

WiFi Networking and Design

(or, An Argument with Physics)

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Born and raised in Texas, Chris studied history at the University of Chicago before getting sidetracked into the worlds of Apple and computer networking.

Part of the Seattle consulting community since 1999 and Principal Systems Engineer for Wheelwrights, LLC since 2007, Chris provides support, solutions, planning, and training for a variety of business and education customers in Western Washington.

Chris spends his spare time working in the kitchen with items that do *not* require firmware upgrades.



Before we start...

Huge shout out for curriculum to:

Jeanette Lee

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[@ruckusgirl](#)

Let's Talk About

- WiFi overview
- WLAN design principals
- Planning for high density
- Troubleshooting and Performance Testing

WiFi Fundamentals

What is it?

What is WiFi?

- A perfectly cromulent neologism
- IEEE wanted a catchier name than “IEEE 802.11b Direct Sequence”
- 802.11 is a standard for describing wireless local area networks for computer communication using radio waves.

What is WiFi?

- Fundamentally, a set of technologies for Ethernet via radio instead of copper cable.
- Client devices use built-in radios to talk to the network via Wireless Access Points, which are also equipped with one or more radios.

Wireless Access Point

- Think of it like an Ethernet hub (as of 2014)
- Not an Ethernet switch, a hub
- The distinction is critical for understanding real world performance

It's a Shared Medium

- By design, when one device on a channel talks, everything else has to listen; the waiting typically referred to as “co-channel interference”
- Performance specs are thus somewhat idealized
- Things get “interesting” when you start adding devices or mixing device types
- Serious implications for design

One Client, One WAP

WiFiPerf

Client Server

Test Duration: 30 Data/BandWidth Format: ☒ Mbps ☐ Kbps Transfer Direction: ☐ Client To Server ☒ Server To Client ☐ Voice Alert Test Type: TCP Run Test

Stats Interval: 2 Graph Max Speed (Mbps): 1000

Stats Interval: 2 sec Transfer Direction: Server To Client Test Type: TCP

Interval	Transfer	S/R Bandwidth	Interface Name	SSID	RSSI	Tx Rate	Signal/Noise	PHY Mode
0.00-30.00 sec	480.50 MB	134.35 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
26.07-28.08 sec	32.00 MB	133.48 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
24.07-26.07 sec	33.38 MB	139.94 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
22.07-24.07 sec	32.75 MB	137.33 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
20.07-22.07 sec	32.38 MB	135.67 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
18.06-20.07 sec	33.00 MB	137.64 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
16.05-18.06 sec	32.00 MB	134.10 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
14.05-16.05 sec	31.38 MB	131.41 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
12.05-14.05 sec	32.38 MB	135.65 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
10.04-12.05 sec	31.75 MB	132.67 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
8.04-10.04 sec	32.12 MB	134.32 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
6.02-8.04 sec	32.50 MB	135.32 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
4.02-6.02 sec	32.62 MB	136.56 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
2.00-4.02 sec	33.00 MB	137.39 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
0.00-2.00 sec	27.38 MB	114.72 Mbps	WiFi	Wheelwrights	-55	270	37	802.11n

Address: 10.253.254.21 TCP

Two Clients, One WAP

WiFiPerf

Client Server

Test Duration: 30 Data/BandWidth Format: ☒ Mbps ☐ Kbps Transfer Direction: ☐ Client To Server ☒ Server To Client Test Type: TCP

Stats Interval: 2 Graph Max Speed (Mbps): 1000 ☐ Voice Alert Run Test

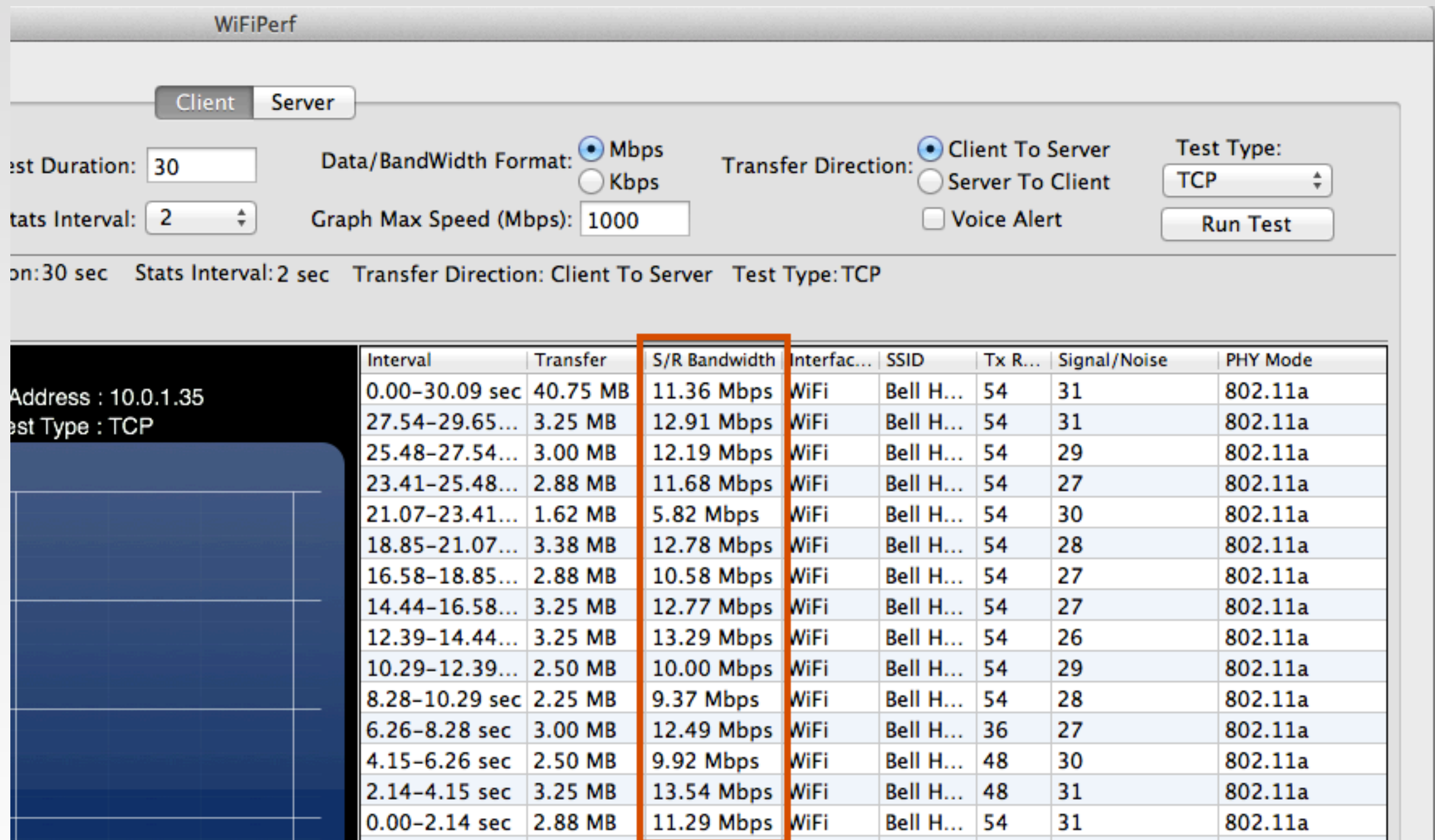
Stats Interval: 2 sec Transfer Direction: Server To Client Test Type: TCP

Interval	Transfer	S/R Bandwidth	Interface Name	SSID	RSSI	Tx Rate	Signal/Noise	PHY Mode
0.00-30.01 sec	296.00 MB	82.74 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
26.11-28.11 sec	13.00 MB	54.51 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
24.09-26.11 sec	11.38 MB	47.22 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
22.09-24.09 sec	13.38 MB	55.93 Mbps	WiFi	Wheelwrights	-52	270	40	802.11n
20.08-22.09 sec	11.00 MB	45.90 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
18.07-20.08 sec	11.62 MB	48.53 Mbps	WiFi	Wheelwrights	-53	300	39	802.11n
16.05-18.07 sec	13.00 MB	53.94 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
14.04-16.05 sec	15.75 MB	65.94 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
12.04-14.04 sec	12.88 MB	53.96 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
10.03-12.04 sec	24.38 MB	101.79 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
8.03-10.03 sec	33.38 MB	139.95 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n
6.03-8.03 sec	33.88 MB	141.78 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
4.01-6.03 sec	33.12 MB	137.71 Mbps	WiFi	Wheelwrights	-54	270	38	802.11n
2.01-4.01 sec	32.00 MB	134.13 Mbps	WiFi	Wheelwrights	-53	270	15	802.11n
0.00-2.01 sec	27.00 MB	112.77 Mbps	WiFi	Wheelwrights	-53	270	39	802.11n

