AIRHEADS meetup

aruba
a Hewlett Packard Enterprise company

Istanbul
29/07/2018

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High Density 802.11ac Network Design

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Basic Design & Deployment

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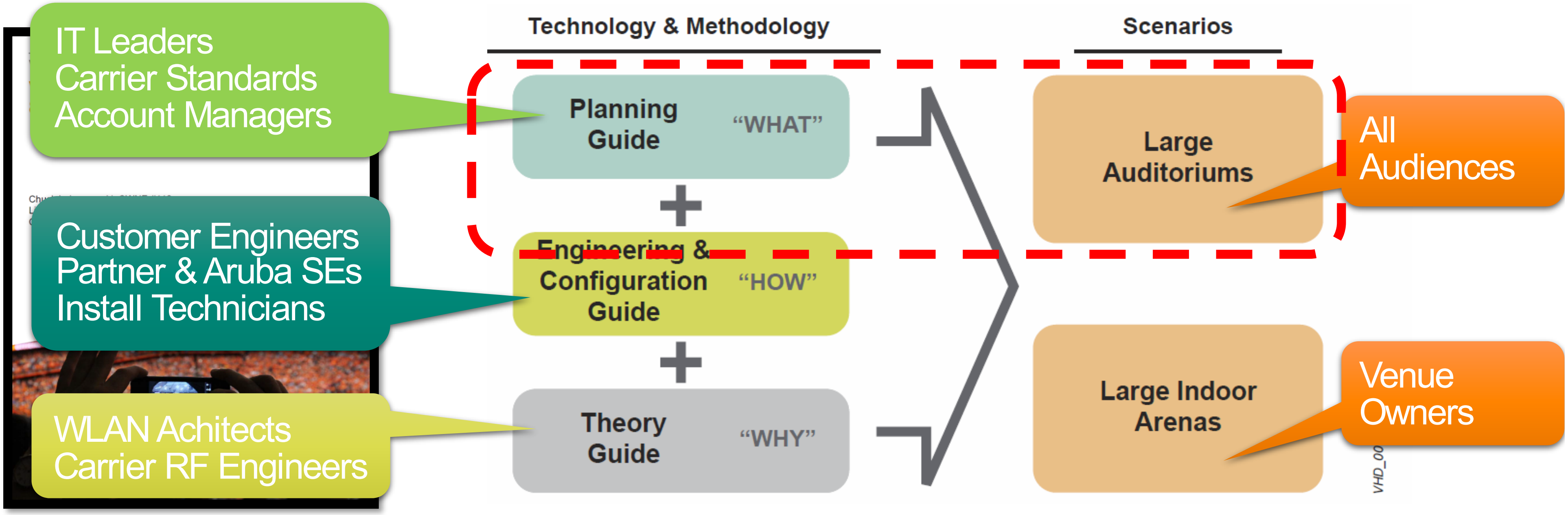
Agenda

- Welcome & introduction
- Dimensioning very high density networks
- 80-MHz vs. 40-MHz vs. 20-MHz channels
- Use of DFS channels
- Basic RF design for very high density areas
- Example: Adjacent large auditoriums
- Q & A

Based on Aruba's Very High Density VRD



http://community.arubanetworks.com/t5/Validated-Reference-Design/Very-High-Density-802-11ac-Networks-Validated-Reference-Design/ta-p/230891

How Far We’ve Come

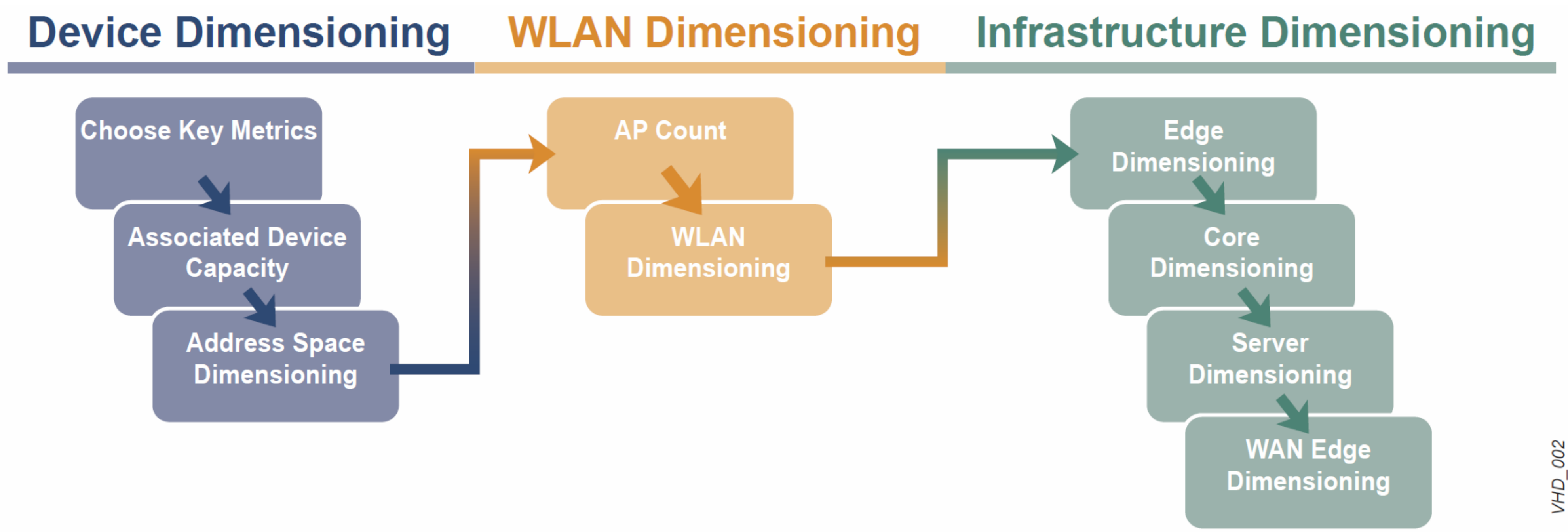
- “Coverage” WLANs came first
- These evolved into “Capacity” WLANs (with limited HD zones)
  - $250m^2$ / $2500\ ft^2$ = 25 devices per cell
- BYOD made every capacity WLAN a high-density network
  - 3 devices/person = 75 per cell
- HD WLANs from 2015 are now very high-density (VHD)
  - 100+ devices per “cell”. Devices may be associated to multiple BSS operators in same RF domain.

Waiting for the new Pope in St. Peter’s Square

NBC Today Show, February, 2013, [redacted]

Dimensioning VHD Systems

Aruba VHD Dimensioning Methodology



Step 1- Key Design Criteria for Typical VHD WLAN

Metric	Definition	Typical Value
Seating capacity	Number of people the facility can hold.	Varies
Average devices per person	Typical number of discrete Wi-Fi enabled devices carried by a person visiting the VHD facility.	1 to 5
Take rate	Percentage of seating capacity with an active Wi-Fi device.	50% - 100%
Associated device capacity (ADC)	Take rate multiplied by the average number of Wi-Fi enabled devices per person.	Varies
Seats or area covered per AP	How many square meters (square feet) or seats each AP must serve – essentially the physical size of a radio cell.	Varies
Associated devices per radio	The design target of how many associated devices should be served by each radio on an AP.	150
Average single-user goodput	What is the minimum allowable per-user bandwidth when multiple users are attempting to use the same AP?	512 Kbps to 2 Mbps
5 GHz vs. 2.4 GHz split	Distribution of clients across the two bands.	5 GHz: 75% 2.4 GHz: 25%

Step 2 – Estimate ADC

- Start with the seating / standing capacity of the VHD area to be covered
- Then estimate the take rate (50% is a common minimum)
- Choose the number of devices expected per person. This varies by venue type. It might be lower in a stadium and higher in a university lecture hall or convention center salon.
  - For example, 50% of a 70,000 seat stadium would be 35,000 devices assuming each user has a single device
  - 100% of a 1,000 seat lecture hall where every student has an average of 2.5 devices would have an ADC equal to 2,500
- More users should be on 5-GHz than 2.4-GHz. ADC should be computed by frequency band. In general you should target a ratio of 75% / 25%.
- Association demand is assumed to be evenly distributed throughout the coverage space.

