Performance analysis of 802.11ac Access Points: The Power of Smart Antenna Technology

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Key findings:

- 802.11ac Access Points (APs) from Aruba, Cisco, Ruckus and ZyXEL were tested by the Wireless Networking Group at the University of Brescia to measure their maximum performance in delivering traffic to stations.

- Tests covered two different aspects: i) evaluate the maximum throughput to single stations characterized by propagation patterns of increasing difficulty; ii) determine the aggregate throughput of two Access Points that serve multiple stations on the same channel and are hence exposed to mutual interference.

- Results show that reconfigurable antenna technologies are key for improving throughput and for reducing co-channel interference in Wi-Fi networks.

- More specifically, the AP from ZyXEL with Smart Antenna technology outperforms other APs in the majority of the single station test scenarios: by considering the most difficult locations, the ZyXEL AP achieves the best average gain (66%) with respect to the slowest competitor in the 2.4GHz band.

- In the co-channel interference test ZyXEL AP reports the best aggregate throughput in seven deployments over the eight considered: it also achieves an average gain of 75% with respect to the AP with the lowest aggregate throughput.

The Wireless Networking Group at the University of Brescia is specialized in the analysis, design and experimental characterization of the performance of wireless networks at the physical and medium access control layers. Research activities include the opportunistic exploitation of 802.11 networks for localization, jamming, and pseudo-deterministic channel access algorithms.

Executive Summary

After years of development, the IEEE association has approved in 2014 the 802.11ac standard amendment which finally brings the power of multi-gigabit networking to the wireless domain. This has the potential to deeply change the way people connect to the network: ubiquitous wireless access will soon make the fixed wired infrastructure obsolete.

Higher throughputs, however, require the allocation of large portions of the spectrum into few non-overlapping channels, which could make the 5GHz band very crowded all of a sudden. Co-channel interference between neighboring Access Points configured on the same channel may deeply affect the user experience.

The Wireless Networking Group at the University of Brescia partnered with ZyXEL Communications Corp. and demonstrated with the experiments reported in this document that the Smart Antenna technology is able to reduce this issue: this is enabled by a continuous reconfiguration of the radiation pattern that focusses the energy emitted by the Access Point towards its associated receivers reducing the interference that it could cause to other nodes.

The experiments demonstrate that the Smart Antenna technology of ZyXEL has the ability to deliver a higher aggregate throughput when two neighboring APs operate on the same channel: this result designates the SA technology as key to enable the gigabit per second speed promised by the 802.11ac standard.

Introduction

The IEEE 802.11ac standard published in 2014 introduced so many enhancements at the physical layer that wireless networks are now ready to meet the ever increasing users' demand: bandwidth-eager applications once confined to the wired domain can live today on mobile nodes. This has been possible thanks to the improvement made by IEEE along three directions: larger aggregate channel bandwidth; denser modulations together with more aggressive Forward Error Correction (FEC) mechanisms; and more Multiple Input/Multiple Output (MIMO) spatial streams.
The latter mechanism, in particular, boosts the physical data-rate by increasing the number of signals transmitted at the same time through multiple antennas: feedbacks from receivers may be also used by a transmitter to better encode such signals through a technique known as *beamforming* that maximizes the chance such signals are correctly delivered to the corresponding receiver.
As the standard leaves manufacturer free to develop their own antenna technology, throughput perceived by users can be improved with the usage of *reconfigurable antenna* or *Smart Antennas* (SAs): by adapting the radiation pattern, a transmitting node may increase the signal-to-noise ratio for the specific receiver of a given packet. This also helps to reduce problem related to co-channel interference.

The Wireless Networking Group (WNG) at the University of Brescia tried to quantify experimentally the performance gain made possible by the usage of SAs in Enterprise 802.11 Access Points by running two different types of experiment:

- one aimed at assessing the maximum performance when sending unidirectional data to a single client. As we will see SA turns out to be winning technology for delivering data at higher throughputs, and to make clients work even when positioned in tough locations;

- and one aimed at measuring the aggregate throughput delivered by two neighboring APs to their clients when operating in the same channel. This scenario will become very common with the increasing adoption of the larger channels made available by the 802.11ac standard. This experiment helped understanding how SA technology is key to reduce co-channel interference and increase the aggregate throughput.

To understand the impact of SA on the over-all performance, we selected two APs embedding some SA technology and two without. In the experiments, however, we configured all the Access Points (APs) under tests with the most similar settings regarding emitted power and layer 2 features to emphasize any difference that could result from the adoption of SA technology. We also considered several client locations and different orientations of the APs to get an *average picture* from every AP.

We are aware that each vendor's product may have its own *optimal* configuration that may lead to different results. And the same could happen by changing its firmware with a new one. We also underline that results may quantitatively change in a different environment because of the radio-signal propagation. However, we are confident that the results that we obtained represents what others can expect on average and on a qualitative basis: the chosen deployments, in fact, have been selected almost randomly and without following any specific vendors' guideline.