Address : 10.253.254.21
: TCP

This Conference Center

11:03 AM



Frequency Band Fundamentals

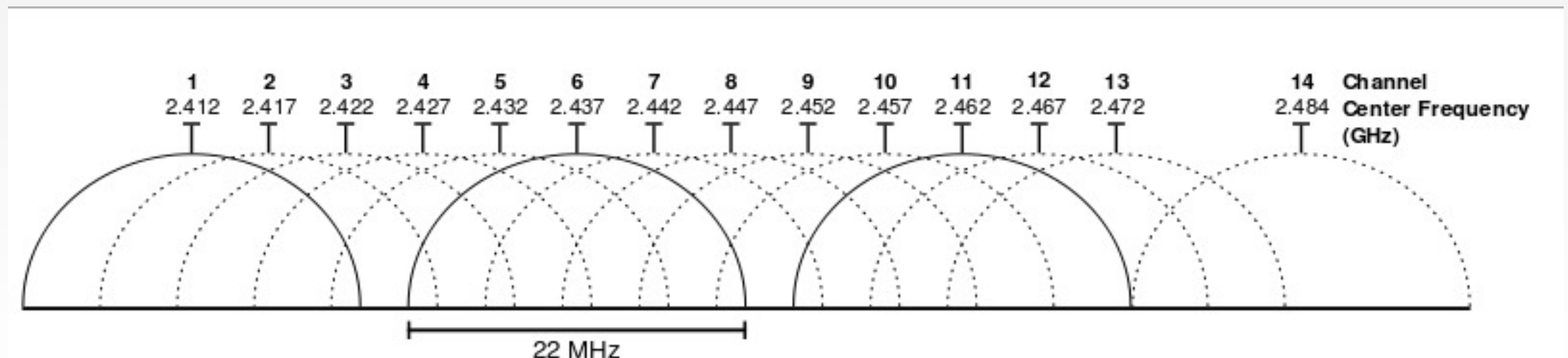
802.11 principles and standards

802.11 Standards

Standard	Frequency	Supported Data Rate	Modulation	Date release
802.11	2.4GHz	1, 2 Mbps	FHSS, DSSS	1997
802.11b	2.4GHz	1,2,5.5, 11 Mbps	DSSS	Sept 16th, 1999
802.11a	5GHz	6,9,12,18, 24,36,48,54	OFDM	Sept 16th, 1999
802.11g	2.4 GHz	1,2,5.5,6,9,11,12,18,24,36,48,54	DSSS, OFDM	June 2003
802.11n	2.4 / 5 GHz	Up to 600Mbps	All previous, plus HT-OFDM	Sept 11th, 2009
802.11ac	5 GHz	Up to 6.93 Gbps	OFDM	Draft

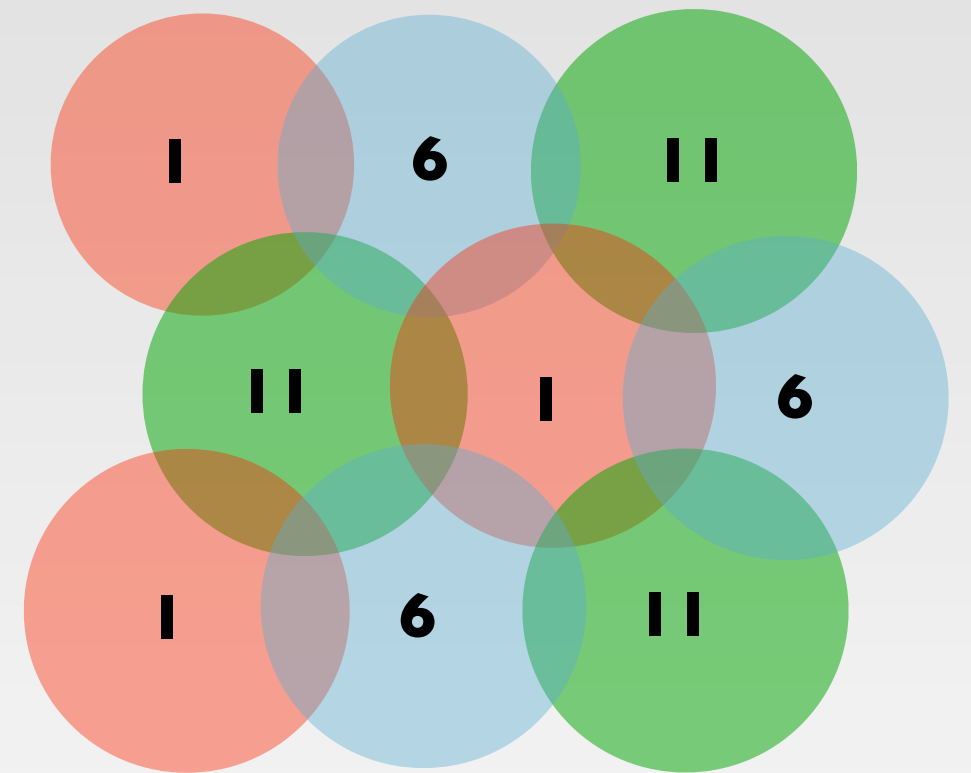
2.4 GHz Spectrum

- Only 3 non-overlapping channels (1, 6 and 11)
- Propagates readily through obstructions such as walls and support columns
- Heavily used due to early adoption; millions of devices from computers to phones
- Heavily congested frequency
- 40MHz channels is not feasible

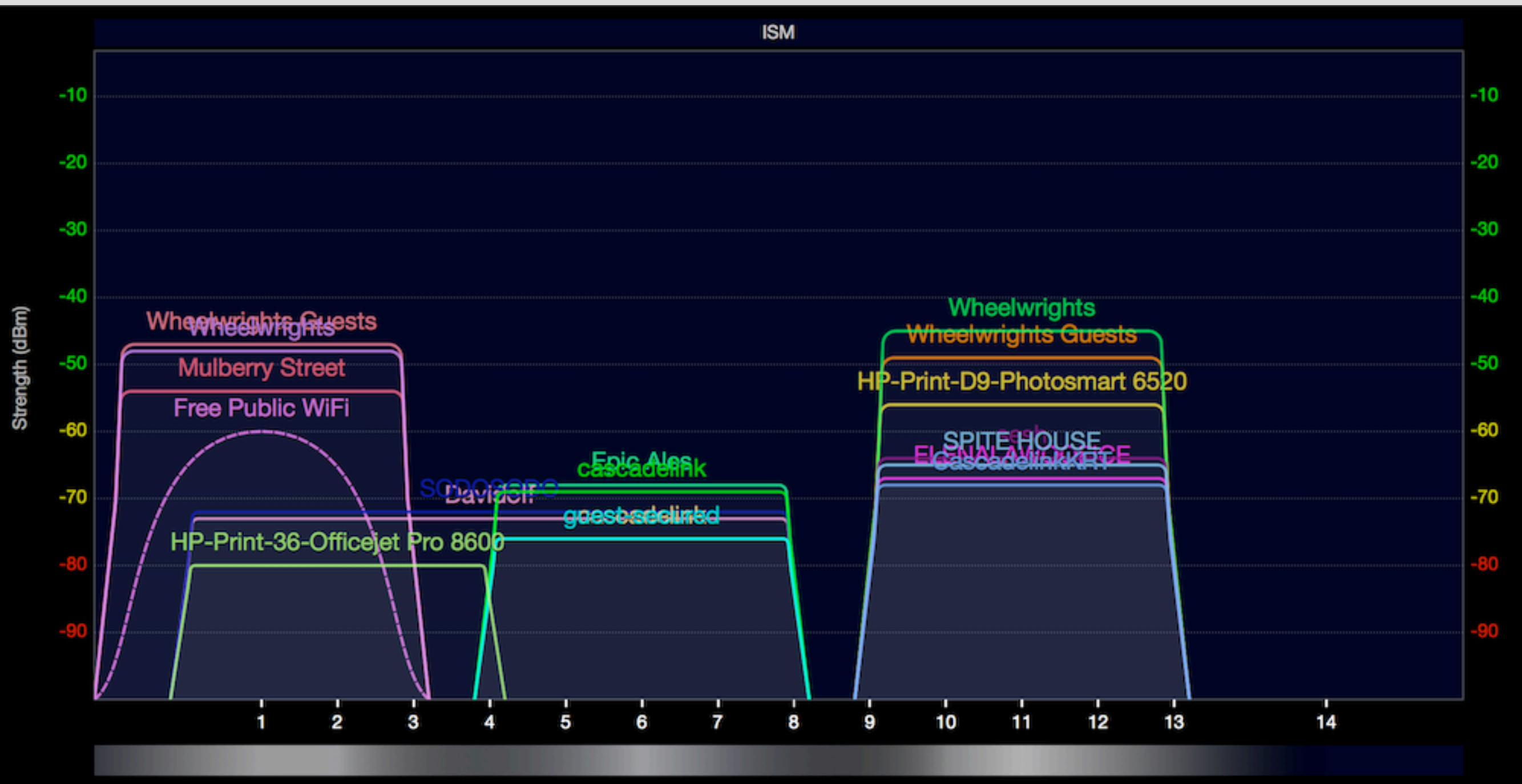


2.4 GHz Channel Planning Theory

- Goal: As little interference as possible with non-overlapping channels



2.4 GHz Here, on Earth (from my desk)



Why 2.4 GHz Presents Problems

- Lots of APs on 2.4 GHz, particularly in urban areas.
- Attenuation (reduction in strength) of 2.4 GHz happens relatively slowly, meaning suite or apartment networks can interfere with one another either via co-channel or adjacent channel interference
- Some kit comes from the factory with odd channel assignments (not 1, 6, or 11), which can cause adjacent channel interference.

Adjacent Channel Interference

- Two sets of transmitters are assigned to channels close enough that each's will broadcast in the other's spectrum. This garbles things.
- As a poor analogy, imagine eavesdropping on a conversation.
- Now imagine trying to eavesdrop simultaneously on a second conversation, with that second conversation occurring in another language.

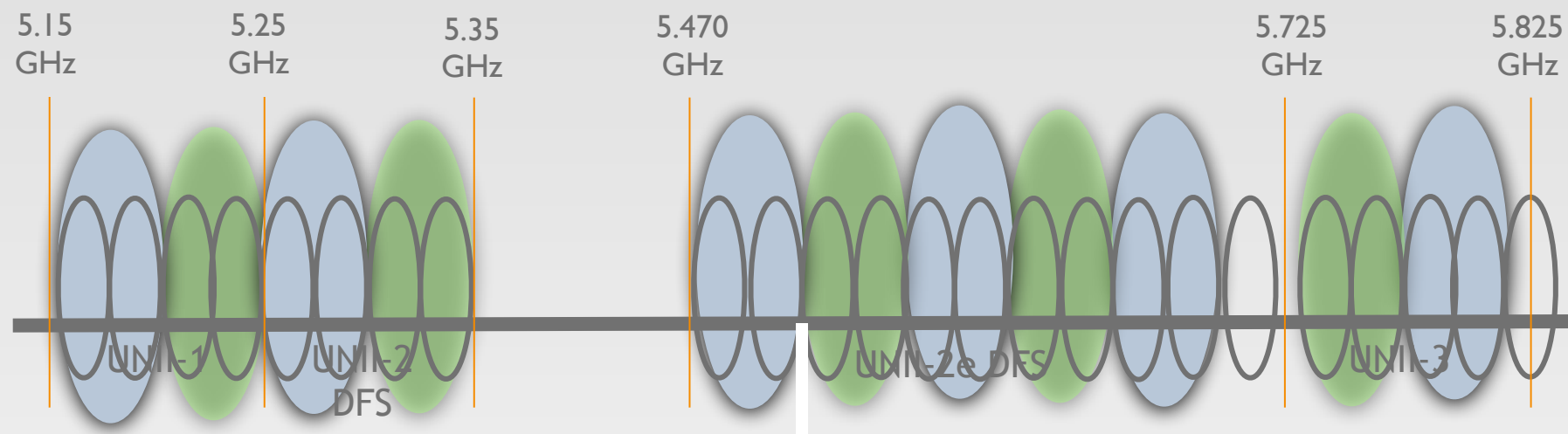
Channels 1, 6, and 11 can be a Problem, Too

- Lots of APs on these channels in urban environments
- Most of those APs are far away from our AP
- Most of those APs are using 1mbps for beacon/mgmt
- Constant sea of 1mbps beacons and probe responses
 - Very low rx power at our AP
 - Irrelevant to our AP
 - Can easily 'overpower' them for our own clients
- Leaving 1,6,11 can fix this problem!