Step 3 – Address Dimensioning

Table P2-2 Sample ADC and Address Space Estimates for Indoor 20,000 Seat Arena

User Group	Devices (Now)	Devices (Future)	%5 GHz	%2.4 GHz	Minimum Subnet Size
Guest / Fan	5,000 *(25% take rate)*	10,000 *(50% take rate)*	75%	25%	/18
Staff	100	300	100%	0%	/23
Ticketing	50	100	100%	0%	/24
POS	50	200	100%	0%	/24
Team	15	100	100%	0%	/24
TOTAL	**5,215**	**10,700**	**8,200**	**2,500**	**-**

Step 4 – Estimate AP Count

$$\text{AP Count} = \text{5-GHz Radio Count} = \frac{\text{Associated Device Capacity (5 GHz)}}{\text{Max Associations Per Radio}}$$

- Plan for 150 associations per radio, and 300 per AP
- ArubaOS supports up to 255 per radio
  - 150 = 60% loading with 40% headroom
- All VHD areas experience inrush/outrush
  - Planning for extra headroom allows for user “breathing”
- Remember to increase max users in SSID profile

Step 5 – Dimension Controllers That Terminate APs

- Up to 32K users, platform size must be >= ADC
- Redundant PSU are critical (do not use 7205 or 70XX series)
- Active/active redundancy

Model	7210	7220	7240
			
Maximum number of LAN-connected access points	512	1,024	2,048
Maximum number of users	16,384	24,576	32,768
Active firewall sessions	2,015,291		
Firewall throughput	20 Gbps	40 Gbps	40 Gbps
AES encrypted firewall throughput	6 Gbps	20 Gbps	40 Gbps
MAC Addresses per VLAN	64000	128000	128000
FW Session Creation Rate (1000 sessions/sec)	249	326	481
802.1x Auth Rate (transaction/sec), EAP ON	169	219	297
802.1x Auth Rate (transaction/sec), EAP OFF	115	185	220
Captive Portals (transactions/sec), 2K bit	81	114	132
1000Base-T ports	2		
10 Gigabit Ethernet ports (SFP+)	4		
Redundant PSU	Yes		

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Step 5 – Sizing for ADCs Over 32K

- VHD areas with ADC >= 32K must be split across two or more separate local controller HA pairs

Table P2-5 Example Controller Requirements for Stadiums of Different Size

Facility Example	Associated Device Count	Controller Solution
Basketball, Hockey	16K – 32K	two pairs of Aruba 7210
Baseball, Soccer	32K – 48K	two pairs of Aruba 7220
NFL Football, Soccer	48K – 64K	two pairs of Aruba 7240
College Football, Soccer	65K – 96K	three pairs of Aruba 7240
NASCAR	96K – 250K	one pair of Aruba 7240 for every 32K devices

Step 5 – Sizing Master Controllers

- Terminating APs on master in master/local cluster is OK up to 16K users (arbitrary threshold – use your judgment)
- Use dedicated masters for ADC > 48K users
- 7210 recommended for dedicated masters, otherwise size based on ADC if terminating APs

Step 6 – Edge Dimensioning

- Full non-blocking 1GE ports downstream to APs
- Full 802.3at PoE with 30W on all ports
- Cat-6A cabling
- 2x10GE uplinks for redundant core connects
- Most IDFs in stadiums serve 10-20 APs
- Highest rate 1 radio can generate with 4SS VHT20 is 346.7 Mbps

Step 7 – Core Dimensioning

- Verify that ARP cache and forwarding tables in core switches are large enough to handle big flat user VLAN
- Controller-to-core uplinks are sized at 2X the WAN throughput computed in the capacity plan
  - 1-2 Gbps OTA = 2-4 Gbps on controller uplink
- Do not make controller default gateway
- First hop redundancy is critical

Step 8 – Server Dimensioning

- DHCP/DNS – key metric is transaction time.
  - Should be <= 5ms.
  - This is MUCH more critical than transaction rate.
    - Model at 5% of seating capacity over 5 minutes
    - 18K arena * 5% / 300 seconds = 3 discovers per second
  - Carrier-grade DHCP/DNS servers strongly recommended (Infoblox)
  - Lease times should be 2X duration of event (8 hours suggested)
  - Model DNS at 1 request/device/second
- Captive portal rate = DHCP arrival rate
- RADIUS loads depend on whether guests using 802.1X

Step 9 – WAN Edge Dimensioning

- WAN uplink bandwidth is estimated using the Aruba Total System Throughput process
- Minimum BW is dual, load-balanced 1Gbps links for a country with 20+ channels in 5-GHz using all/most DFS channels
  - **Any VHD area with 20+ APs should easily be able to generate 1Gbps of load**
- WAN uplinks >2Gbps may be required if RF spatial reuse is being attempted
- All edge equipment must be fully HA

80-MHz vs. 40-MHz vs. 20-MHz Channel Widths

Worldwide Channel Availability at 3/1/2015

Channel	Frequency	United States & Canada	Brazil	Europe & Turkey	United Kingdom	Russia	Saudi Arabia	South Africa	Israel	China	Japan	Korea	Singapore	Taiwan	Australia	New Zealand
36	5180	Yes	Indoors	Indoors	Indoors	Yes	Indoors	Indoors	Indoors	Indoors	Indoors	Indoors	Yes	No	Indoors	Indoors
40	5200	Yes	Indoors	Indoors	Indoors	Yes	Indoors	Indoors	Indoors	Indoors	Indoors	Indoors	Yes	No	Indoors	Indoors
44	5220	Yes	Indoors	Indoors	Indoors	Yes	Indoors	Indoors	Indoors	Indoors	Indoors	Indoors	Yes	No	Indoors	Indoors
48	5240	Yes	Indoors	Indoors	Indoors	Yes	Indoors	Indoors	Indoors	Indoors	Indoors	Indoors	Yes	No	[illegible]	[illegible]
52	5260	DFS	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Yes	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	DFS/TPC	DFS/TPC	Yes	Indoors/ DFS/TPC	DFS/TPC
56	5280	DFS	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Yes	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	DFS/TPC	DFS/TPC	Yes	Indoors/ DFS/TPC	DFS/TPC
60	5300	DFS	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Yes	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	DFS/TPC	DFS/TPC	Yes	Indoors/ DFS/TPC	DFS/TPC
64	5320	DFS	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Yes	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	Indoors/ DFS/TPC	DFS/TPC	DFS/TPC	Yes	Indoors/ DFS/TPC	DFS/TPC
100	5500	DFS	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
104	5520	DFS	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	[illegible]	[illegible]
108	5540	DFS	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
112	5560	DFS	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
116	5580	DFS	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
120	5600	DFS[1]	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC
124	5620	DFS[1]	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC
128	5640	DFS[1]	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC	DFS/TPC	No	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC	No	DFS/TPC
132	5660	DFS	DFS/TPC	DFS/TPC	DFS/TPC	Yes	DFS/TPC	DFS/TPC	No	No	DFS/TPC	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
136	5680	DFS	DFS/TPC	DFS/TPC	DFS/TPC	Yes	DFS/TPC	DFS/TPC	No	No	DFS/TPC	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
140	5700	DFS	DFS/TPC	DFS/TPC	DFS/TPC	Yes	DFS/TPC	DFS/TPC	No	No	DFS/TPC	No	DFS/TPC	DFS/TPC	DFS/TPC	DFS/TPC
144	5720	Do not use for VHD areas until 802.11ac penetration > 50%														
149	5745	Yes	No	Licensed	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
153	5765	Yes	No	Licensed	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
157	5785	Yes	No	Licensed	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
161	5805	Yes	No	Licensed	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
165	5825	Yes	No	Licensed	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
TOTAL NON-DFS		9	9	4	4	16	8	4	4	9	4	8	9	9	9	9
TOTAL DFS		12[1] / 15	15	15	15	0	15	15	4	4	15	12	15	11	13	15
TOTAL		21[1] / 24	24	19	19	16	23	19	8	13	19	20	24	20	25	24

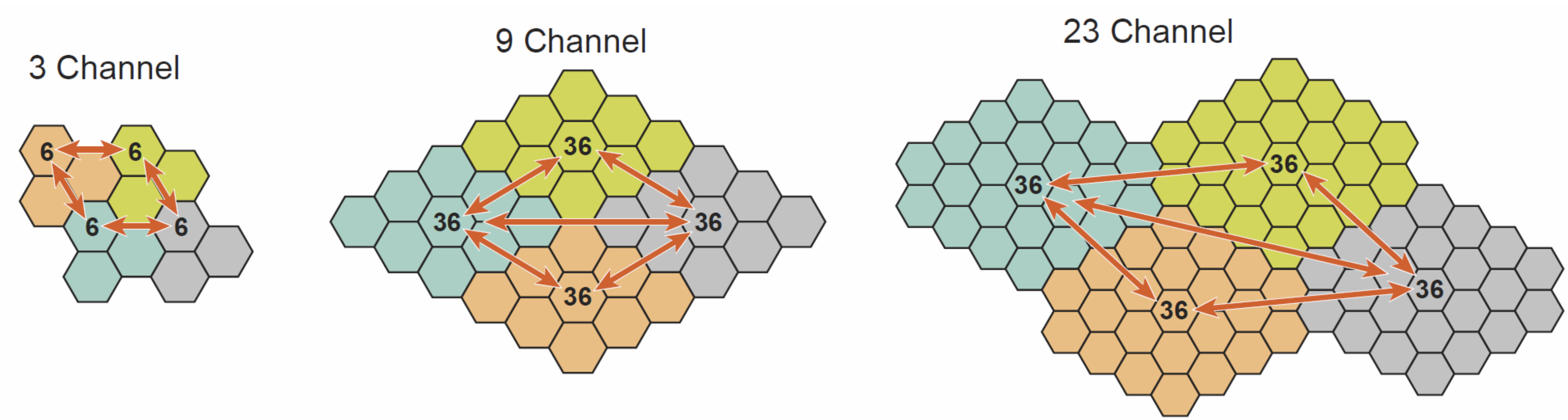
1. These channels were temporarily disallowed in 2013-2014 in the US. APs released from 2015 on may use these channels if they pass DFS certification.