Equipment and testing environment

The two APs with classic, non-reprogrammable antennas are from Aruba Networks and Cisco. The two APs with SA technology are from Ruckus Wireless and ZyXEL Communications Corp. All APs support 11ac wave 1 in the 5GHz band, and 11n in the 2.4GHz band, and they manage up to three spatial streams in both bands. We report details for each of the four APs in the following:

- Aruba Networks **AP-225** + Aruba Networks Controller 650:
  - Broadcom BCM43460 (2.4 and 5GHz)
  - AP & Controller firmware version: 6.4.2.3
  - Antenna type: non-SA

- Cisco **2702i**:
  - Marvell Avastar 88W8764C (2.4GHz) and Avastar 88W8864C (5GHz)
  - AP firmware version: AP3G2-K9W7-M
  - Antenna type: non-SA

- Ruckus Wireless **R700**:
  - Qualcomm Atheros QCA9880-2R4E (5GHz), Ruckus Wireless MPE2N33A (2.4GHz)
  - AP firmware version: 9.8.0.0.373
  - Antenna type: SA

- ZyXEL Communications Corp. **WAC6503D-S**:
  - Qualcomm Atheros
  - AP firmware version: V4.21(AASF.1) / V2.1
  - Antenna type: SA

In the case of Aruba Networks we connected the AP to the corresponding separate controller as the AP could not work in a stand-alone configuration differently than all the other considered APs.
We configured the APs with the most similar settings allowed by the corresponding administration interfaces[1]: in principle they should achieve the same throughput performance

- same country setting (US)
- channel 9 of the 2.4GHz spectrum with 20MHz bandwidth
- channel 157 of the 5GHz spectrum with 80MHz bandwidth
- support for short guard interval
- support for AMPDU aggregation.

In all our tests we used Asus c200 Chromebook equipped with an Intel AC7260 chipset: this supports 802.11ac in the 5GHz band and 802.11n in the 2.4GHz band and manages two spatial streams. When connecting to the APs under test, the 5GHz Very-High-Throughput physical layer (VHT-PHY) supports two-stream Modulation and Coding Schemes (MCS) with data-rate up to 866.6Mb/s; the 2.4GHz High-Throughput physical layer (HT-PHY) supports MCS up to 144.4Mb/s.
Clients were running Gallium OS operating system based on Linux kernel 4.4.1. The version of the firmware loaded by the Intel iwlmwm Wi-Fi driver was 25.30.13.0.

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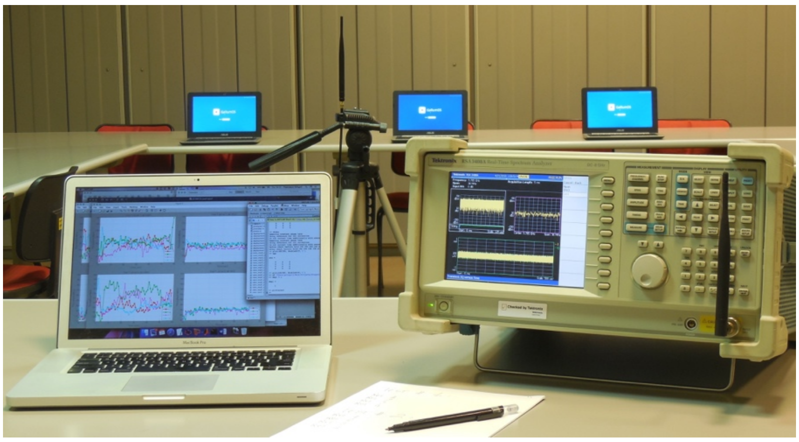
[1] This could be either a console or the web interface expect for the Aruba as we used the web interface of the controller.

As for the software we used “iPerf - The network bandwidth measurement tool” - version 2.0.5: depending on the specific experiment we ran UDP sessions in downlink or uplink, and TCP sessions in downlink. For all the throughput experiments we ran data sessions between the clients and a Desktop PC connected to the AP under test, that was able to support all the sessions without being a bottleneck (i.e., Intel Core i7 with Gigabit interface).

Finally, the environment chosen for the execution of the experiments was the Department of Information Engineering (DII) at the University of Brescia. DII develops on the first floor of a three stories building: while floors are reinforced concrete structures, walls are generally drywalls with few exceptions being either brick or concrete walls. The department is a typical University environment and it hosts multiple offices, laboratories and conference rooms. The ceiling is suspended and allowed us to easily mount and quickly replace the APs as can be seen in the picture on the right. We report maps specific for each of the experiments later.

We performed experiments during non-working hours – night or weekends – to ensure nobody was moving around: this guaranteed a static environment that makes the results obtained with the four AP brands fairly comparable and repeatable.

For the choice of the Wi-Fi channels we first forced the University wireless network[2] on channel 1 @2.4GHz and on channels 36 and 40 @5GHz; we then accurately monitored the rest of the spectrum and we determined with the help of a Tektronix RSA-3408A real-time spectrum analyzer that channel 9 @2.4GHz and channel 157 @5GHz were totally free as we show in the picture.



To carry out this activity WNG partnered with ZyXEL Communications Corp. which has kindly provided their own APs. All the remaining equipment, including the APs from competitors and the clients under test, have been purchased from on-line resellers.

[2] The entire wireless network is managed by a centralized controller and can be easily configured on specific channels.