2.4 GHz

- Damned if you do, damned if you don't.

5 GHz Spectrum



NON-DFS CHANNELS	36 40	40MHz
	44 48	40MHz
	149 153	40MHz
	157 161	40MHz

- 24 non-overlapping 20 MHz channels
- 11 non-overlapping 40 MHz channels
- Only 4 non-DFS channels for bonding
- Creates channel planning problems similar to 2.4 GHz
- 5 GHz isn't a panacea, RF management is still king

5 GHz: The Future of Wi-Fi

- 5GHz band has 6-7 times the available bandwidth of 2.4GHz in most countries.
- Large number of channels allows frequency reuse factors of 4,7,9, or 12+ (compared to 3 for 2.4)
- Attenuates more readily
- Allows much denser AP placement
- 8 to 20x the mbps/m² of 2.4 GHz band (!)

2ND FLOOR

MOTTMAN BUILDING
TENANT IMPROVEMENT

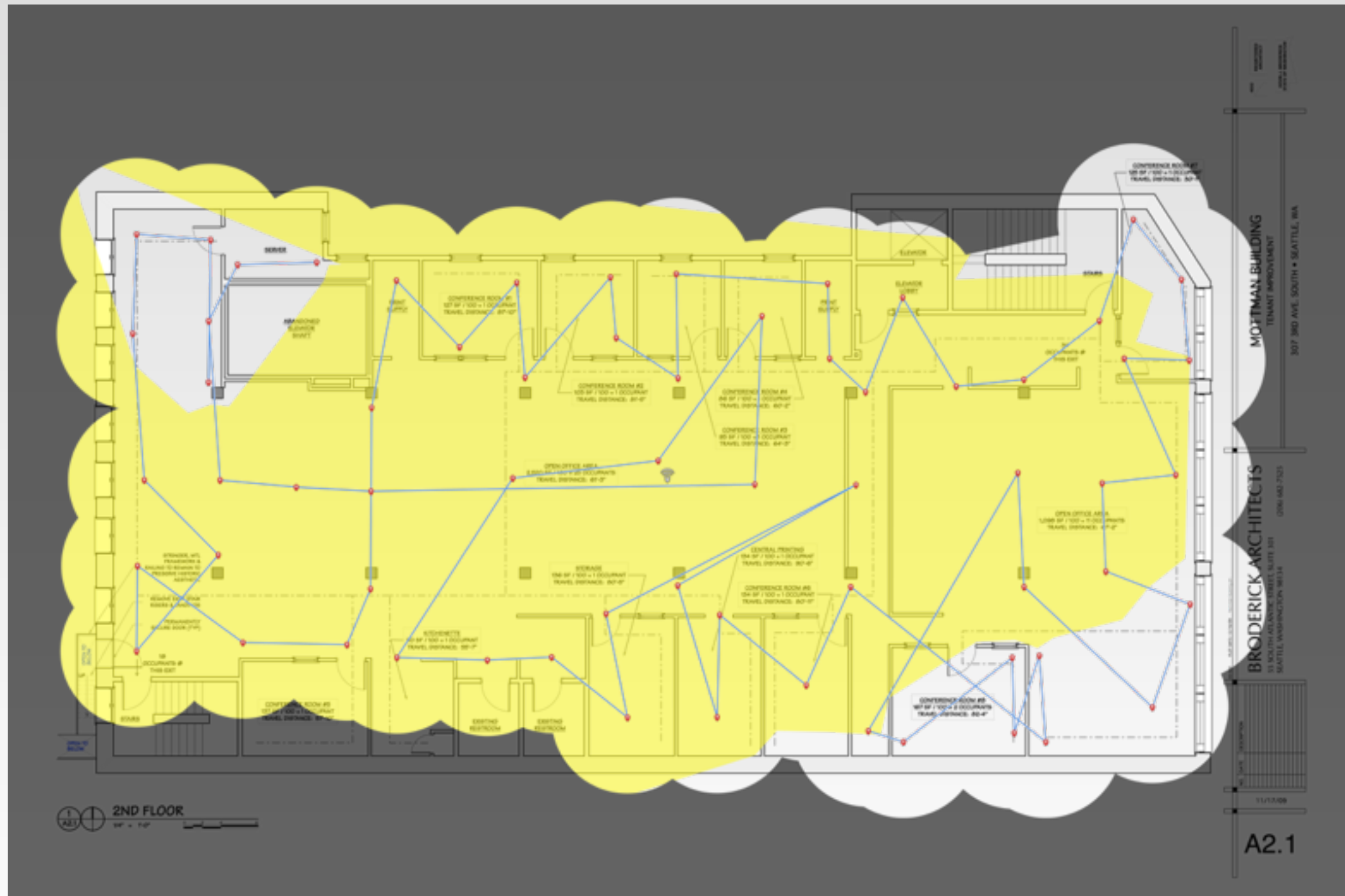
BRODERICK ARCHITECTS
51 SOUTH ALDEN STREET, SUITE 301
SEATTLE, WASHINGTON 98134

307 3RD AVE. SOUTH • SEATTLE, WA

DATE: 10/17/09

A2.1

5 GHz Coverage Example



Sweet 5 GHz Relief



802.11n: The Going Gets Weird

- Multiple Transmit/Receive chains (MIMO)
 - Uses Tx:Rx notation, e.g. 3x3
 - Multi-path is more robust and suffers fewer errors
- Spatial multiplexing
 - Different bits travel different paths (MOAR throughput)
 - Streams indicator notation: 3x3:3

	Minimum Tx/Rx Chains	Spatial Streams	Maximum Link Speed
Single stream	1x1	1	150 Mbps
2 stream	2x2	2	300 Mbps
3 stream	3x3	3	450 Mbps
4 stream	4x4	4	600 Mbps

802.11n: The Going Gets Weird

- Data rates become complicated in 802.11n
- A variety of specs combine to give data rate
 - Channel width (20 MHz or 40 MHz)
 - Number of spatial streams (1, 2 or 3)
 - Guard interval (delay between bytes transmitted)

