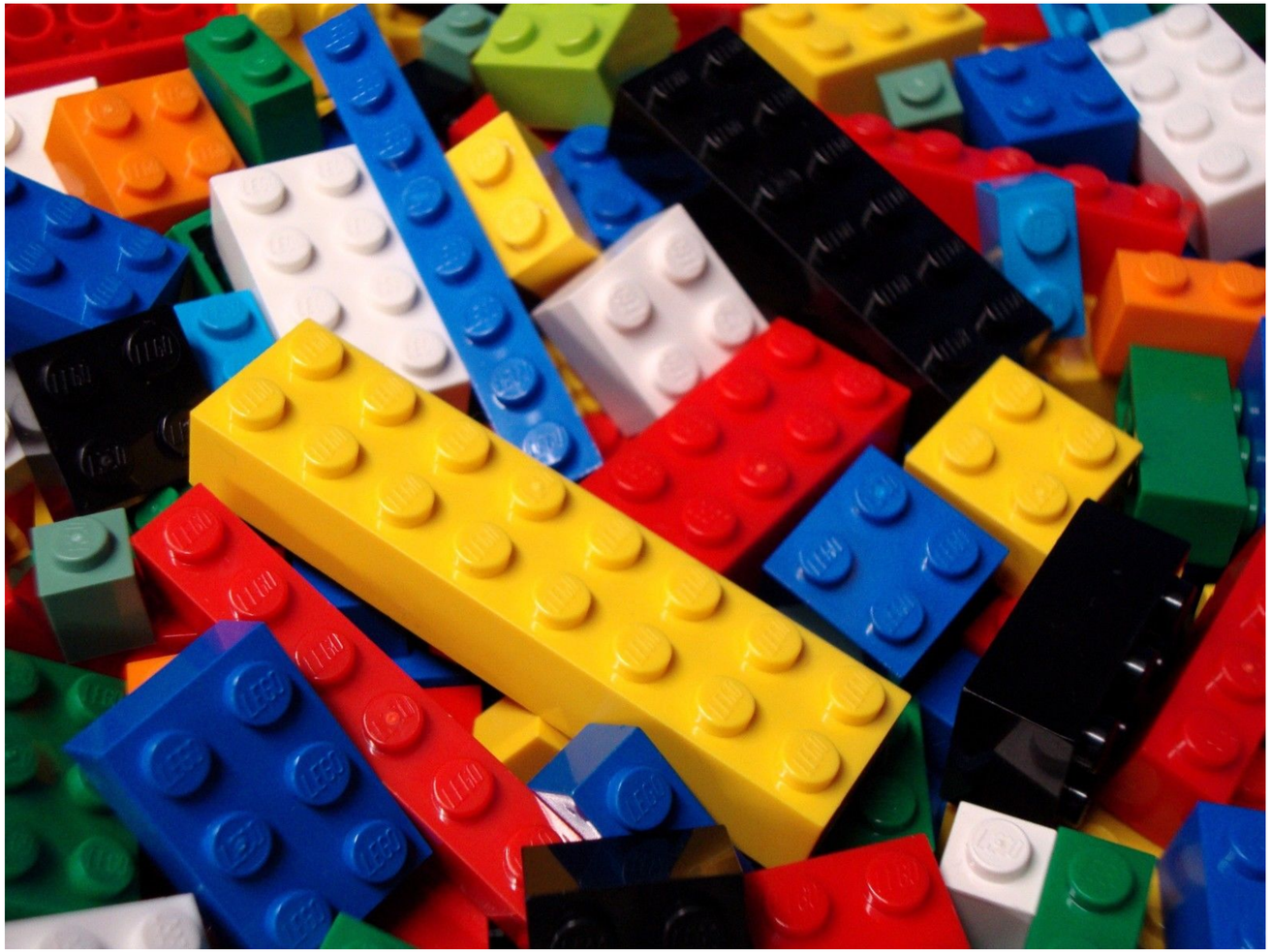


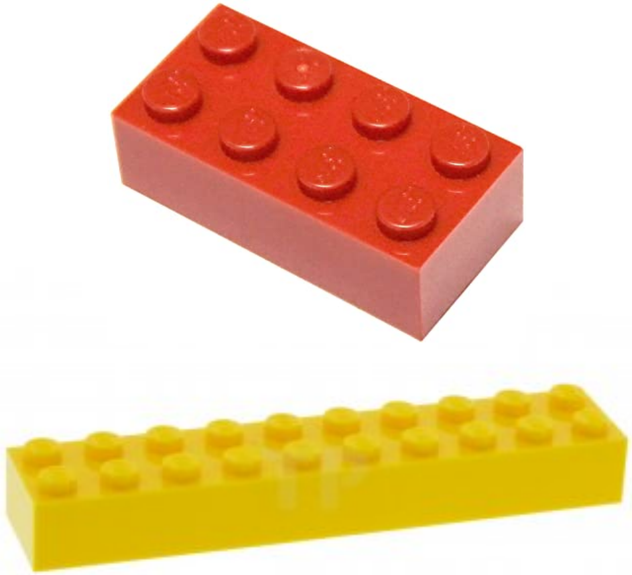




LEGO Building & Requirements

Choose the correct Brick for the job!





What to do next

- ENGAGE with the Wireless LAN Community
- Truly UNDERSTAND the parts of Wi-Fi
- Home Lab - Highly Recommended
- Never stop learning!
- Training, YouTube, Blogs, Websites

Top Ten WLAN Design Tips

1. Know the PHY
2. Know your Requirements
3. It is NOT about the Green
4. Follow Best Practices
5. Do NOT use Marketing Ratios
6. Always Validate, Always
7. Choose Access Points First
8. Meet ALL Requirements
9. Understand Capacity
10. Document Everything

Thanks!