8 indoor channels in EMEA

11 outdoor channels

Why 20-MHz Channels – Reuse Distance

- More channels = more distance between same-channel APs



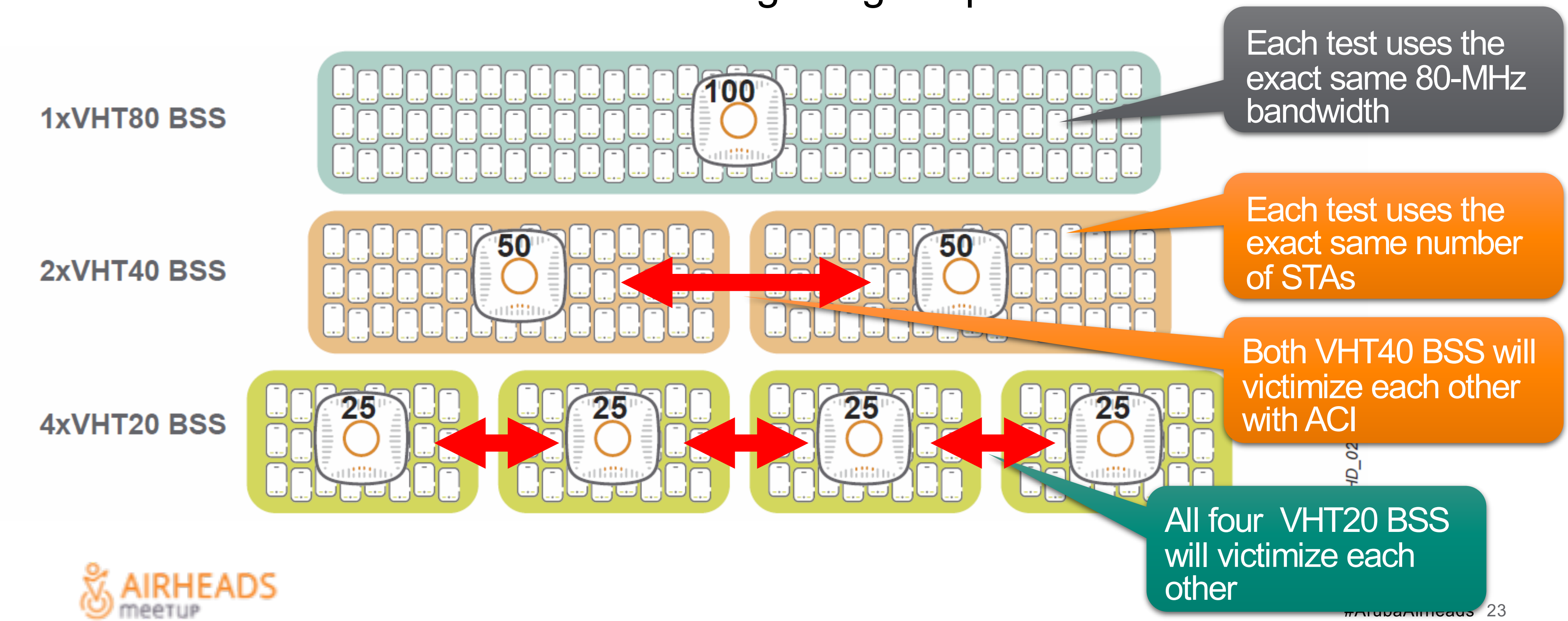
Why 20-MHz Channels – More RF Reasons

- Reduced Retries – Bonded channels are more exposed to interference on subchannels
  - Using 20-MHz channels allows some channels to get through even if others are temporarily blocked

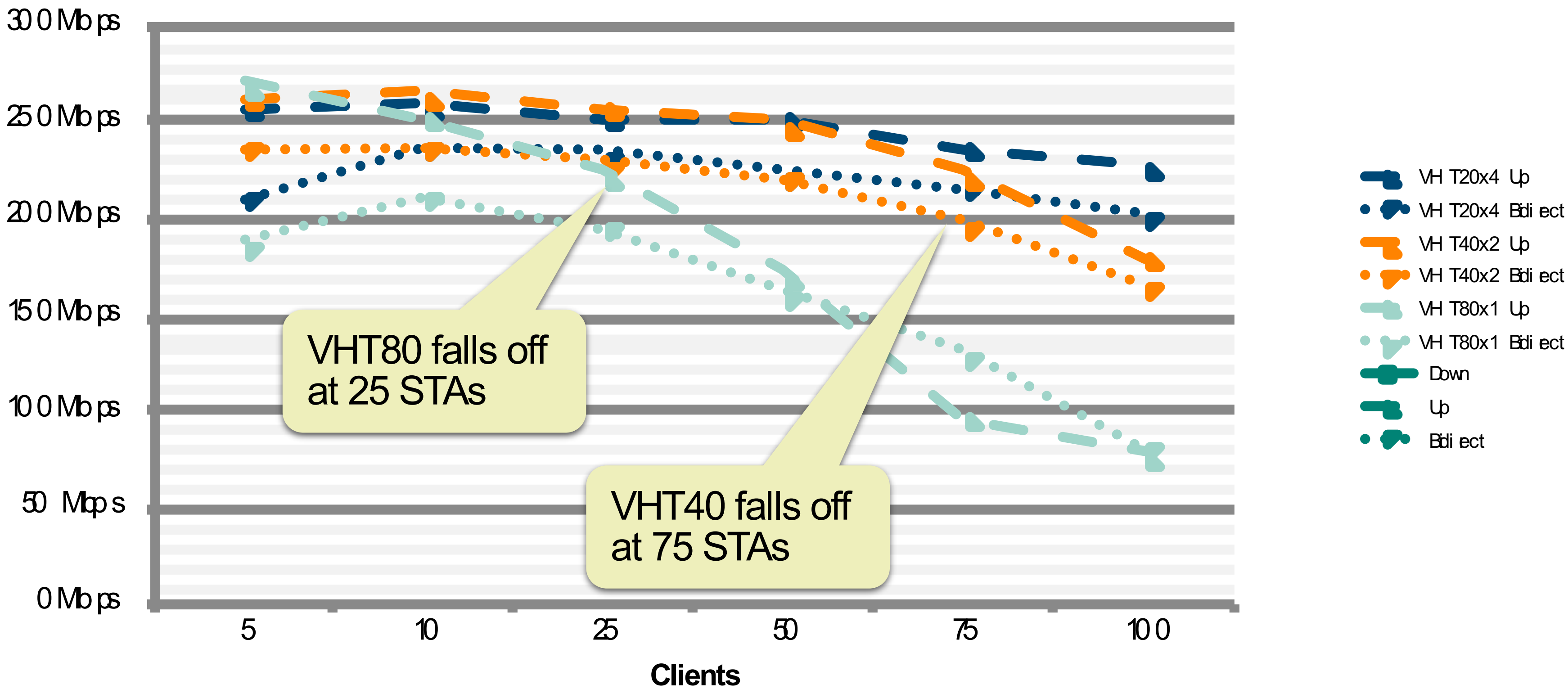
- Higher SINRs – Bonded channels have higher noise floors (3dB for 40-MHz, 6dB for 80-MHz)
  - 20-MHz channels experience more SINR for the same data rate, providing extra link margin in both directions

Why 20-MHz Channels - Performance

- Which Chariot test will deliver higher goodput?



VHT20 Beats VHT40 & VHT80 – 1SS Client Example



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Use of DFS Channels

General Rule

Use DFS channels for VHD areas!!

- The number of collision domains is the primary constraint on VHD capacity
- The number of STAs per collision domain is the second major constraint on capacity
- VHD networks are ultimately about tradeoffs

The benefit of employing DFS channels almost always* outweighs the cost.

Balancing the Risks & Rewards

- Client capabilities
  - As of 2018, the vast majority of mobile devices shipping now supports DFS channels
  - Non-DFS clients will be able to connect due to stacking of multiple channels (although perhaps at lower rates)
  - It is easily worth it to provide a reduced connect speed to a an unpredictable minority of clients, in exchange for higher connect speeds for everyone else all the time
- Radar events
  - It is worth having a small number of clients occasionally interrupted in exchange for more capacity for everyone all the time

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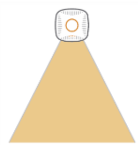
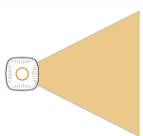
Basic RF Design for Very High Density Coverage Areas

RF Coverage Strategies

- Radio coverage can be done in three ways, regardless of the type of area to be served.



Overhead Coverage: APs are placed on a ceiling, catwalk, roof, or other mounting surface directly above the users to be served.

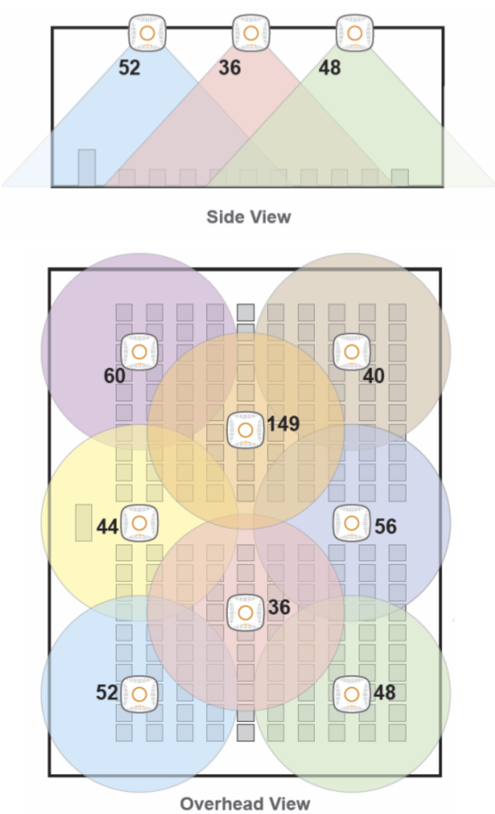


Side Coverage: APs are mounted to walls, beams, columns, or other structural supports that exist in the space to be covered.