Experiment 1 – Single AP, Single Client: Throughput vs Location "difficulty"

We ran this test to evaluate the performance gain that SA technology achieves when the AP is transmitting unidirectional UDP traffic to a single client.

We placed the AP in an open-space room as we show in Figure 1. We then placed a single client in the ten different locations that we show in the figure: by considering the variety of walls (e.g., drywall, brick- and concrete), each location exhibits a distinct propagation profile, i.e., line-of-sight, single or multiple reflections, refraction phenomena, etc. To avoid to take into account effects due to the reciprocal orientation of the AP and the client, we considered four rotations of the AP (0, 90, 180 and 270 degrees): for each rotation we repeated the same throughput test twice. Each test is composed of the following phases:

1) association of the client from a disconnected state;
2) transmission of an initial 30 seconds downlink session that we assume let the AP stabilize the communication towards the client (i.e., selection of the optimal MCS and SA configurations);
3) transmission of a 60 seconds downlink data session that we use to assess the communication performance by evaluating the average achieved throughput.

For each AP we then considered the best result obtained for each of the four rotations. We finally compute the average value over the four rotations.

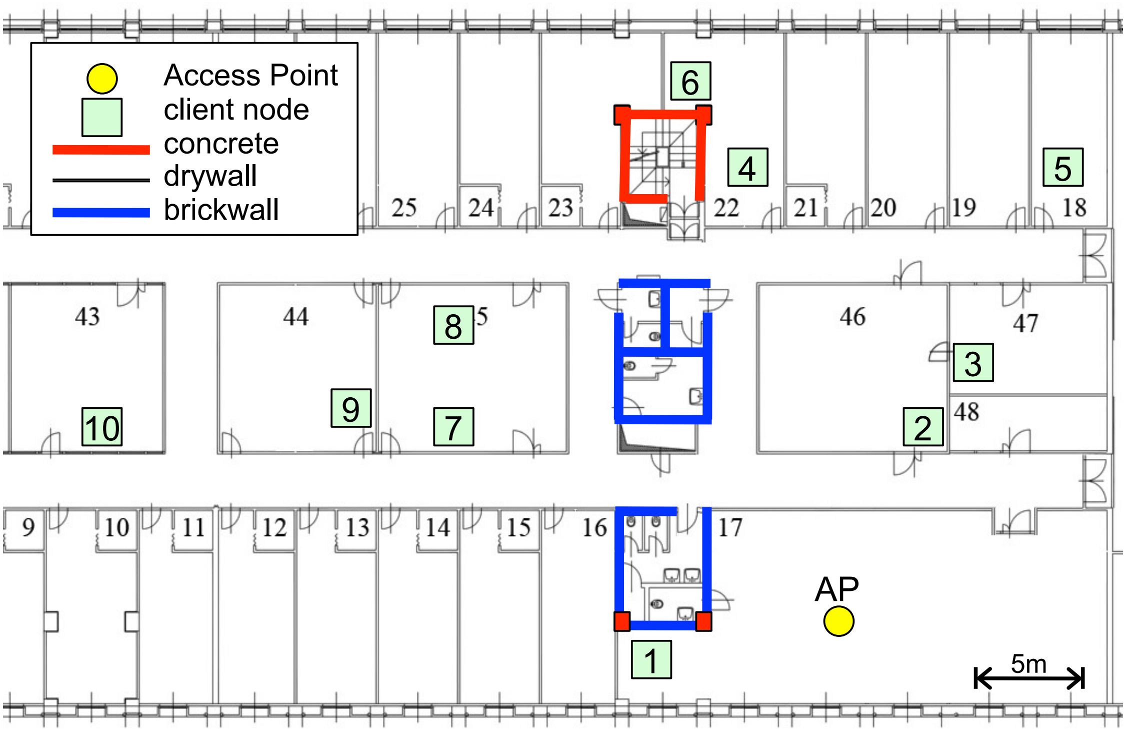


Figure 1 Deployment topology for single-client/single-ap experiment

We report results for the 5GHz and 2.4GHz bands in Table 1 and Table 2 respectively. We also report the corresponding bar plots for the two bands in Figure 2 and Figure 3 respectively.

Table 1 Throughput [Mb/s] vs Location
Band 5GHz: difficult locations red boxed

Loc.	Aruba	Cisco	Ruckus	ZyXEL
1	431.82	367.35	371.99	**497.61**
2	373.06	453.71	377.58	**493.11**
3	288.62	247.34	**299.09**	291.38
4	248.83	258.82	284.10	**333.04**
5	77.13	72.46	**125.03**	99.76
6	125.73	108.78	**162.15**	149.11
7	103.56	76.88	122.34	**141.35**
8	105.32	95.87	128.92	**144.24**
9	37.97	28.33	**76.83**	55.59
10	7.94	10.26	21.61	**21.96**
Σ	457.65	392.58	636.88	612.01
gain	17%	/	62%	56%