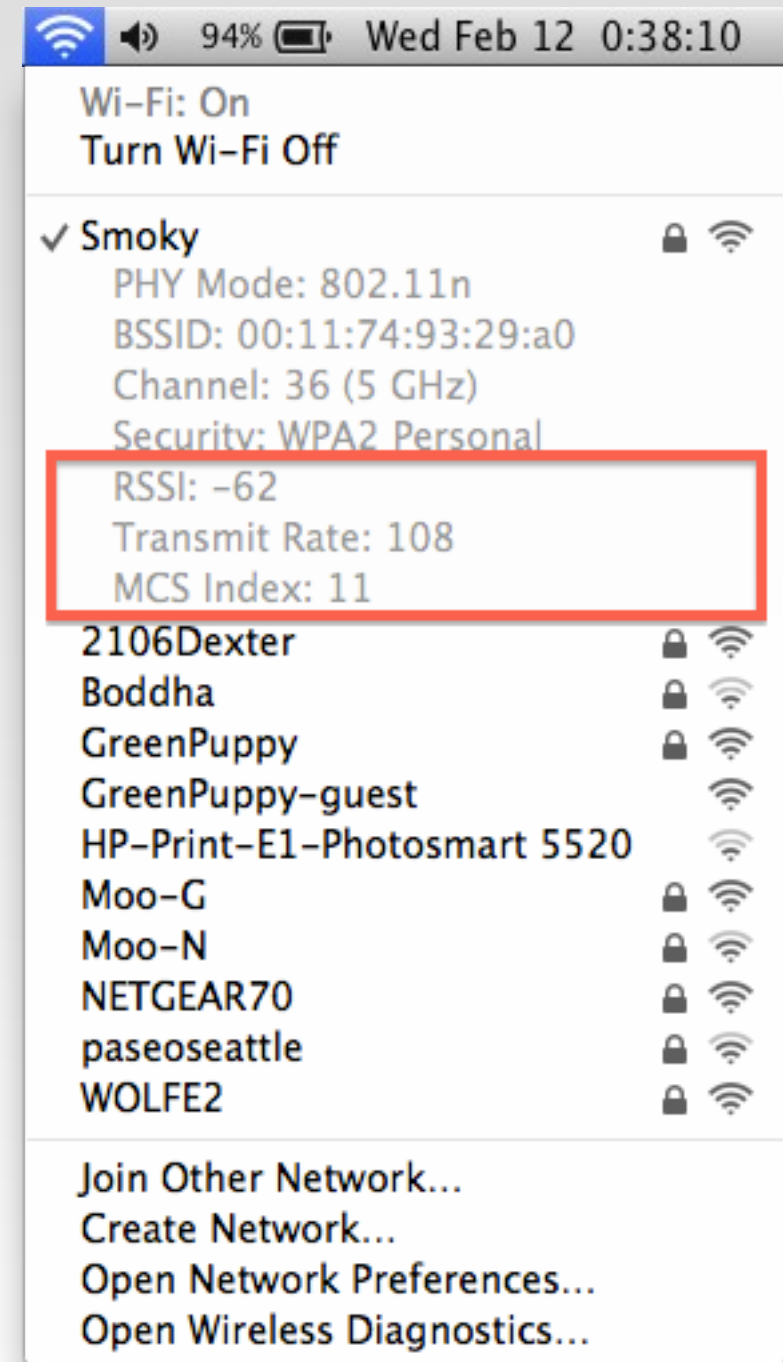
802.11 MCS Rates Your Best Friend

MCS Index	Type	Coding Rate	Spatial Streams	Data Rate (Mbps) with 20 MHz CH		Data Rate (Mbps) with 40 MHz CH	
				800 ns	400 ns (SGI)	800 ns	400 ns (SGI)
0	BPSK	1 / 2	1	6.50	7.20	13.50	15.00
1	QPSK	1 / 2	1	13.00	14.40	27.00	30.00
2	QPSK	3 / 4	1	19.50	21.70	40.50	45.00
3	16-QAM	1 / 2	1	26.00	28.90	54.00	60.00
4	16-QAM	3 / 4	1	39.00	43.30	81.00	90.00
5	64-QAM	2 / 3	1	52.00	57.80	108.00	120.00
6	64-QAM	3 / 4	1	58.50	65.00	121.50	135.00
7	64-QAM	5 / 6	1	65.00	72.20	135.00	150.00
8	BPSK	1 / 2	2	13.00	14.40	27.00	30.00
9	QPSK	1 / 2	2	26.00	28.90	54.00	60.00
10	QPSK	3 / 4	2	39.00	43.30	81.00	90.00
11	16-QAM	1 / 2	2	52.00	57.80	108.00	120.00
12	16-QAM	3 / 4	2	78.00	86.70	162.00	180.00
13	64-QAM	2 / 3	2	104.00	115.60	216.00	240.00
14	64-QAM	3 / 4	2	117.00	130.00	243.00	270.00
15	64-QAM	5 / 6	2	130.00	144.40	270.00	300.00
16	BPSK	1 / 2	3	19.50	21.70	40.50	45.00
...
31	64-QAM	5 / 6	4	260.00	288.90	540.00	600.00

Not just data rates 1, 2, 5.5 and 11 any more. Are you using a single, dual or three stream device? What do your performance numbers mean?

Check Your MCS

- MCS will tell the real story
- RSSI is relative, and only marginally useful
- Data rates change over time, a one time glance guarantees nothing in the next second!



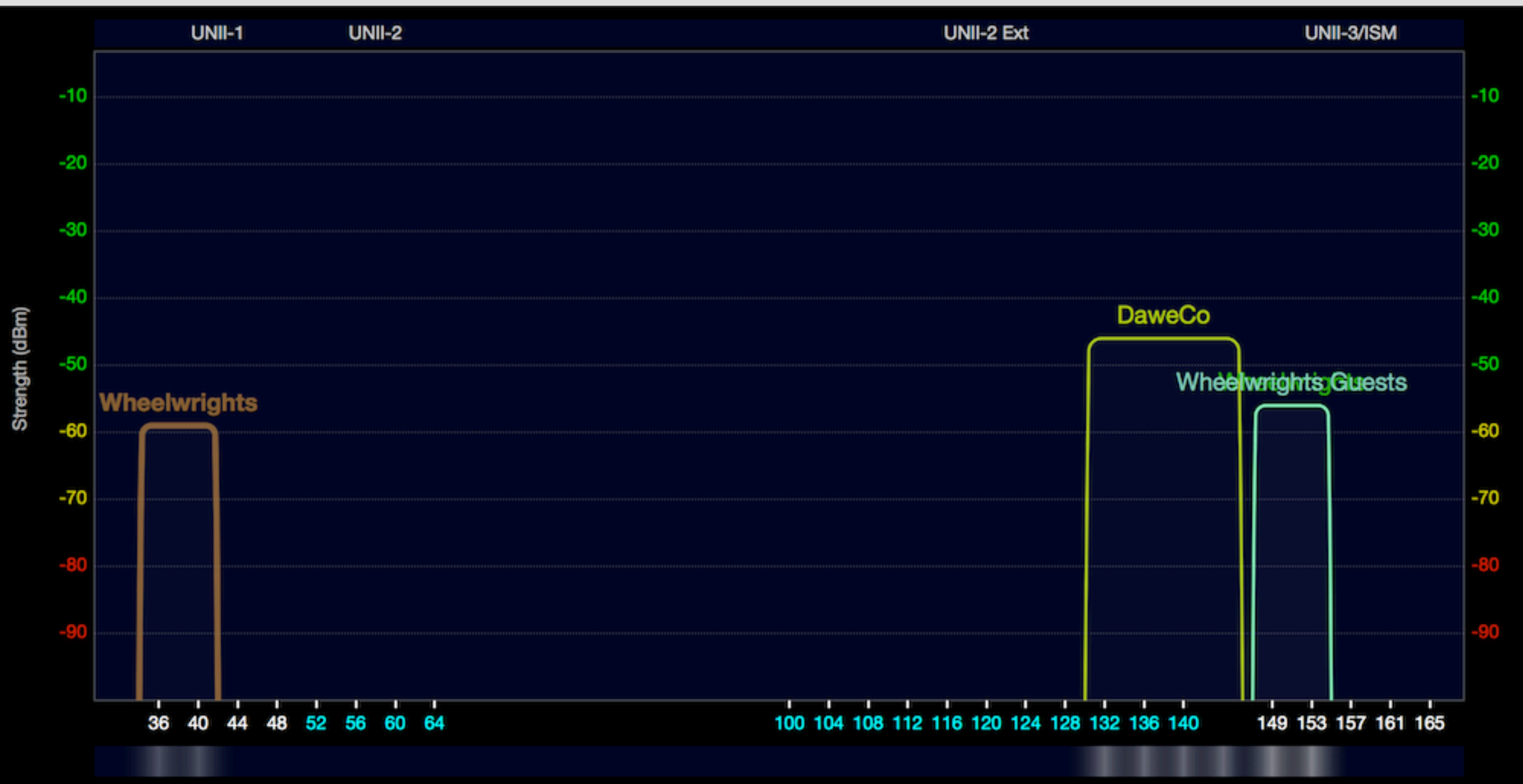
802.11ac: The New Kid

- The trigger for 5GHz everywhere
- Led by Apple and other consumer specialists
 - In-home device sync, video, backup, etc
 - “Gigabit Wi-Fi” on retail shelves
- 5GHz only: it’s best feature
- Apple devices equipped with 802.11ac
 - “Haswell” MacBooks Pro and Air + iMacs
 - Airport Extreme 802.11ac

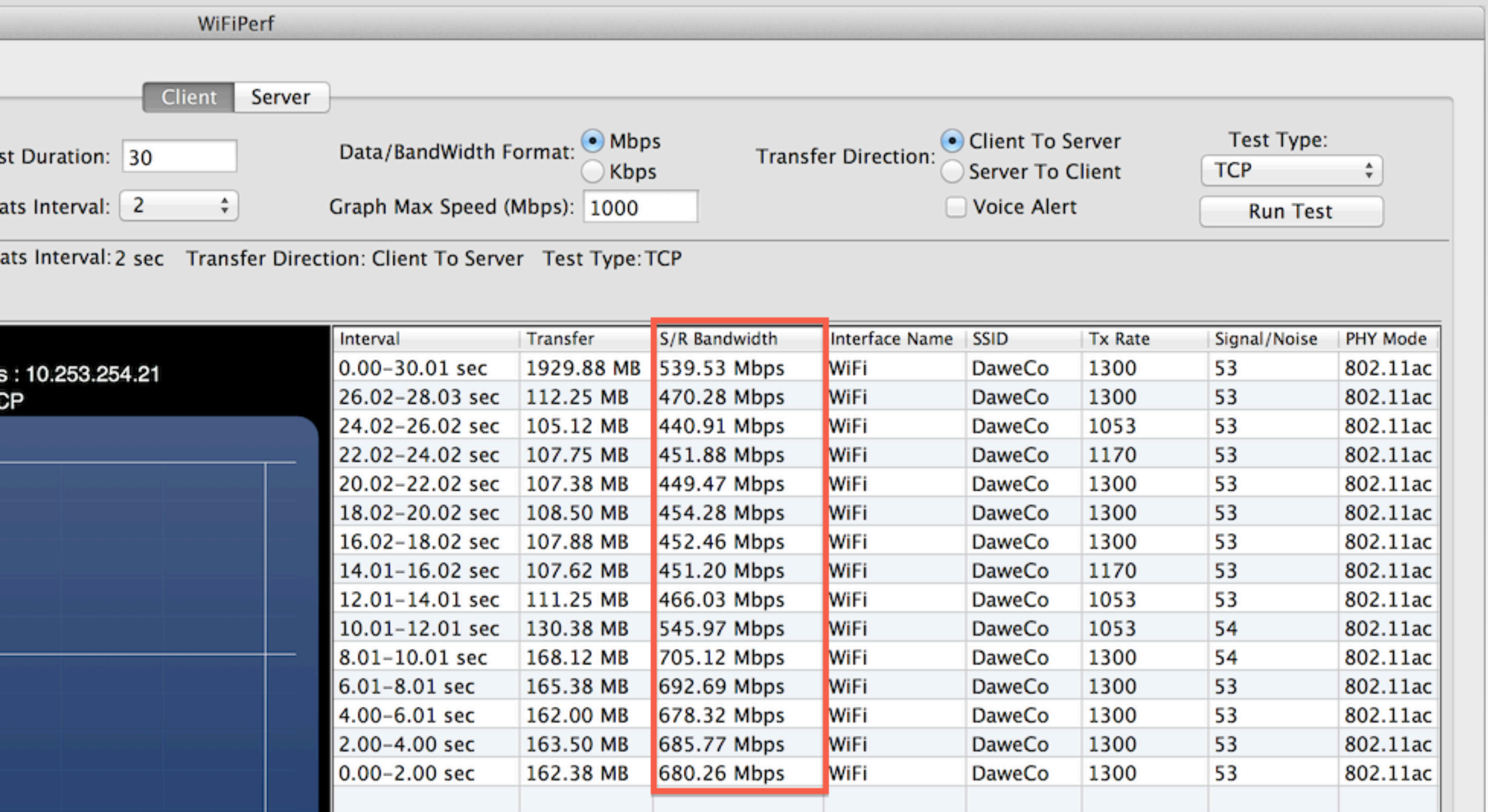
802.11ac Performance

- Wave 1 (now)
 - Wider channels (80-160 MHz versus 20-40 MHz for 802.11n)
 - Modulation: up to 256 QAM
- Wave 2 (2014+)
 - MOAR! spatial streams (up to 8)
 - Multi-user MIMO (Phase 2)
 - Multiple stations transmit/receive simultaneously
 - Streams separated spatially not by frequency

Add an 802.11ac AP



802.11ac Performance



WLAN Design

Define Network Requirements (What are we designing for?)