Floor Coverage: This design creates picocells using APs mounted in, under, or just above the floor of the coverage area.

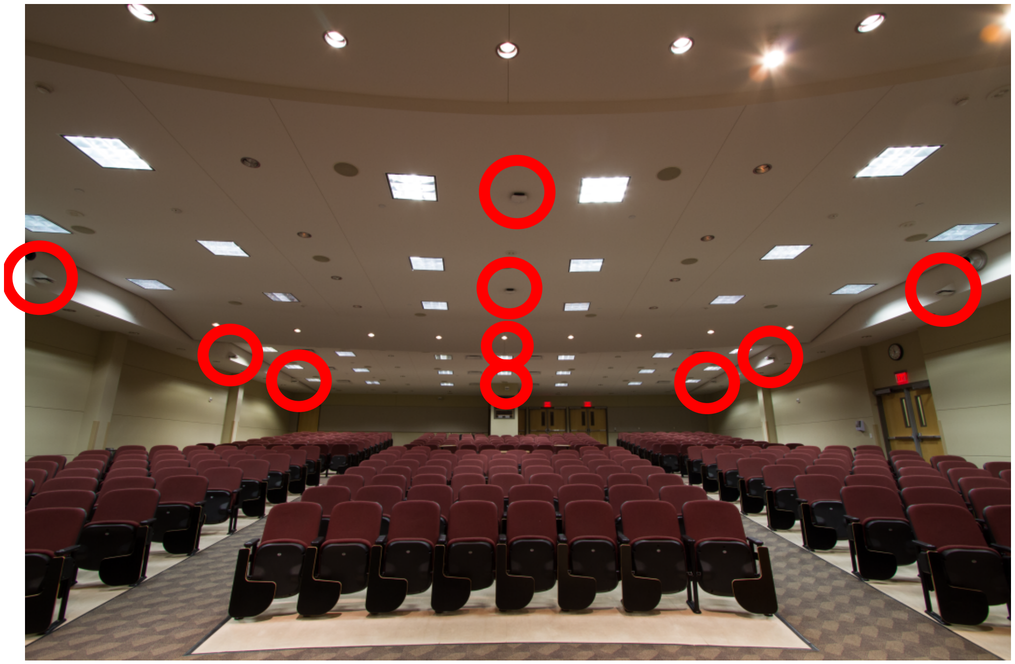
- APs with integrated antennas are used for any VHD area of under 5,000 seats (very few exceptions)

Overhead Coverage



- Overhead coverage is a good choice when uniform signal is desired everywhere in the room.
- No RF spatial reuse is possible because of the wide antenna pattern and multipath reflections.
- Integrated antenna APs should always be used for ceilings of 10 m (33 ft) or less.
- Note the 20-MHz channel width, and that no channel number is used more than once.
  - This is an example of a static, non-repeating channel plan intentionally chosen by the wireless architect.
- Requires access the ceiling with minimal difficulty or expense to pull cable and install equipment.

Examples – Overhead Coverage #1



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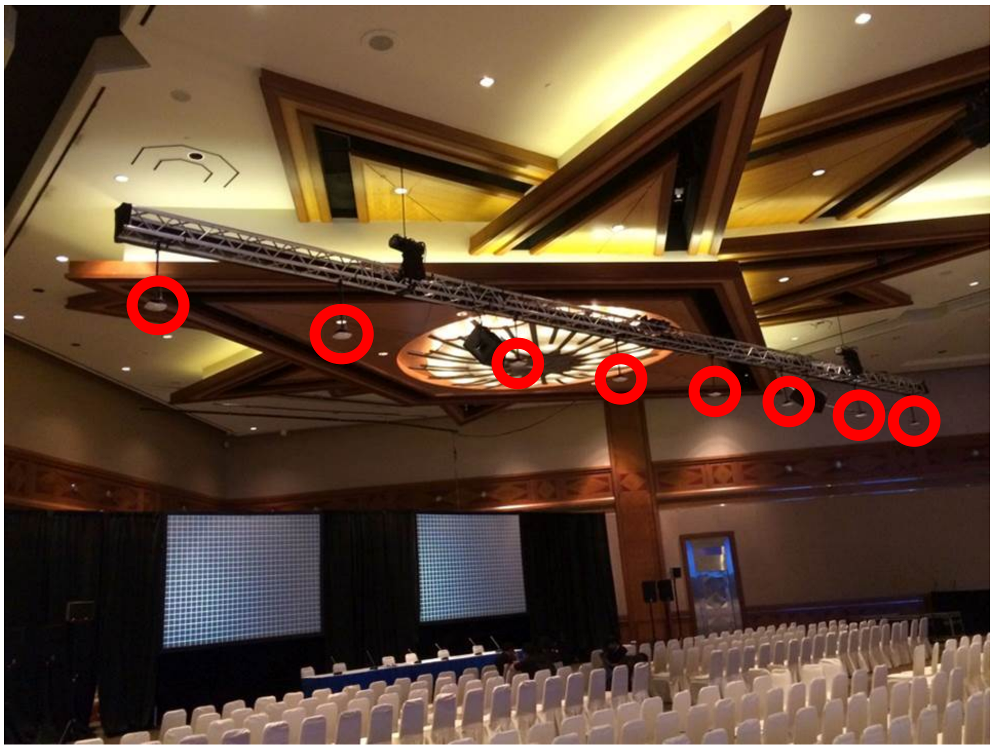
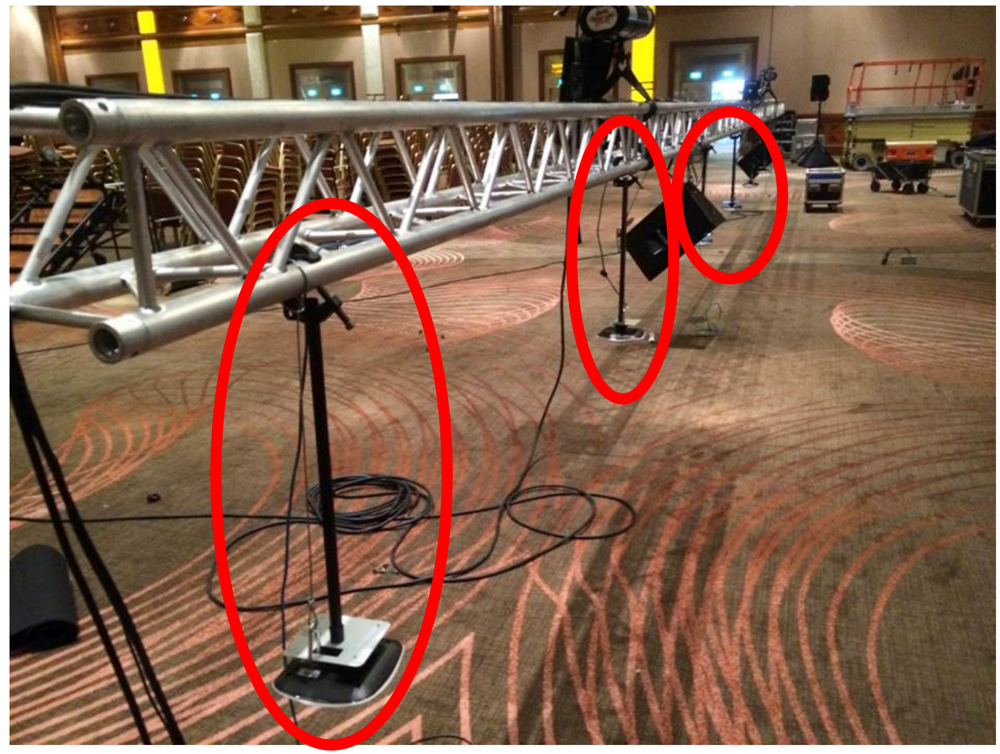
Examples – Overhead Coverage #2