Table 2 Throughput [Mb/s] vs Location
Band 2.4GHz: difficult locations red boxed

Loc.	Aruba	Cisco	Ruckus	ZyXEL
1	110.59	111.55	**115.32**	111.90
2	**120.77**	116.42	117.92	119.44
3	112.56	102.90	111.24	**116.97**
4	109.12	99.88	106.20	**117.14**
5	41.00	72.05	0.16	**85.03**
6	47.74	49.06	65.37	**80.84**
7	60.28	64.96	35.22	**80.67**
8	50.70	46.16	36.61	**63.94**
9	46.95	37.75	**64.88**	61.25
10	26.62	25.31	**45.62**	40.92
Σ	273.29	295.29	247.86	412.65
gain	10%	19%	/	66%

The two tables display the APs that ranked first and second in orange and green respectively: in both bands ZyXEL leads as it wins in six locations and ranks second in the others. The second most winning AP is Ruckus, that similarly to ZyXEL adopts reconfigurable antennas: in the 5GHz band it wins four times, while in the 2.4GHz band it wins three out of the four 2.4GHz cases where ZyXEL ranks second. This demonstrates that SAs are key for delivering higher throughput.
The reported throughputs are strongly influenced by the physical properties of the environment: i.e., in the first four locations they are much higher than in the remaining six which are tough to reach either because of the brick and concrete walls or the number of the drywalls that separate AP and clients, as reported in Figure 1. We hence surround results achieved in these difficult locations with red lines in the tables and we report the sum of the corresponding throughputs in row "Σ" as a mean of comparison: after identifying the lower throughput as a reference (it appears as / in the "gain" row) we compute the percentage gain of the others with respect to this reference. It turns out that in the 5GHz band the benefit deriving from the adoption of SA technology allows 62% and 56% gain respectively for Ruckus and ZyXEL. In the 2.4GHz band, the ZyXEL SA technology allows a 66% gain with respect to the reference that here is represented by Ruckus: in this band, in fact, the Ruckus antenna technology fails in location 5 where the AP delivers only a few Kb/s of traffic to the client.

As a bottom line we believe that the SA technology of ZyXEL may achieve better performance than the other.