- Coverage area
- Applications (what kind of data and how much?)
- Type of devices and performance
 - All 1x1? 3x3:3?
- Number of expected devices
- Number of simultaneous devices

Coverage vs. Capacity

	Coverage	Capacity
AP count	Low	High
Limiting factor	Distance	Interference
Obstacles	Bad	Good
Client speed	N/A	High as possible
Design metric	SNR	SINR
Number of channels	Conservative	Every channel possible

How Much? How Far?

- How far can an AP effectively transmit?
- Answer: It depends.
- Factors:
 - Obstructions (walls, windows, etc.)
 - Construction material (dry wall vs. steel doors)
 - Interference (SNR)
 - How many devices?
 - Minimum application requirements

Determining AP Capacity

- Determined by number of clients and their airtime consumption

$$\text{Airtime} = \frac{\text{bandwidth required}}{\text{max. throughput}} * 100$$

$$\text{AP capacity} = \text{airtime} * \text{base capacity}$$

- 1 Mbps streaming video on tablet w/max throughput of 40 Mbps:

$$1 \text{ Mbps} / 40 \text{ Mbps} * 100 = 2.5\%$$

2.5% airtime = maximum 40 devices per radio

70% base capacity = 28 devices per radio

- Always plan to leave some capacity for future growth.

Adding Up the Costs

- Take the actual client throughput ...
 - TCP: 40%-60% of data rate (PHY)
 - UDP: 60% of data rate (PHY)
- And subtract ...
 - Loss from contention/congestion
 - Dependent on number of simultaneous clients
 - Loss from RF interference
 - Dependent on number of networks on same channel as well as errors from adjacent channels
 - Non-802.11 noise

	Throughput Loss	Achievable Rate
TCP protocol	~50% (overhead)	75 Mbps
In a clean environment	Very little	~70-75 Mbps
In a busy network (congestion only, no CCI)	Significant (~25%)	~50 Mbps
Some outside interference (CCI/adjacent/non-802.11)	Significant (~25%)	~37 Mbps
With heavy interference	Huge	??

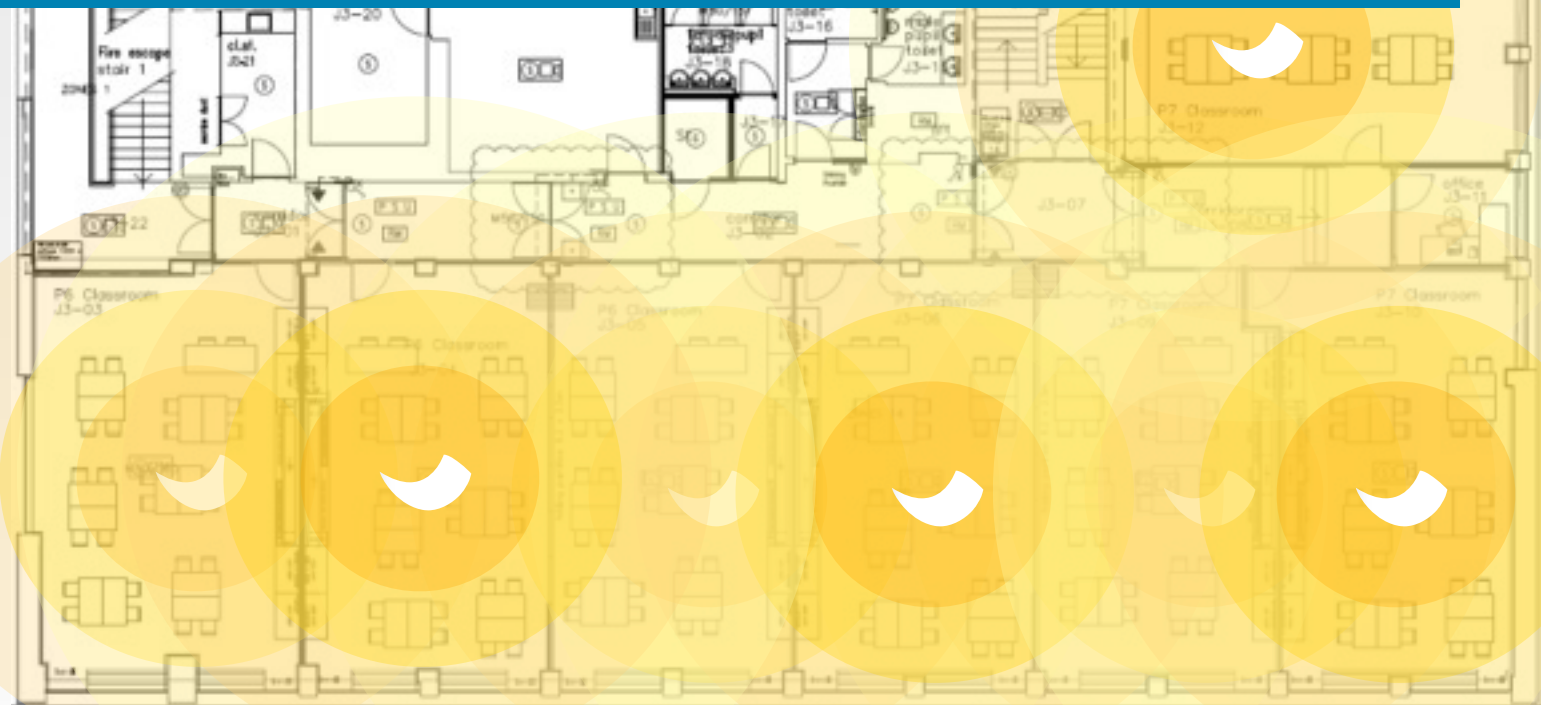
High Density Math Example

- 7 classrooms with 30 students using 1x1:1 5 GHz tablets
 - Need low latency and about 1 Mbps each for streaming video
 - Simultaneous usage

Number of devices = 210

$210 / 7 \text{ radios (5 GHz)} = 30 \text{ clients/radio}$ – no channel overlap

$210 / 14 \text{ radios (dual)} = 15 \text{ clients/radio}$ – 4 channel overlap (2.4 GHz)



High Density Strategies

- Shoot for 5GHz
- Increase AP count to the extent possible
- Use attenuation (obstacles) to your advantage
- Frequency re-use via structural separation
- Configuration optimizations & adaptive algorithms

Reducing Transmit Power

- Sometimes recommended in high density deployments or in deployments with lower powered devices.
- Sometimes recommended when you have different power output ratings on devices than APs.

Reducing Transmit Power

- Does not help signal to interference at all
- Guaranteed to reduce signal to external interference; this can counterproductive
- Lower power = lower transmit speed = clients take longer to get on/off the air
- Reduces capacity

More Strategies

- Review the vendor mounting documentation; shapes are important
- Disable background scanning (non-Apple clients)
- Limit # of SSIDs if possible (more SSIDs generate more network overhead)

Real World Scenario

- Rolling out iPads
- Prepping using Configurator
- Enrolling in Cloud MDM
- It all goes “boom”