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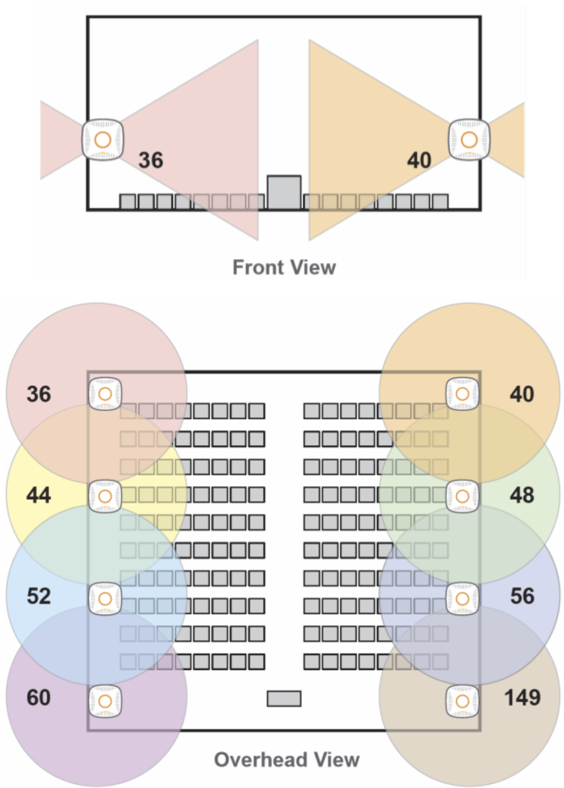
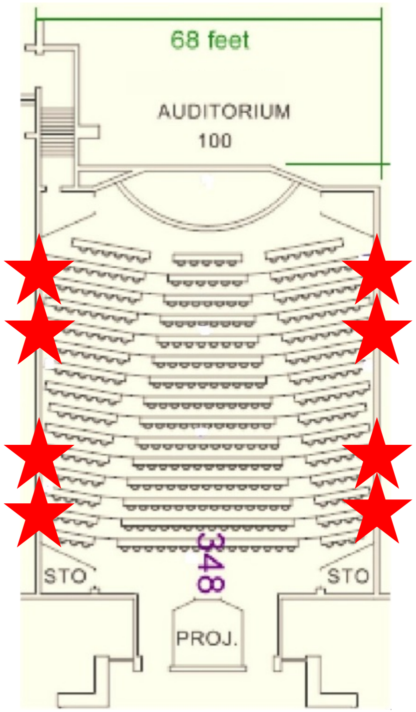
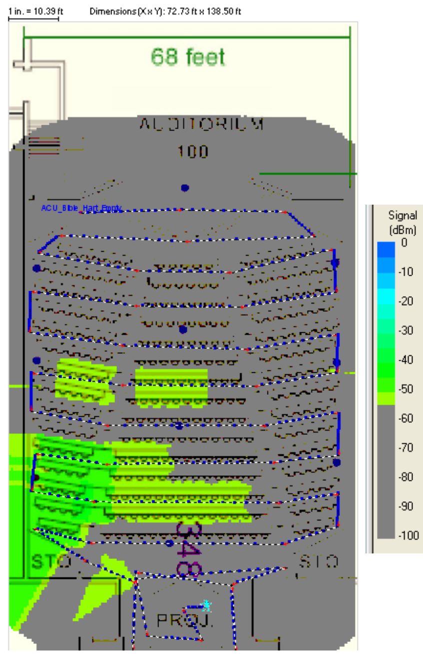
Side Coverage



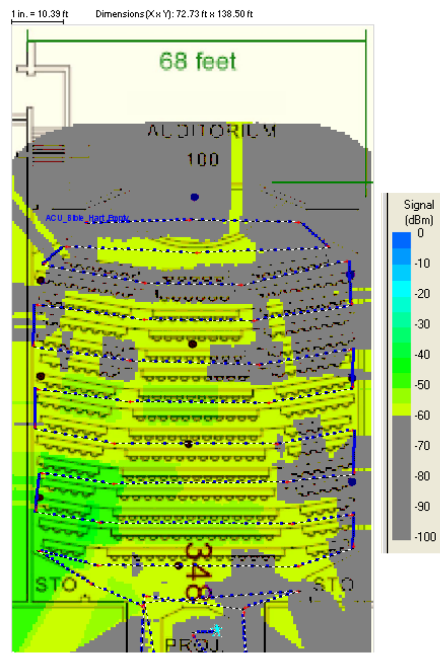
- Wall, beam, and column installations with side-facing coverage are very common in VHD areas.
- Some ceilings are too difficult to reach, others have costly finishing that cannot be touched, or there may be no ceiling such as open-air atriums.
- No RF spatial reuse in indoor environments is possible when mounting to walls or pillars.
- 50% of the wall-mounted AP signals are lost to the next room (and 75% of the signal in the corners).
- Note that adjacent APs on the same wall always skip at least one channel number.

What Does No RF Spatial Reuse Mean?

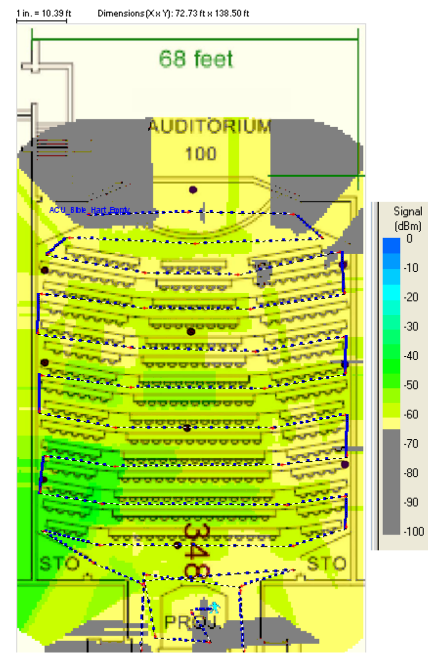




-55dBm Filter



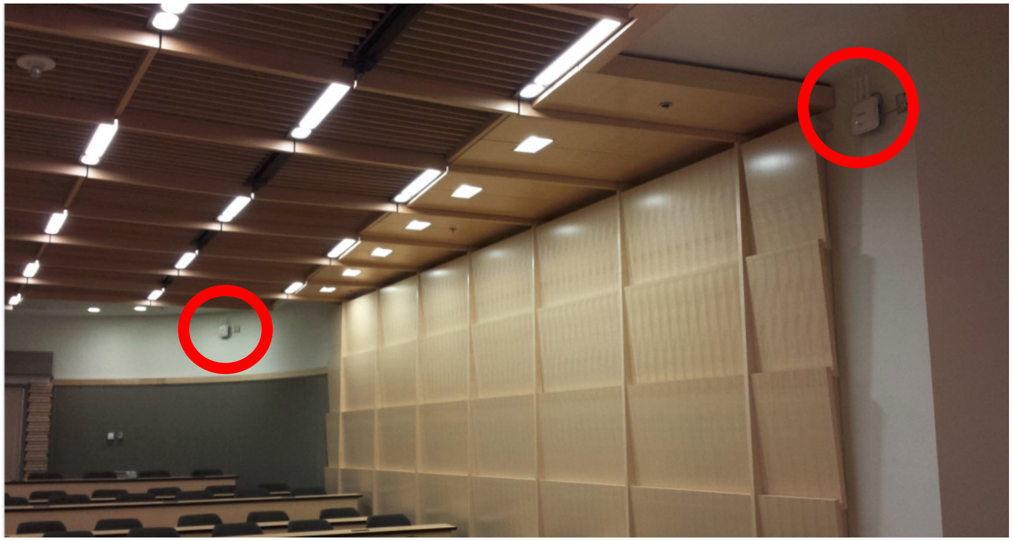
-60dBm Filter



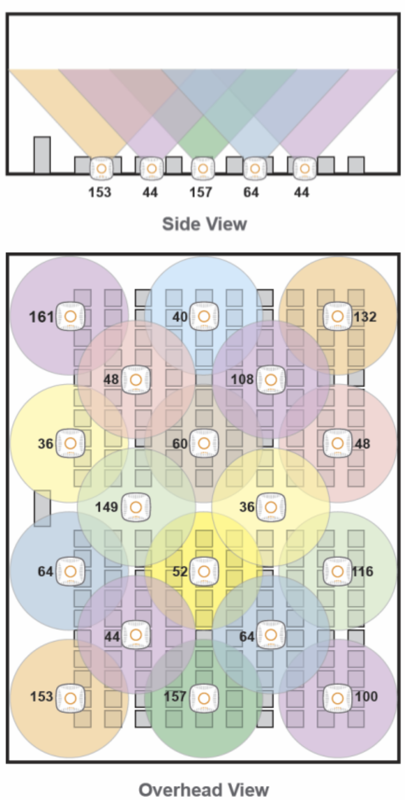
-65dBm Filter

Every AP can be heard everywhere in the room

Examples – Side Coverage



Floor Coverage



- Venues <= 10K seats should always use overhead or side coverage.
- Above > 10K seats, a more exotic option called “picocell” has been proven to deliver significant capacity increases.
- Density of picocell can be much higher than overhead or side coverage.
- Picocell design leverages absorption that occurs to RF signals as they pass through a crowd (known as “crowd loss”).
- Cost and complexity of picocells may not always justify the extra capacity generated.