Figure 2 Throughput vs Location difficulty: Band 5GHz, downlink

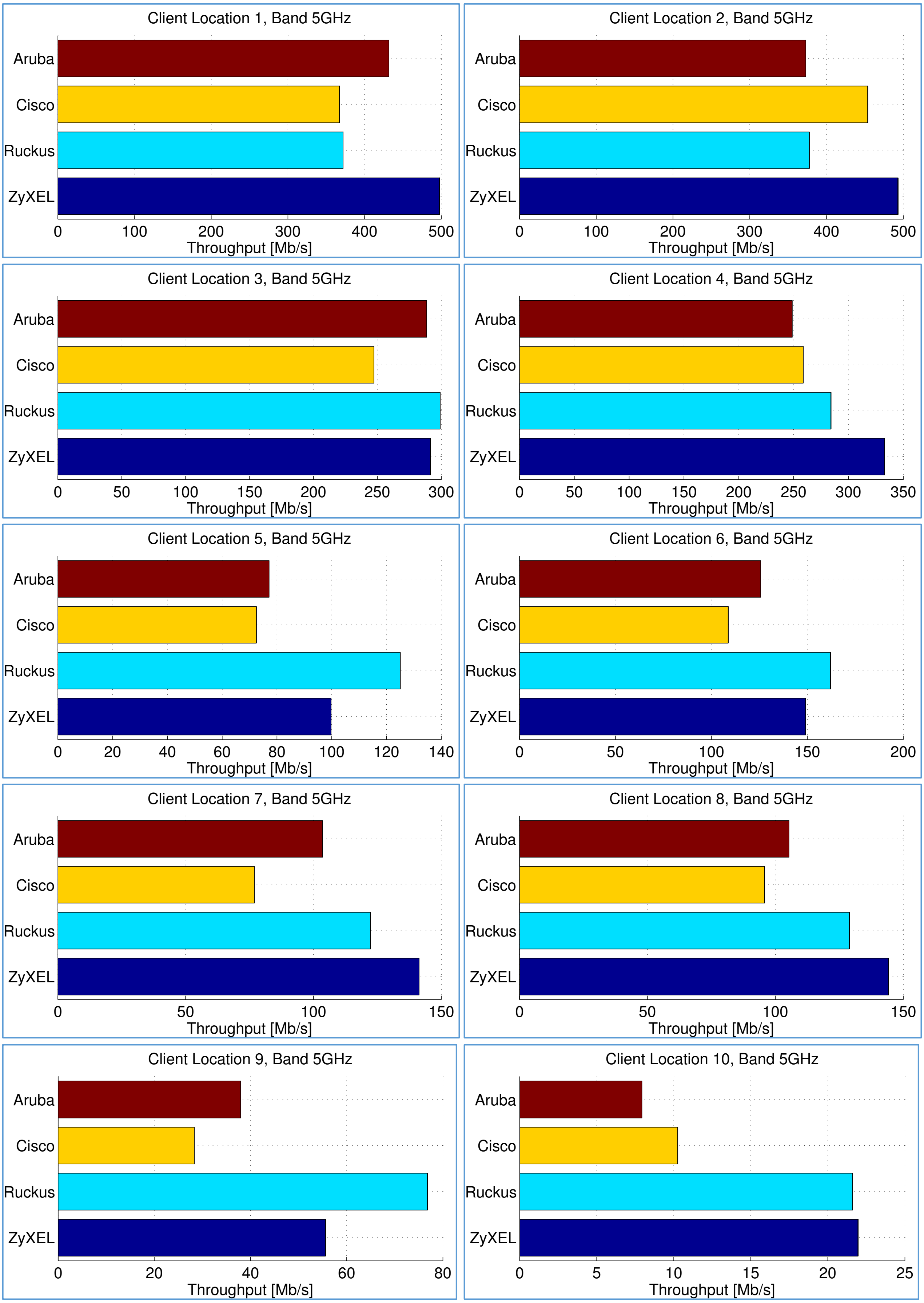
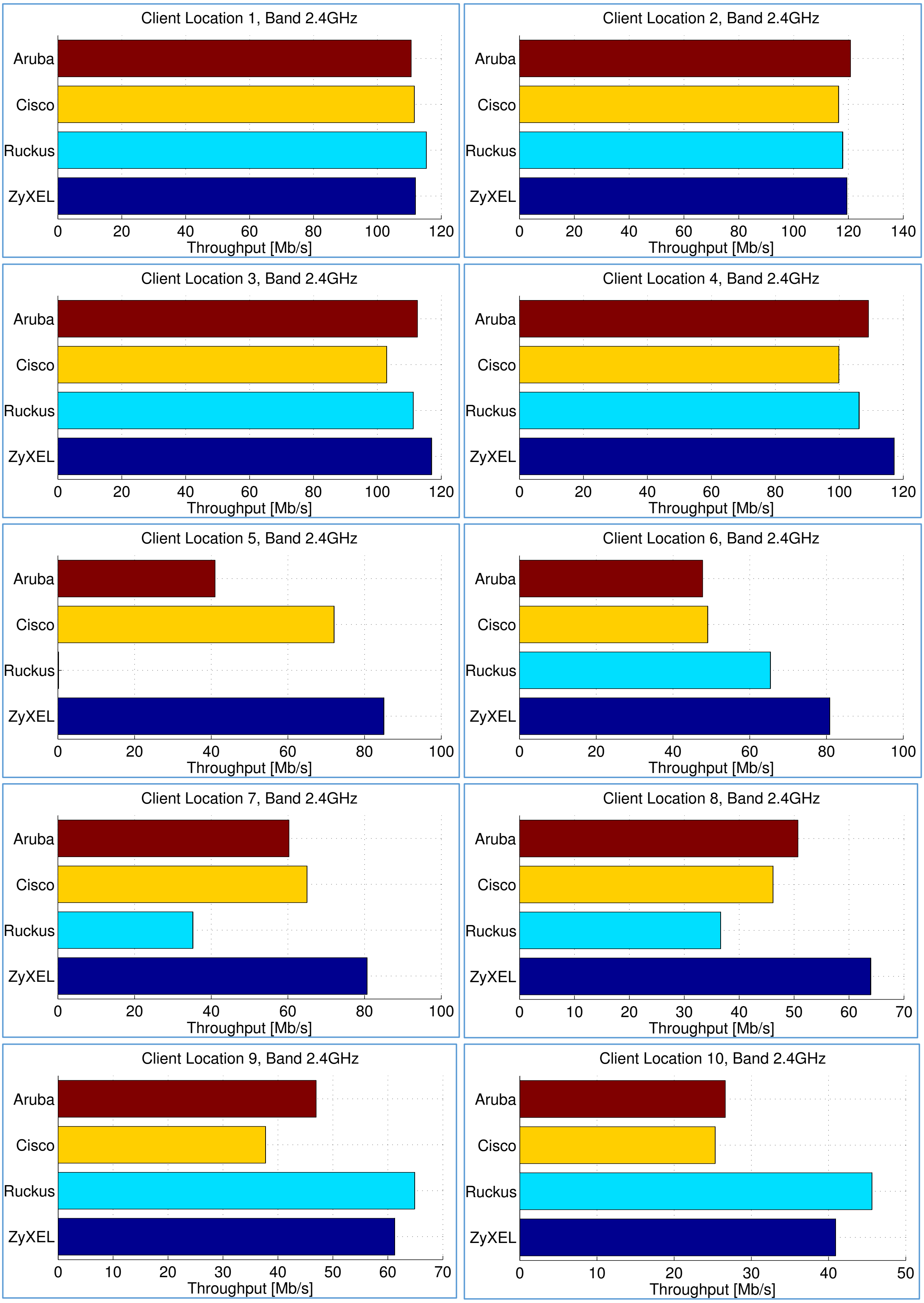
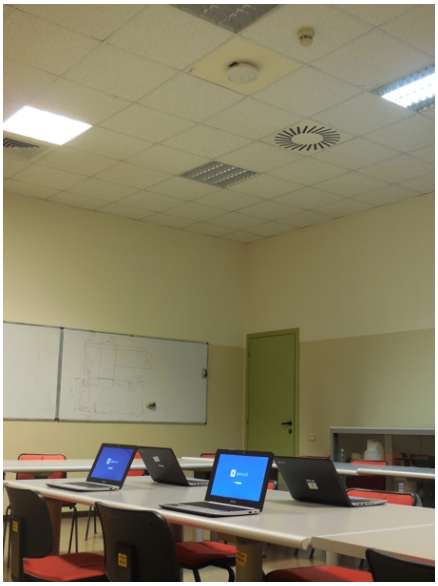