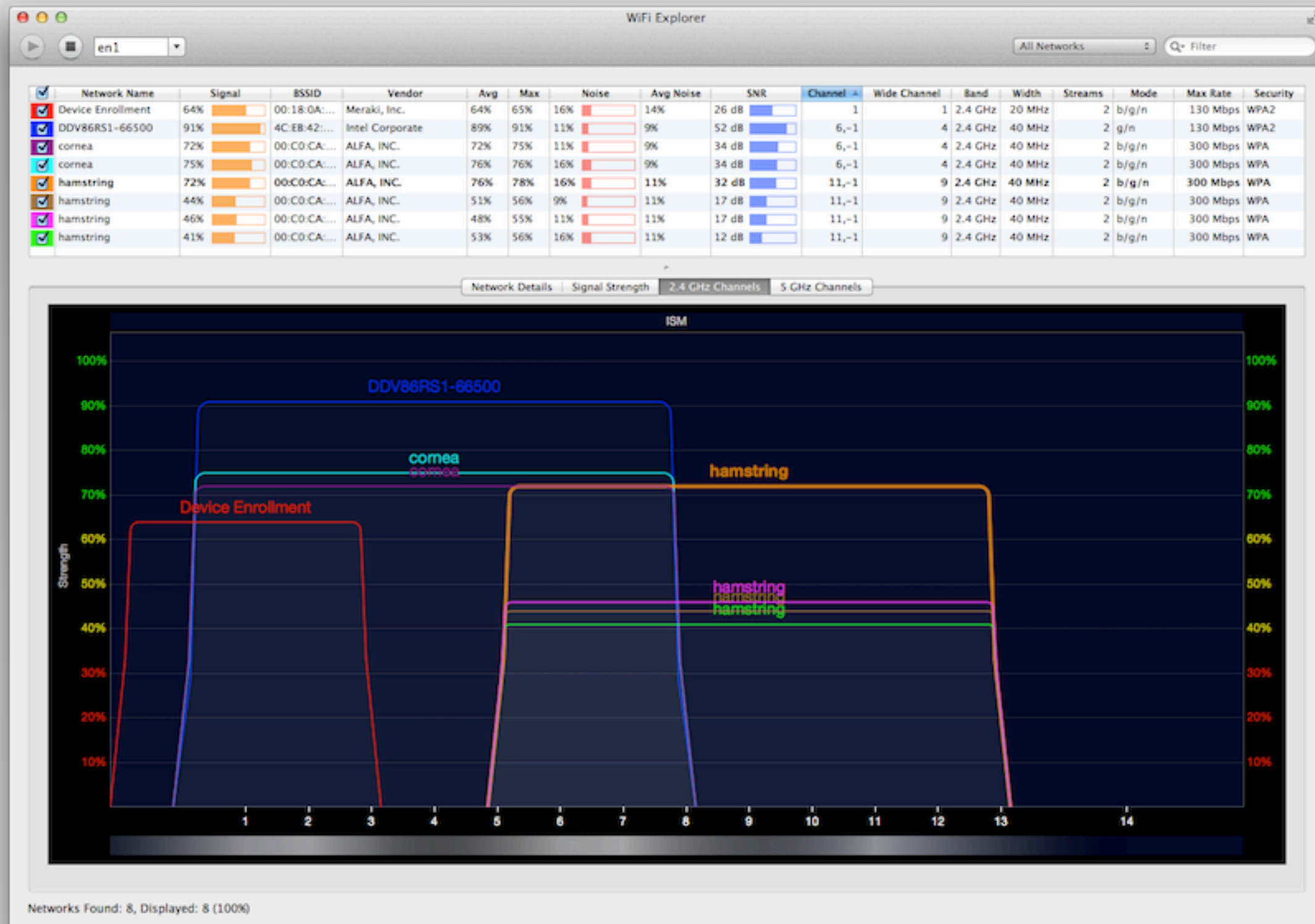
Real World Scenario

```
dawe — bash — 81x54 — 1
pLast login: Wed Jan 22 15:03:03 on console
dbp:~ dawe$ ping [REDACTED]
PING [REDACTED] (192.168.2.3): 56 data bytes
Request timeout for icmp_seq 0
64 bytes from 192.168.2.3: icmp_seq=1 ttl=128 time=57.541 ms
64 bytes from 192.168.2.3: icmp_seq=2 ttl=128 time=536.253 ms
64 bytes from 192.168.2.3: icmp_seq=3 ttl=128 time=111.824 ms
64 bytes from 192.168.2.3: icmp_seq=4 ttl=128 time=166.844 ms
64 bytes from 192.168.2.3: icmp_seq=5 ttl=128 time=52.888 ms
64 bytes from 192.168.2.3: icmp_seq=6 ttl=128 time=225.154 ms
Request timeout for icmp_seq 7
64 bytes from 192.168.2.3: icmp_seq=8 ttl=128 time=114.438 ms
64 bytes from 192.168.2.3: icmp_seq=9 ttl=128 time=3.157 ms
64 bytes from 192.168.2.3: icmp_seq=10 ttl=128 time=27.193 ms
64 bytes from 192.168.2.3: icmp_seq=11 ttl=128 time=943.632 ms
Request timeout for icmp_seq 12
Request timeout for icmp_seq 13
64 bytes from 192.168.2.3: icmp_seq=14 ttl=128 time=307.636 ms
64 bytes from 192.168.2.3: icmp_seq=15 ttl=128 time=72.118 ms
64 bytes from 192.168.2.3: icmp_seq=16 ttl=128 time=3.359 ms
64 bytes from 192.168.2.3: icmp_seq=17 ttl=128 time=102.462 ms
64 bytes from 192.168.2.3: icmp_seq=18 ttl=128 time=67.362 ms
64 bytes from 192.168.2.3: icmp_seq=19 ttl=128 time=285.024 ms
Request timeout for icmp_seq 20
Request timeout for icmp_seq 21
```


Real World Scenario

```
Request timeout for icmp_seq 23
64 bytes from 192.168.2.3: icmp_seq=23 ttl=128 time=1110.076 ms
64 bytes from 192.168.2.3: icmp_seq=24 ttl=128 time=206.660 ms
64 bytes from 192.168.2.3: icmp_seq=25 ttl=128 time=1311.519 ms
64 bytes from 192.168.2.3: icmp_seq=26 ttl=128 time=517.517 ms
64 bytes from 192.168.2.3: icmp_seq=27 ttl=128 time=210.539 ms
64 bytes from 192.168.2.3: icmp_seq=28 ttl=128 time=68.770 ms
64 bytes from 192.168.2.3: icmp_seq=30 ttl=128 time=18.328 ms
64 bytes from 192.168.2.3: icmp_seq=31 ttl=128 time=74.831 ms
64 bytes from 192.168.2.3: icmp_seq=32 ttl=128 time=187.202 ms
64 bytes from 192.168.2.3: icmp_seq=33 ttl=128 time=3.940 ms
64 bytes from 192.168.2.3: icmp_seq=34 ttl=128 time=4.120 ms
64 bytes from 192.168.2.3: icmp_seq=35 ttl=128 time=10.200 ms
Request timeout for icmp_seq 36
64 bytes from 192.168.2.3: icmp_seq=37 ttl=128 time=271.073 ms
^C
--- ping statistics ---
38 packets transmitted, 29 packets received, 23.7% packet loss
round-trip min/avg/max/stddev = 3.157/243.850/1311.519/331.519 ms
dbp:~ dawe$
```


Whiskey Tango Foxtrot?



Troubleshooting and Performance Testing

Identify the Problem

“It doesn’t work” is not useful!

- Can the client connect?
- Can it authenticate?
- Low performance?
- Roaming?
- Are certain types of clients affected or all?

Client Can't Connect

- RF interference
- Client is not configured correctly
- Client does not support network configuration
 - OFDM-only will block 802.11b clients entirely
- Are there APs nearby that it can hear strongly?

Classic Symptoms of RF Interference

- Classic symptoms:
 - Clients drop off network randomly or have difficulty connecting
 - High latency or data loss
 - Huge number of PHY errors (>2500 per second)
- Can be difficult to detect without an RF analyzer, because WiFi only knows how to interpret WiFi

RF Interference Mitigation

- Things you can do:
 - Eliminate source of interference
 - Change channel assignments (if clear ones exist)
 - Lower transmit power
 - Move clients to 5 GHz – band steering or change WLAN adapter

Client Can't Authenticate

- Misconfigured authentication
- User name/password incorrect
- Client blacklisted
 - WIPS/WIDS
- Trying to connect to the wrong SSID

Low Performance

- No strong signal available (no nearby AP)
- High interference
- Low connection rate (MCS)
- Client stickiness
 - Roaming
- Too many clients per AP radio
- High latency
- Plain slow client

Performance Fixes

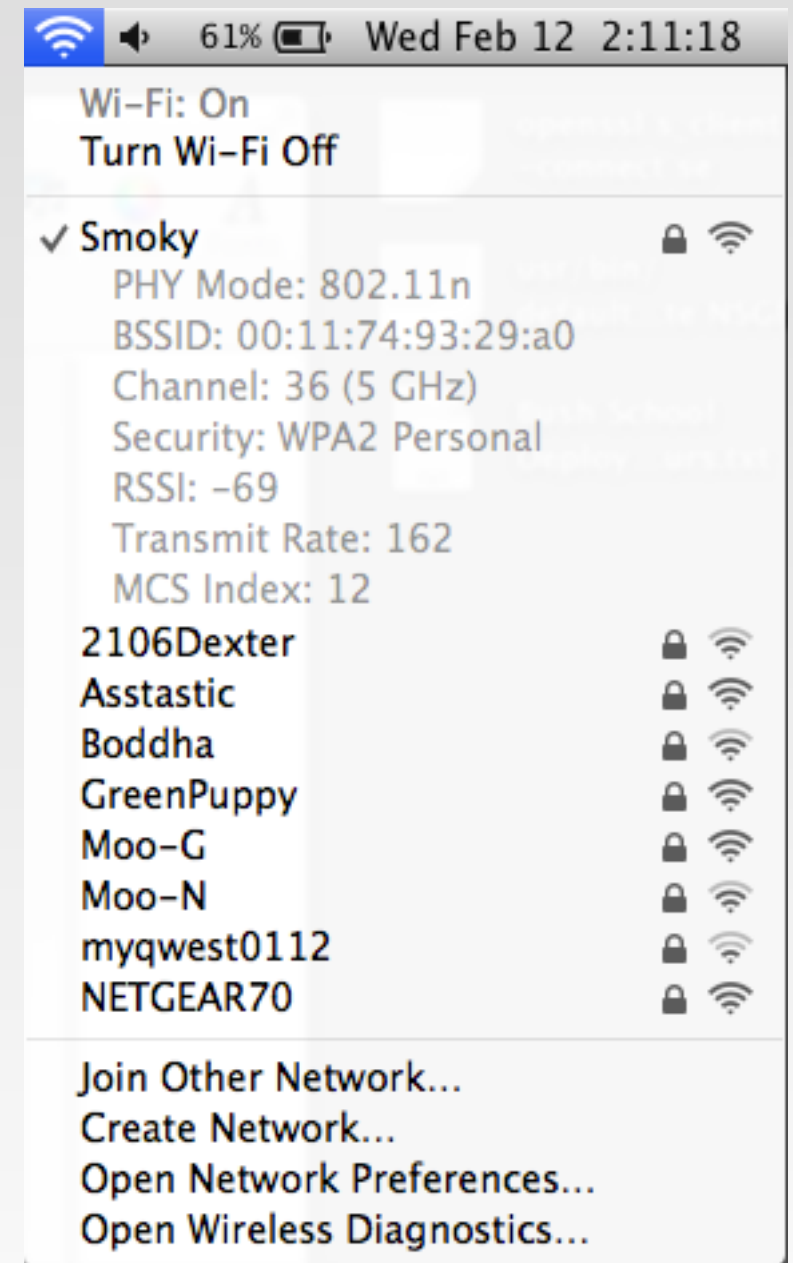
- Add more APs if coverage is too sparse, i.e. clients can get too far away = lower connection rate
- Reduce interference
- More channels
- Increase capacity in areas with excessive number of clients per AP
- Airtime fairness – allows differently capable clients to share medium in a managed fashion

Essential Troubleshooting Tools

- Apple Tools
- Performance test tools
 - iPerf (WiFiPerf)
 - MetaGeek inSSIDer/WiFi Explorer
 - Vendor tools like:
 - Ruckus SWAT, SpeedFlex, Zapper
- RF analyzer (MetaGeek Wi-Spy, AirMagnet, etc.)