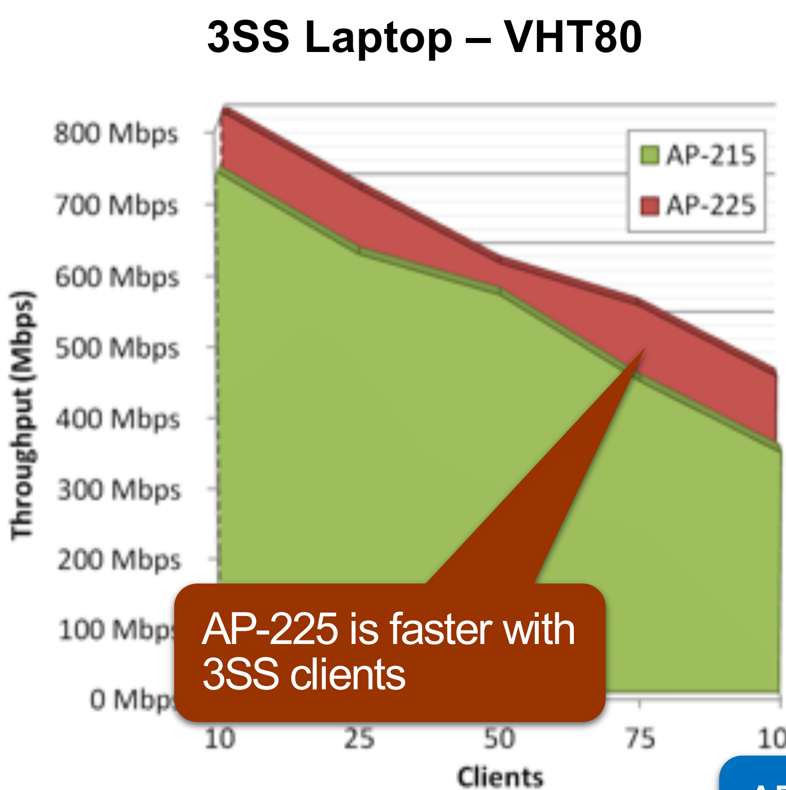
Examples - Picocell

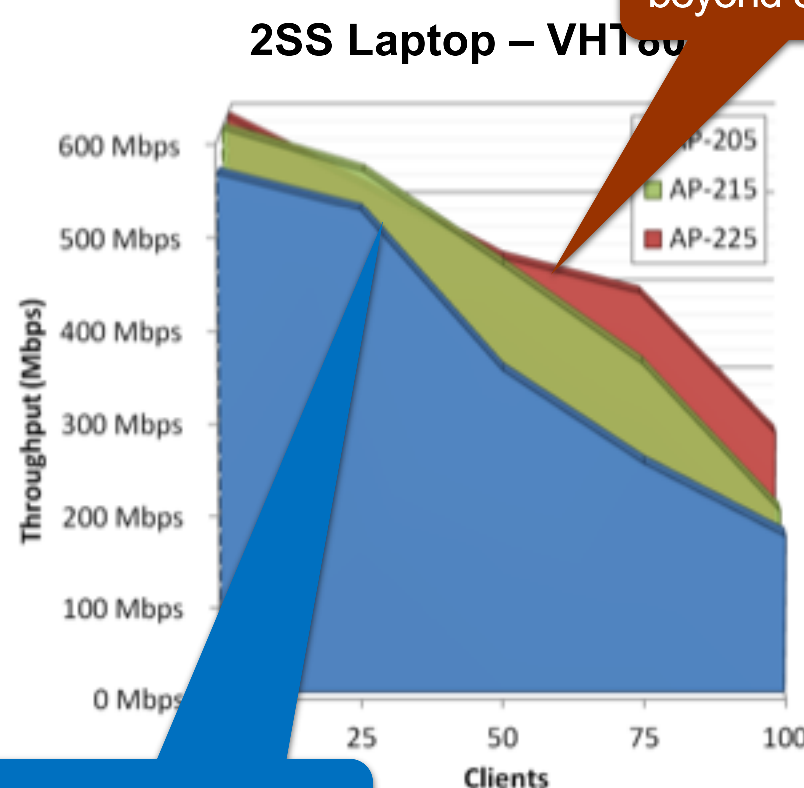
Aruba 802.11ac Indoor APs

- Buy the highest performance AP that you can afford for VHD areas.
- The rest of your deployment may use a more economical model.
- Use the right tool for the job.

	Low Cost	Medium Performance	Maximum Performance
Model	**AP-204 / AP-205** 	**AP-214 / AP-215** 	**AP-224 / AP-225** 
MIMO	2x2:2	3x3:3	3x3:3
CPU	Broadcom 53014A Single core, 1 GHz	Freescale P1010 Single core, 800 MHz	Freescale P1020 Dual core, 800 MHz
Memory	SDRAM – 128 MB Flash – 32 MB	SDRAM – 256 MB Flash – 32 MB	SDRAM – 512 MB Flash – 32 MB
Radio	Broadcom BCM43520	Broadcom BCM43460	
Antenna / Connectors	Integrated downtilt antenna; or 3 diplexed RP-SMA connectors		
Max Conducted Power	+21 dBm (18dBm per chain)	+23 dBm (18dBm per chain)	+23 dBm (18dBm per chain)
Maximum EIRP	+25 dBm (2.4-GHz) +27 dBm (5-GHz)	+28 dBm (both bands)	+26.5 dBm (2.4-GHz) +27.5 dBm (5-GHz)
Operating Temp	0°C to +50°C		
Power	802.3af POE		802.3at POE

Choosing an AP Model for VHD Areas



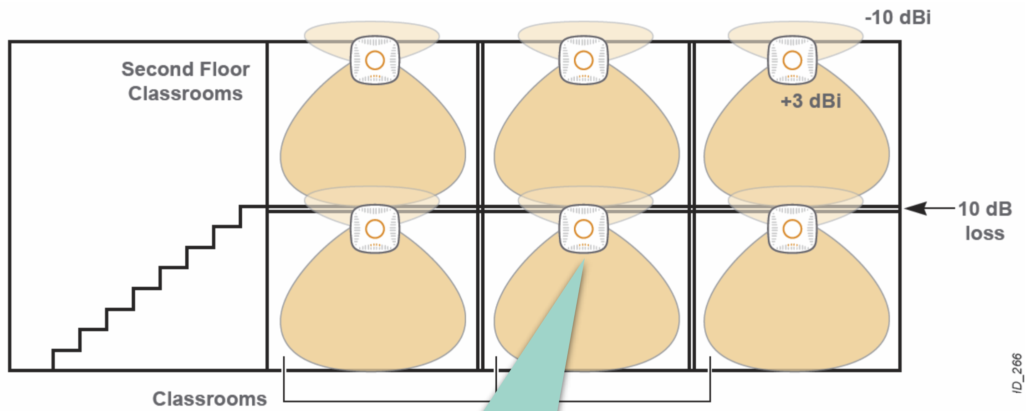


AP-225 is best beyond 50 clients

AP-225 is faster with 3SS clients

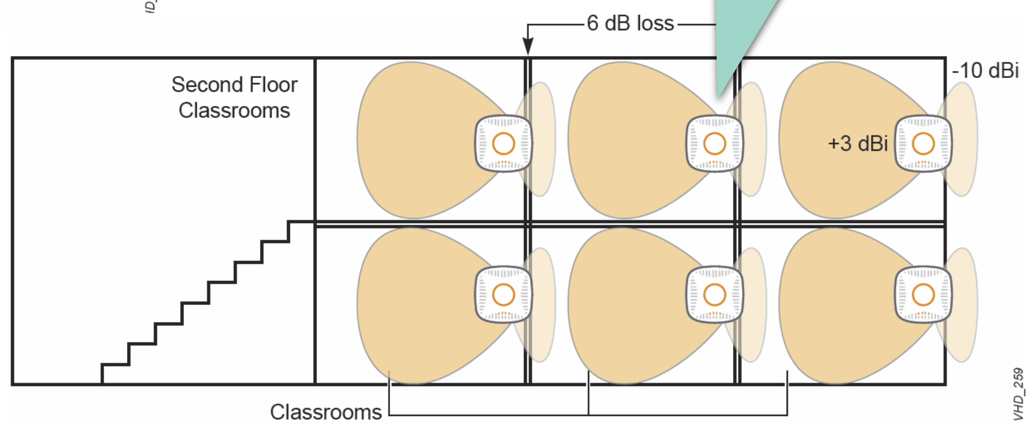
AP-205 works well up to 25 concurrent clients

AP Placement for Adjacent VHD Areas



Place APs all facing same direction. Stagger horizontal placements.

Same rules apply to wall deployments. Use rear lobe to your advantage.



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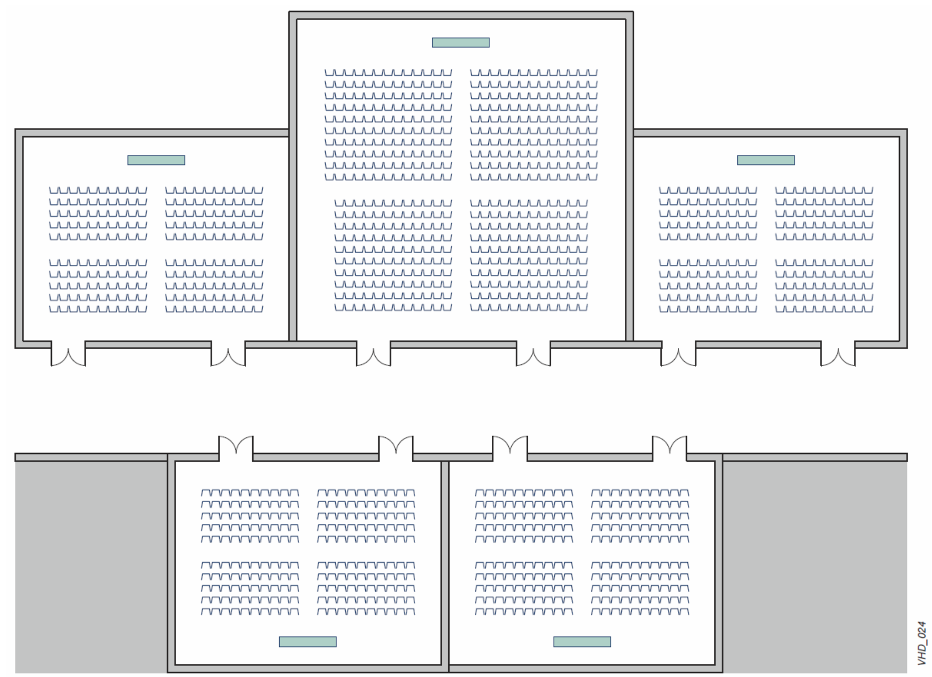
Example:
Adjacent Large Auditoriums