Figure 3 Throughput vs Location difficulty: Band 2.4GHz, downlink

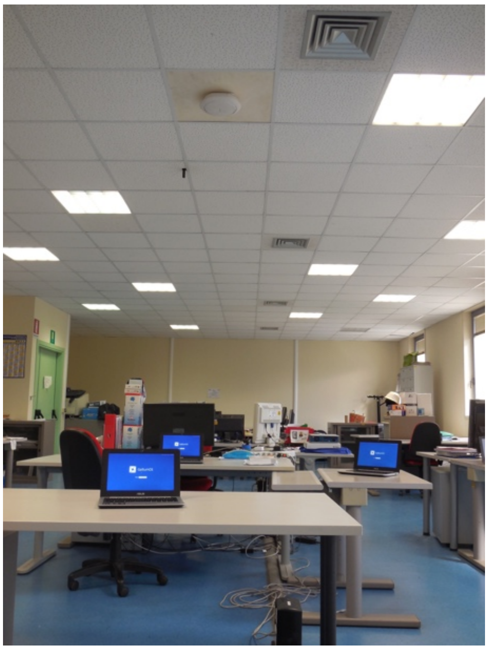


Experiment 2 – Interfering Basic Service Sets: Co-Channel Interference



The increasing adoption of 802.11ac channels could potentially make the 5GHz band very crowded. Spectrum frequencies from the U-NII bands, in fact, have been allocated in such a way that only a few 80/160MHz channels are available, respectively six and two. Furthermore, regulators around the world may even restrict these numbers depending on the specific country.
It follows that in large enterprise networks composed of many APs, the chance of neighboring APs working on the same channel is not negligible making co-channel interference one of the critical technical challenges.
With this test we investigated the potential benefits deriving by the application of SA technology for countering co-channel interference in the 5GHz band. To this end we configured two neighboring APs to operate in the same 80MHz channel 157: we replicated the same scenario for each AP brand keeping the same ceiling mounting positions. More specifically we placed one AP in the same open-space room as before, and the other AP in another meeting room of the Department as reported in Figure 5.

For this test we transmitted downlink data sessions from the two APs to their own associated four clients: we used TCP as transport protocol for reproducing a realistic users' traffic scenario such as web-browsing.



We configured APs with the same transmission power set to 17dBm in order to have fair testing conditions.

Each test was composed of the following phases:

1) association of the clients from a disconnected state to their own BSS leading AP;
2) transmission of three consecutive 60 seconds TCP downlink sessions, from every AP to each of the associated clients.

We then considered the total aggregate throughput of the two BSSs for each of the three transmission tests and we kept the best result for each brand.

We ran experiments for four different deployments of the clients as we report in Figure 4 and Figure 5. More specifically, Figure 4 displays the positions of the clients numbered from 1 to 8 for deployments 1-1 and 1-2: we started with clients in deployment 1-1 and we moved them according to the arrows to get deployment 1-2. Similarly, we display the positions of the clients for deployments 2-1 and 2-2 in Figure 5.

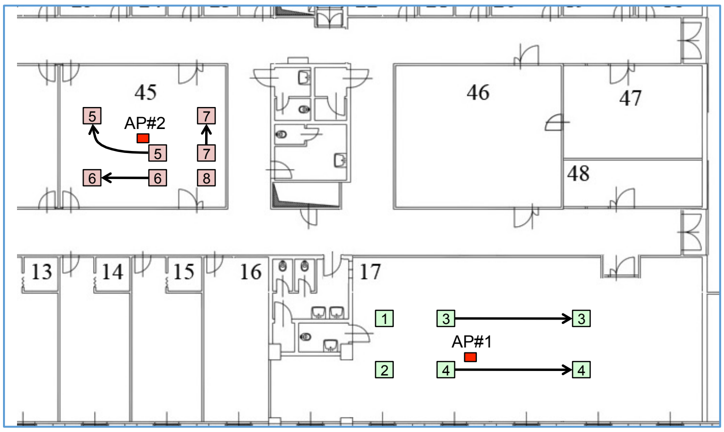


Figure 4 Positions of the clients for deployments 1-1 and 1-2. Transmission power set to 17dBm.

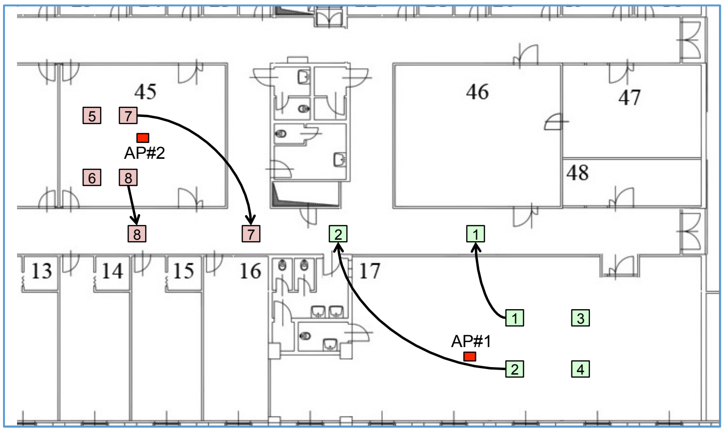


Figure 5 Positions of the clients for deployments 2-1 and 2-2. Transmission power set to 17dBm.