Apple-specific Tools

- Check Wi-Fi connection on Mac
 - Hold down Option key and click airport icon in menu bar
- Hidden CLI Tool
 - airport
 - <http://osxdaily.com/2007/01/18/airport-the-little-known-command-line-wireless-utility/>



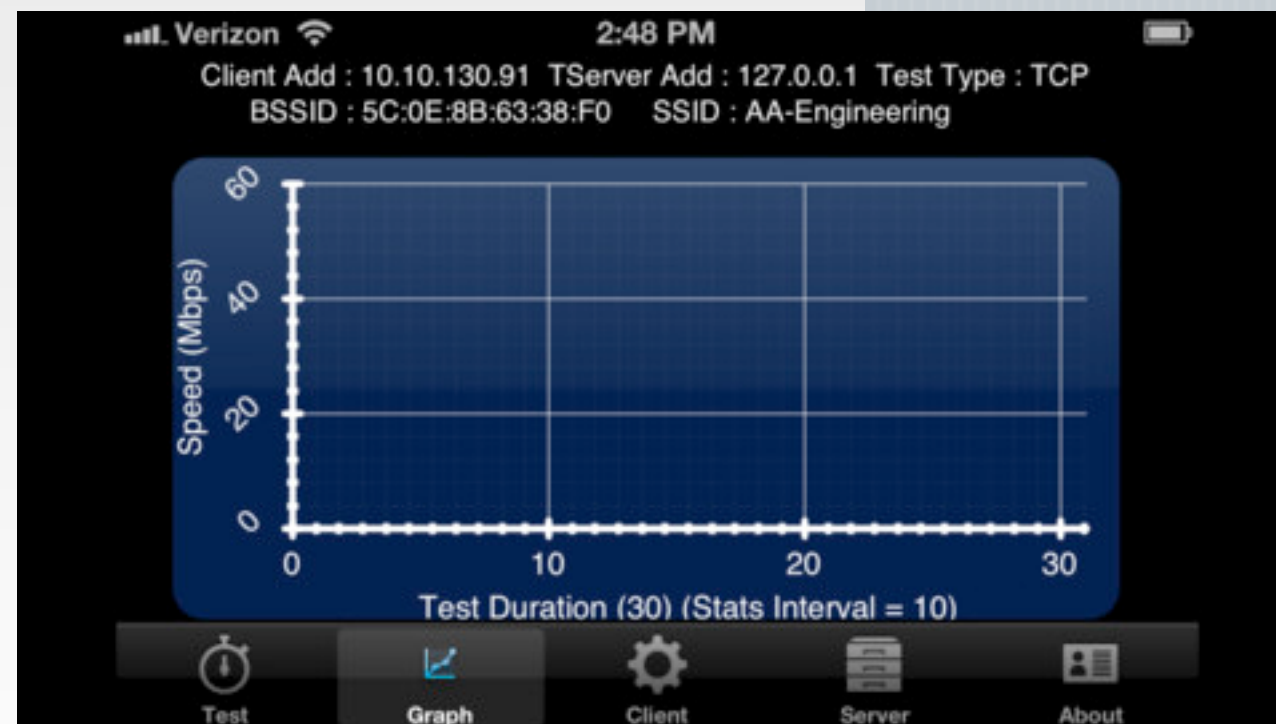
Apple-specific Tools

- wdutil

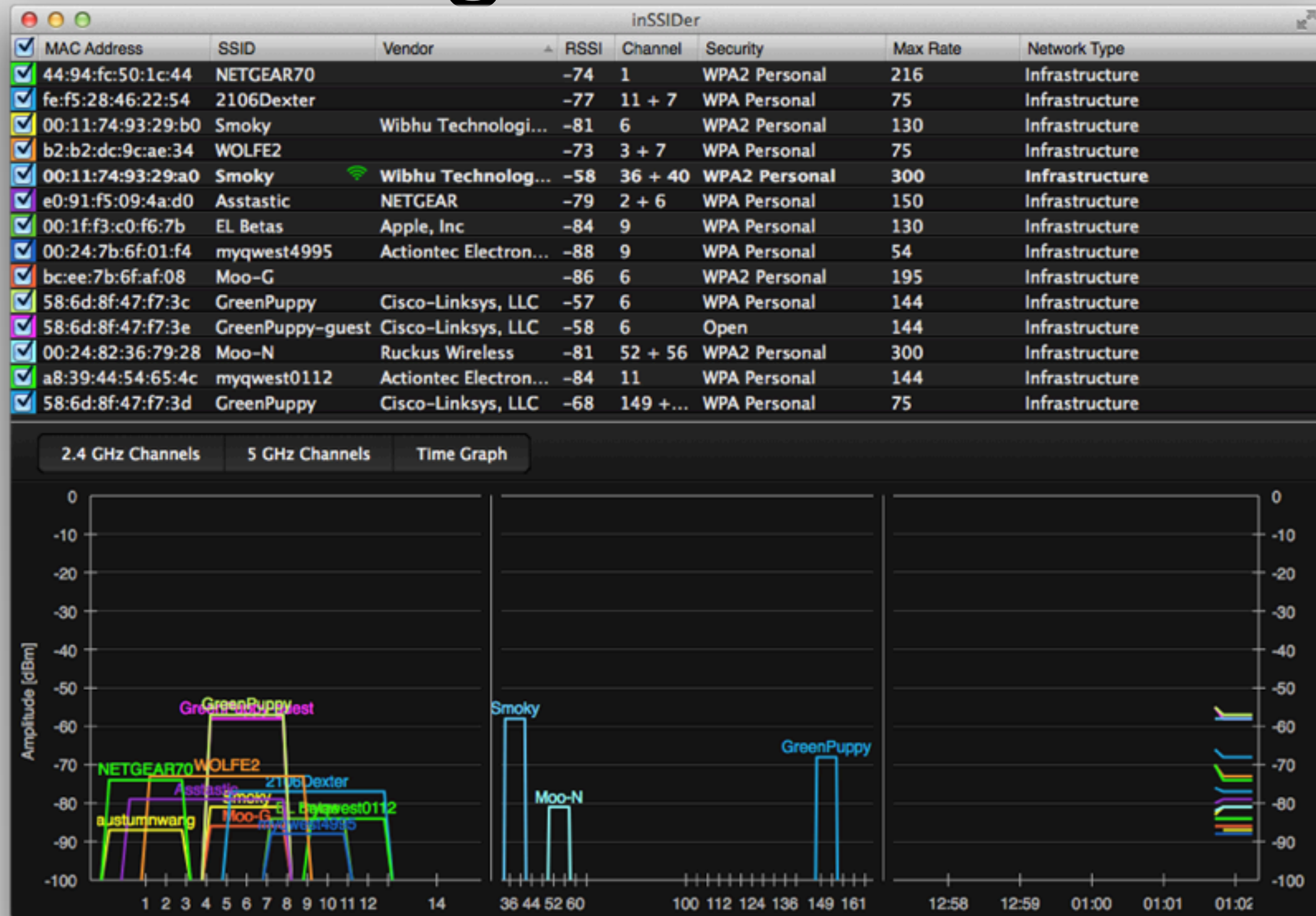
```
DBP:~ dawe$ wdutil info
# --- Wi-Fi Interface
      Interface Name      : en1
      MAC Address         : c8:bc:c8:e4:be:25
      Network Name        : Wheelwrights
      Active PHY Mode     : 802.11n
      Security            : WPA2 Personal
      SSID                 : Wheelwrights
      BSSID                : 08:ea:44:1a:df:a9
      Country             : US
      RSSI                 : -54 dBm
      Noise                : -87 dBm
      Rate                 : 150 Mbps
      Channel              : 36
      Channel Width       : 40MHz
```

ZapPerf and WiFiPerf (Access Agility)

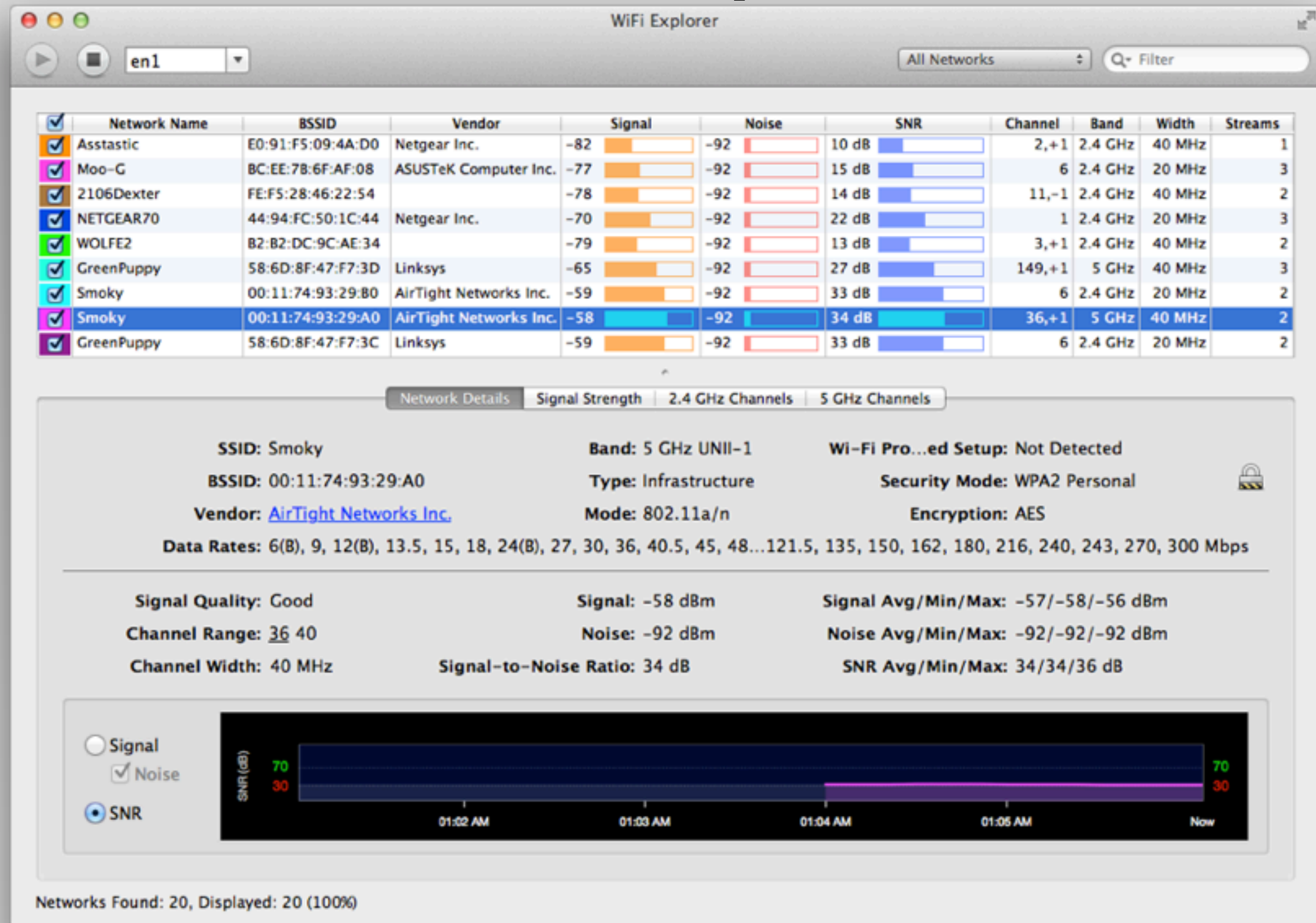
- Based on zap/iperf3
- Available for iOS and Mac OS