Typical Multi-Auditorium Scenario

- Hotel conference center or university building with multiple adjacent auditoriums
- Dimensioning metrics:

Metric	Target
Take Rate	100%
Average devices per person	Work/study – 5 Fan/guest - 2
Associated devices per radio	150
Average single-user goodput	1 Mbps
5 GHz vs. 2.4 GHz split	5 GHz: 75% 2.4 GHz: 25%



Physical Layout

Understanding Offered Load in Auditoriums

Table S1-1 VHD Spatial Stream Blend Lookup Table

VHD Usage Profile	Devices / Person (Now)	Devices / Person (Future)	1SS (%)	2SS (%)	3SS (%)
Work/Study	3	5	30%	60%	10%
Fan/Guest	1	2	50%	50%	0%

Table S1-2 Network Characteristics of Common Auditorium Applications

User Category	Application	Bandwidth	Latency	Duty Cycle
Work/Study	Play courseware (non video)	500 Kbps	Medium	Medium
	Play courseware (video streaming)	1 Mbps+	Low	High
	Test / exam / quiz	Under 250 Kbps	Real-time	Synchronized bursts
Fan/Guest	General internet usage	500 Kbps	Medium	Low
	Email	Under 250 Kbps	High	Low
	Social media	500 Kbps	Medium	Low
	Photo/video cloud sync	1 Mbps+	High	Low

- Common apps are web browsing, email, and office collaboration.
- Class presentation and exam software, are bursty with high concurrent usage.
- Cloud service latency is not visible to users.

Step 2/3 - Estimate Associated Device Capacity

Start with seating capacity

Use per-user device to estimate ADC

Break out by frequency band.

Determine address space

Table S1-4 … and Subnet Plan for Fi… llrooms

Room Number	Seats	ADC (Now)	ADC (Future)	5-GHz ADC (Future)	2.4-GHz ADC (Future)	Minimum Subnet Size
Room A	200	600	1,000	750	250	/22
Room B	200	600	1,000	750	250	/22
Room C	500	1,500	2,500	1,875	625	/20
Room D	200	600	1,000	750	250	/22
Room E	200	600	1,000	750	250	/22
Staff / House	--	25	75	75	0	/24
GUEST ADC	**1,300**	**3,900**	**6,500**	**4,875**	**1,625**	**/19**
STAFF ADC	**--**	**25**	**75**	**75**	**0**	**/24**
TOTAL ADC	**1,300**	**3,925**	**6,575**	**4,950**	**1,625**	

Estimate staff / facility devices separately

Step 4 - Estimate the AP Count

$$\text{AP Count} = \text{5-GHz Radio Count} = \frac{\text{Active Device Capacity (5 GHz)}}{\text{Max Associations Per Radio}}$$

Table S1-5 AP Count for Five Ballrooms

Room Number	5-GHz Guest	5-GHz Staff	Total 5-GHz Devices	Devices per Radio	AP Count
Room A	750	15	765	150	6
Room B	750	15	765	150	6
Room C	1,875	15	1,890	150	13
Room D	750	15	765	150	6
Room E	750	15	765	150	6
Hallway	500	15	515	150	4
TOTAL	**5,375**	**90**	**5,465**		**41**

Take 5-GHz ADC

Divide by per-radio metric

Calculate System Throughput (Excluding CCI)

Table S1-8 System Throughput Calculation Excluding CCI

Room Number	AP Count	Channels – USA (DFS)	Channels – China (no DFS)	Avg. Channel Bandwidth	Aggregate Bandwidth – USA	Aggregate Bandwidth - China
Room A	6	9	9	67 Mbps	603 Mbps	603 Mbps
Room B	6	9	9	67 Mbps	603 Mbps	603 Mbps
Room C	13	16	12	67 Mbps	1,072 Mbps	804 Mbps
Room D	6	9	9	67 Mbps	603 Mbps	603 Mbps
Room E	6	9	9	67 Mbps	603 Mbps	603 Mbps
Hallway	4	7	7	67 Mbps	469 Mbps	469 Mbps
TOTAL	**41**				**3,953 Mbps**	**3,685 Mbps**

Take AP count

Convert to channels

Multiply by estimated channel capacity

Total maximum load if zero CCI

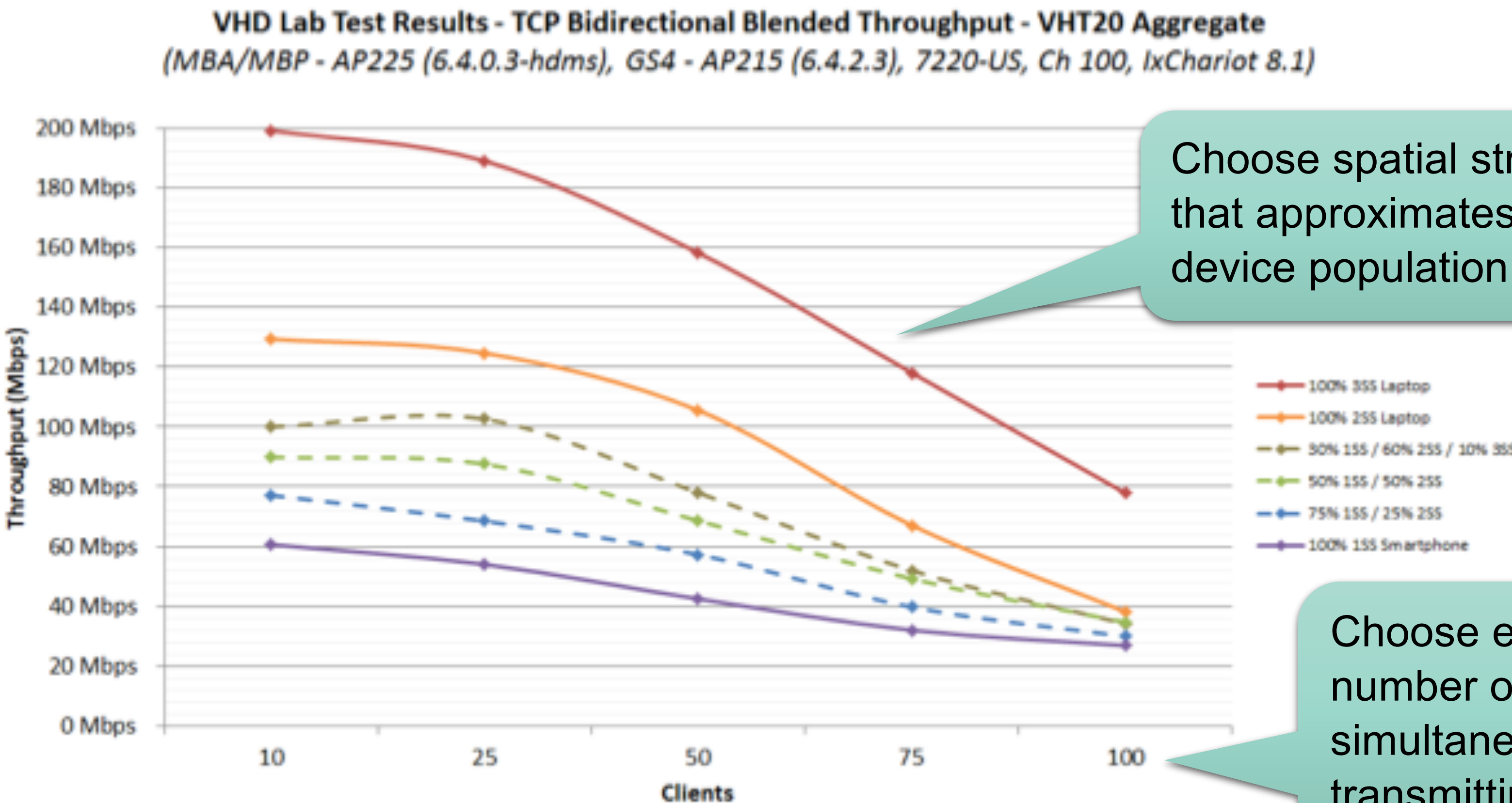
Total System Throughput Formula

$$TST = Channels * Average\ Channel\ Throughput * Reuse\ Factor$$

Where:

- *Channels* = Number of channels in use by the VHD network
- *Average Channel Throughput* = Weighted average goodput achievable in one channel by the expected mix of devices for that specific facility
- *Reuse Factor* = Number of RF spatial reuses possible. For all but the most exotic VHD networks, this is equal to 1 (e.g. no reuse).