We can see in Table 3 that ZyXEL in the first three deployments boosts the total aggregate throughput from a +25.5% minimum to a +46.7% maximum with respect to the second in the rank that is Cisco. Only in the fourth deployment Cisco does better (+14.6%) than ZyXEL that ranks second. We also compute the average throughput (row "mean") and the percentage gain of the average with respect to the reference (/ in row "gain"): ZyXEL leads with 70% gain.
By comparing ZyXEL to Ruckus, whose average gain is 17%, we conclude that ZyXEL gains 45% with respect to its direct competitor: it follows that a specific SA technology could really make the difference in reducing co-channel interference.

Table 3 Total aggregate throughput per deployment (Mb/s): AP transmission power set to 17dBm

	Aruba	Cisco	Ruckus	ZyXEL
Depl. 1-1	317.81	425.82	402.09	544.98
Depl. 1-2	314.20	439.87	385.11	645.36
Depl. 2-1	303.57	452.95	385.74	568.57
Depl. 2-2	268.44	333.30	237.88	290.68
mean	301.00	412.98	352.70	512.40
gain	/	37%	17%	70%

We report in Figure 6 the details with the throughput delivered by each of the two interfering APs to the clients of its own BSS: we note that the brand winning in the total throughput competition wins also in each of the BSS.

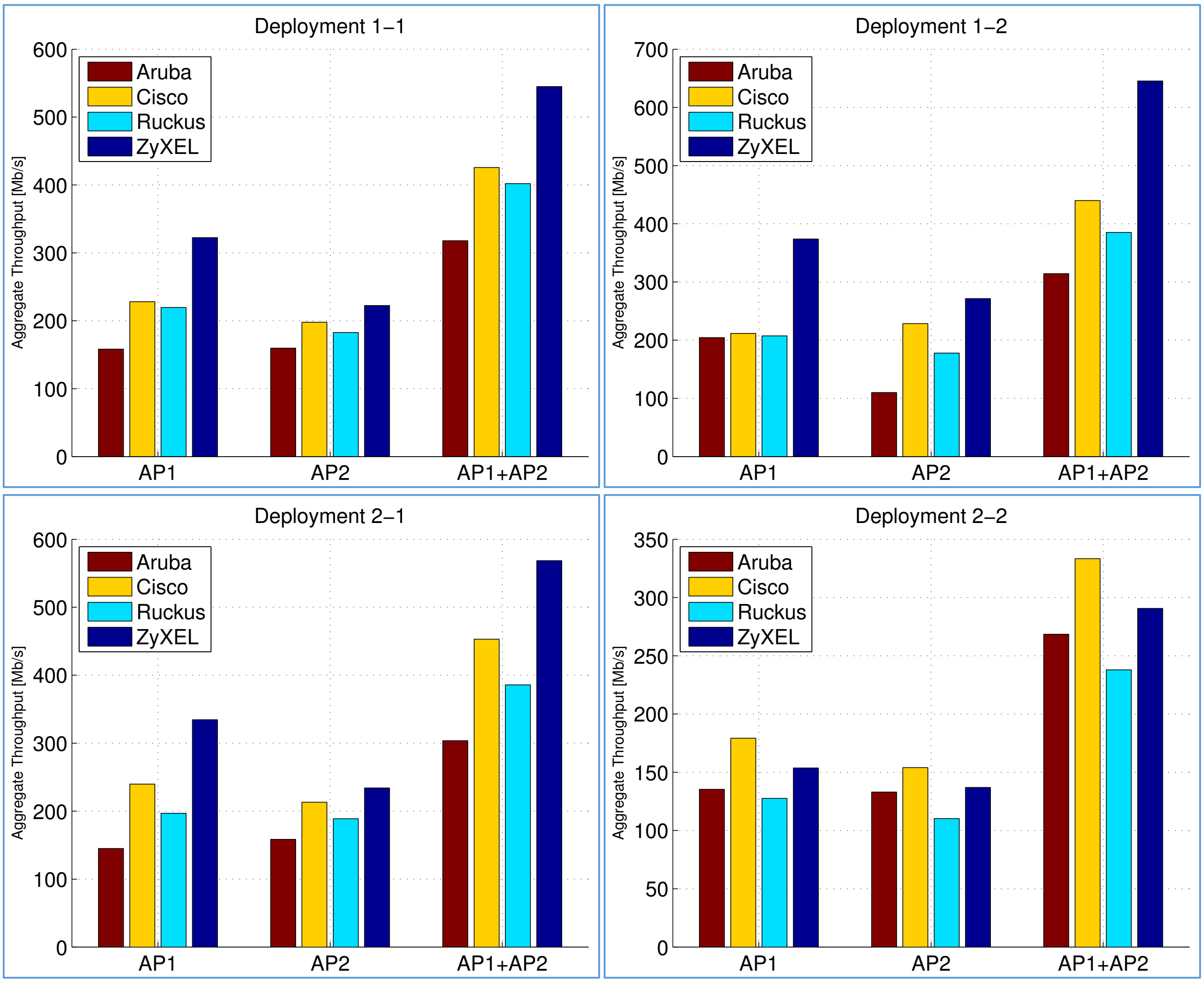


Figure 6 Aggregate throughput delivered by each AP and aggregate per deployment. AP transmission power set to 17dBm