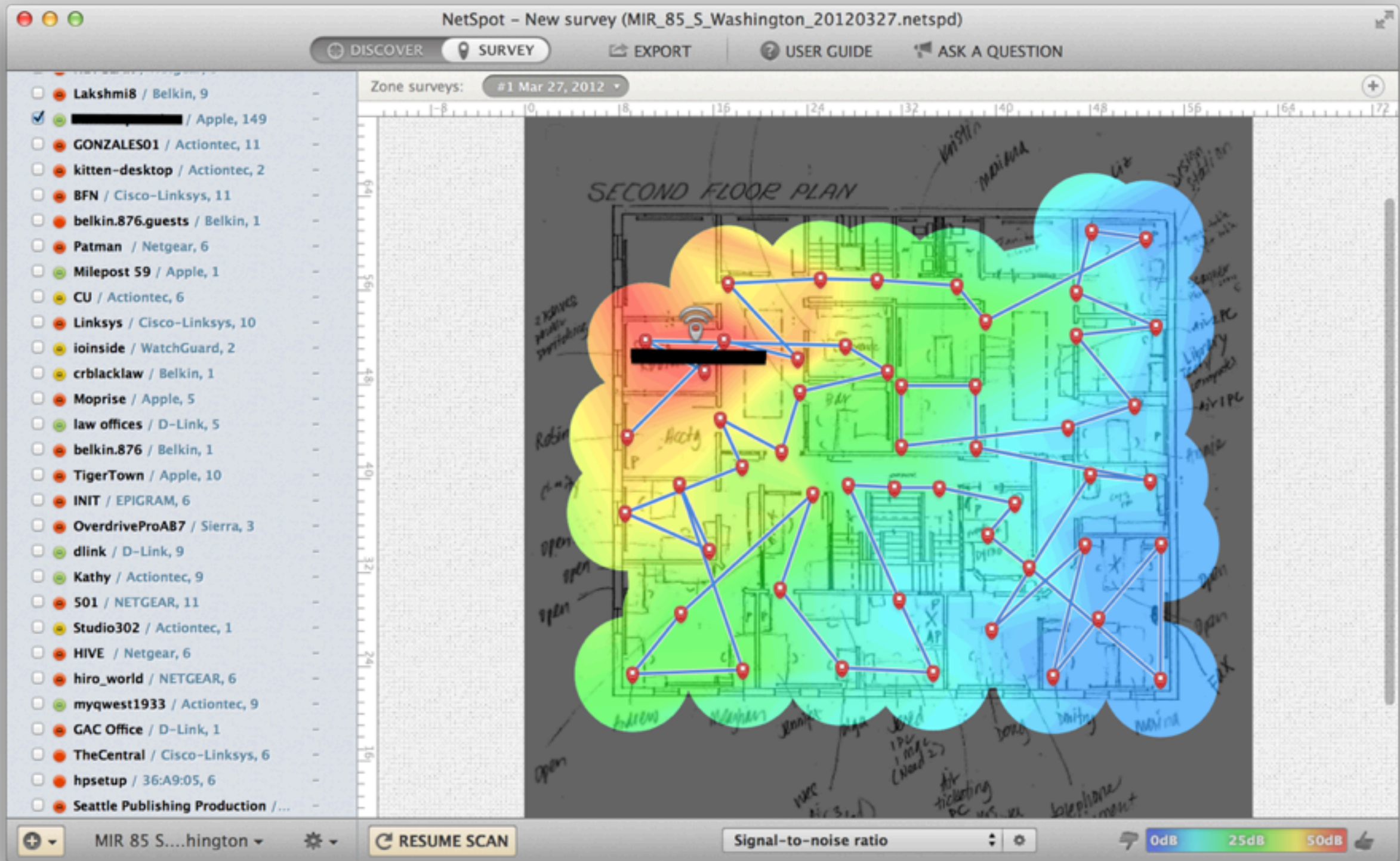
Metageek InSSIDer



Wi-Fi Explorer



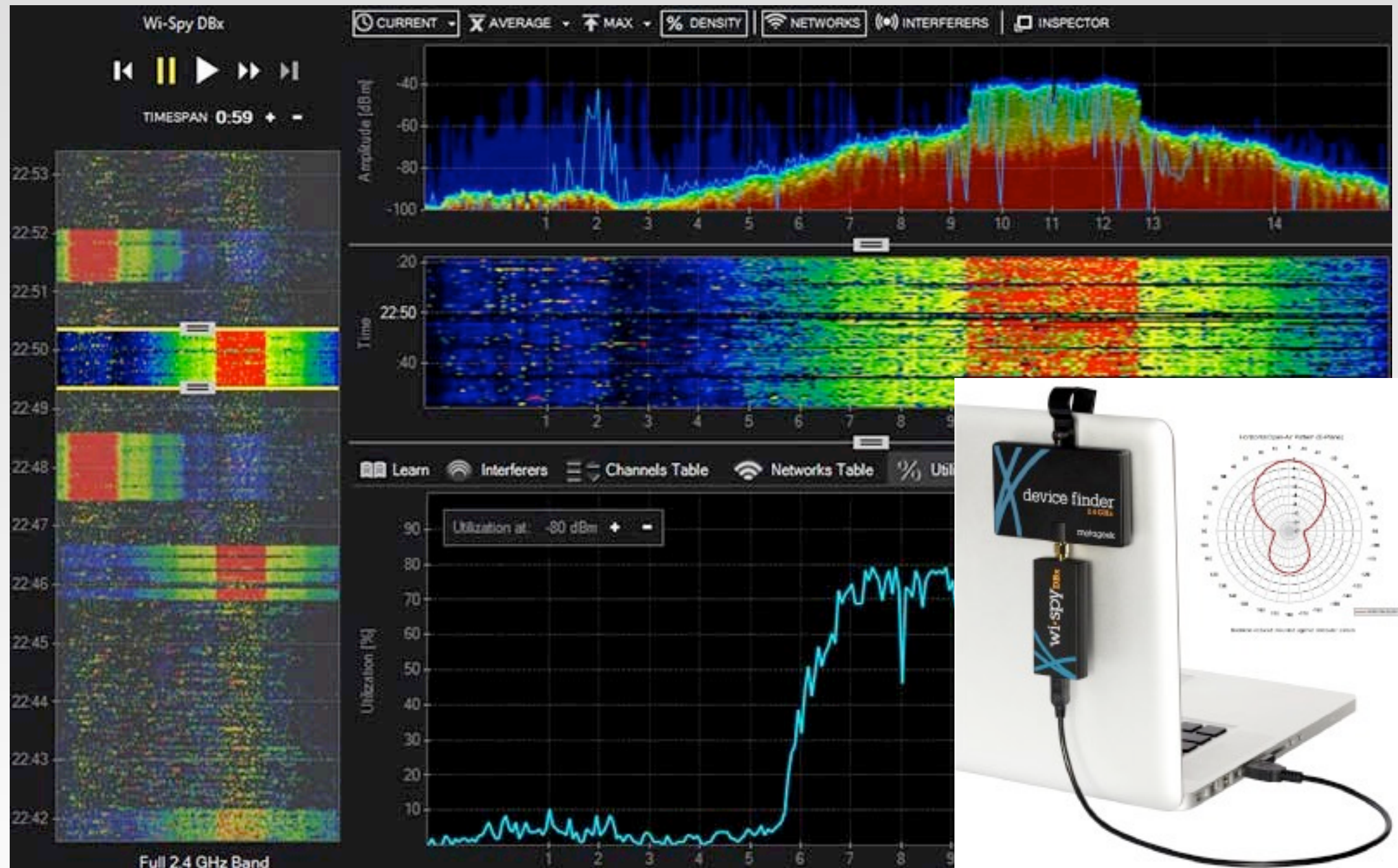
Netspot



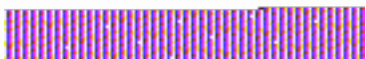
Vendor Apps (Ruckus)

- Apple iOS
 - SWAT
 - Zapper/SpeedFlex
 - ZD Remote
 - Product Guide
- Android
 - SWAT
- More coming soon!
- Mac OS/Windows
 - SpeedFlex

RF Analyzers



And last...



Questions?



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