Estimating Unimpaired Channel Throughput

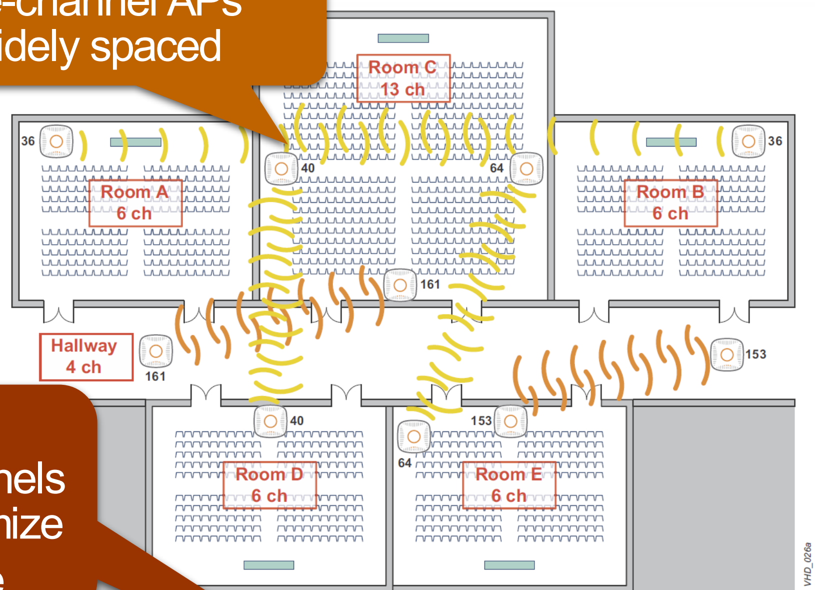


Choose spatial stream mix that approximates expected device population

Choose estimated number of simultaneously transmitting clients

Understanding CCI & Estimating Reuse Factor

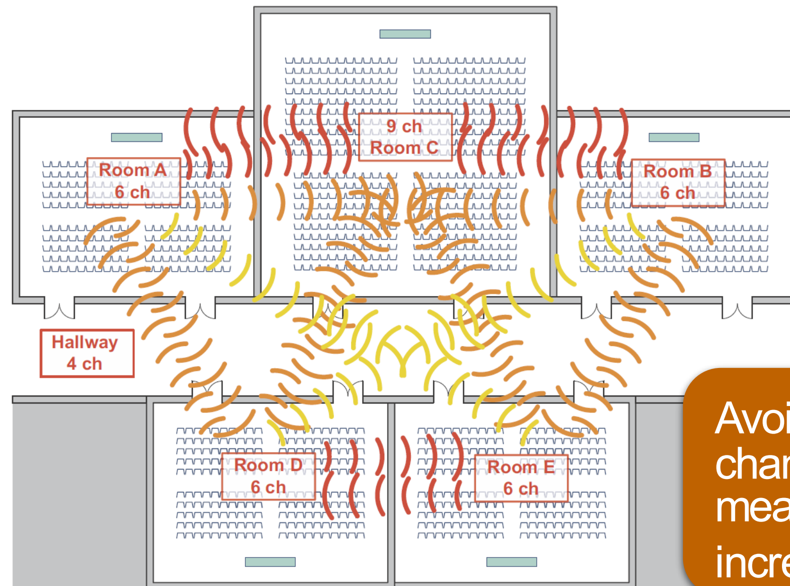
Same-channel APs are widely spaced



DFS channels minimize reuse

Figure S1-3 Estimated 5-GHz CCI with 21-Channel DFS Plan

Channel Group	AP Count	2.4-GHz Channels	5-GHz Channels
Room A	6	1, 6, 11	36, 52, 100, 116, 140, 149
Room B	6	1, 6, 11	36, 52, 100, 116, 140, 153
Room C	13	1, 6, 11	40, 48, 104, 108, 112, 132, 44, 56, 60, 64, 161, 165, 136
Room D	6	1, 6, 11	40, 48, 104, 108, 112, 136
Room E	6	1, 6, 11	44, 56, 60, 64, 161, 157
Hallway	4	1, 6, 11	149, 154, 157, 165



Avoiding DFS channels means greatly increased CCI

Figure S1-4 Estimated 5-GHz CCI with 9-Channel Non-DFS P

Channel Group	AP Count	2.4-GHz Channels	5-GHz Channels
Room A	6	1, 6, 11	36, 40, 44, 48 149, 153
Room B	6	1, 6, 11	36, 40, 44, 48 157, 161
Room C	13	1, 6, 11	36, 40, 44, 48 149, 153, 157, 161, 165
Room D	6	1, 6, 11	36, 40, 44, 48 157, 165
Room E	6	1, 6, 11	36, 40, 44, 48 149, 153
Hallway	4	1, 6, 11	153,157,161,165

Calculate Total System Throughput (Including CCI)

Table S1-9 System Throughput Calculation Including CCI

Reuse Factor	AP Count	Channels – USA (DFS)	Channels – China (no DFS)	Avg. Channel Bandwidth	Aggregate Bandwidth – USA	Aggregate Bandwidth - China
RF = 1.0	41	24	12	67 Mbps	1,608 Mbps	804 Mbps
RF = 1.5	41	24	12	67 Mbps	2,412 Mbps	No reuse
RF = 2.0	41	24	12	67 Mbps	3,216 Mbps	No reuse

Most likely outcomes

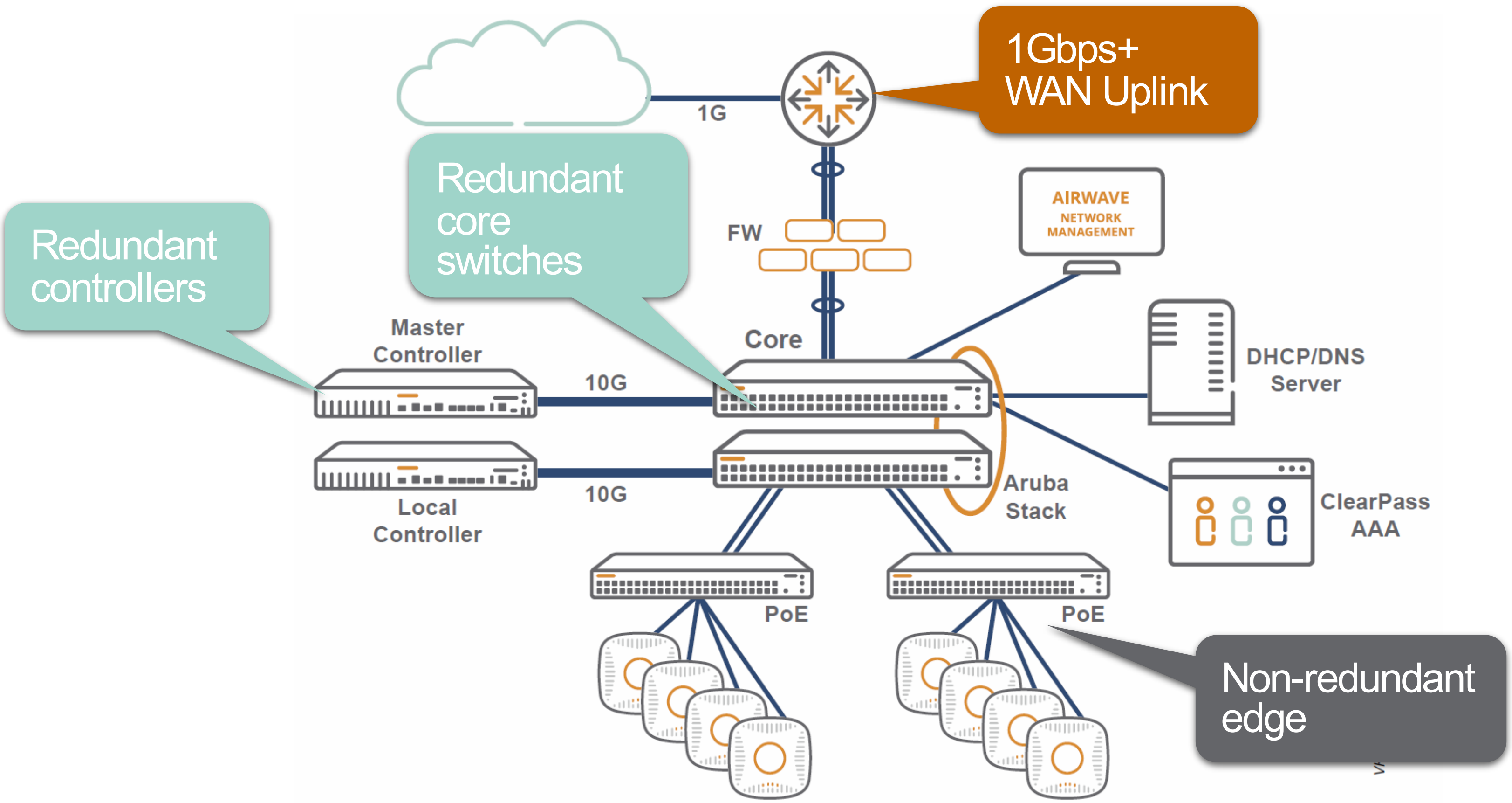
Model different reuse factors

Revised capacity for DFS scenario

Revised capacity for non-DFS scenario

The TST directly dimensions the required WAN uplink.

End-to-End Architecture



Questions?