We repeated a very similar test with four additional deployments targeted to analyzing whether SA technology may address the co-channel interference problem also with higher settings of the transmission power: to this end we increased the transmission power of ZyXEL and Ruckus to 23dBm keeping the others to 17dBm. This should increase the interference between the two APs but only for those equipped with SA technology.

As before we report in Figure 7 and Figure 8 the positions of the clients for the four additional deployments. The first two, 3-1 and 3-2, are in Figure 7; the others, 4-1 and 4-2, are in Figure 8. We use again arrows to indicate how we moved nodes from one deployment to the next.

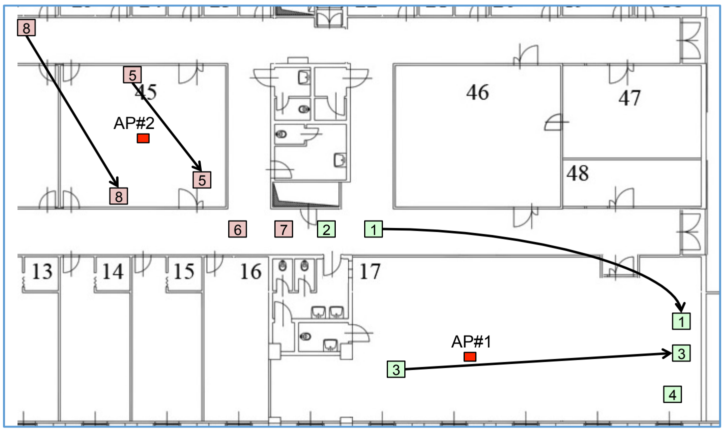


Figure 7 Positions of the clients for deployments 3-1 and 3-2. Transmission power of ZyXEL and Ruckus changed to 23dBm.

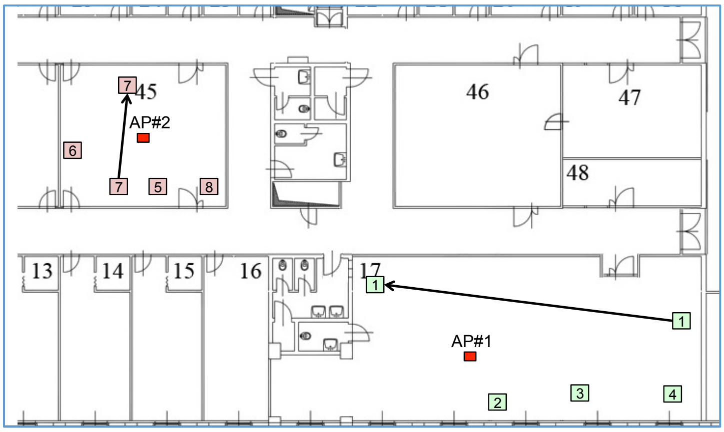


Figure 8 Positions of the clients for deployments 4-1 and 4-2. Transmission power of ZyXEL and Ruckus changed to 23dBm.

As we can see in Table 4 ZyXEL ranks always first with an advantage over Cisco, that ranks always second after ZyXEL, ranging from a +12% minimum up to a +28% maximum. Again we compute the average throughput and the percentage gain with respect to the reference, i.e., the AP with the smaller aggregate throughput: ZyXEL still leads with a 82% gain. The ZyXEL improvement with respect to Ruckus in this case exceeds 40%.

Table 4 Total aggregate throughput per deployment (Mb/s): AP transmission power set to 23dBm for ZyXEL and Ruckus, 17dBm for the others.

	Aruba	**Cisco**	**Ruckus**	**ZyXEL**
Depl. 3-1	220.85	315.28	261.92	353.93
Depl. 3-2	215.42	336.18	280.10	396.35
Depl. 4-1	297.93	448.62	391.25	574.11
Depl. 4-2	295.94	444.03	366.35	546.64
mean	257.53	386.03	324.90	467.76
gain	/	50%	26%	82%

Compared to the previous four deployments the advantage over to the second in the rank is lower. Two are the possible explanations for this result: first, these deployments are slightly different so they cannot be really compared to the previous ones; and second, because of the increased power setting for the ZyXEL, co-channel interference is harder to counter: still, the SA technology of ZyXEL is effective in fighting this challenging issue.

We report in Figure 9 the details with the aggregate throughput per deployment: we note that the AP brand that achieves the best aggregate throughput exhibits the highest per-AP throughput except for deployment five.

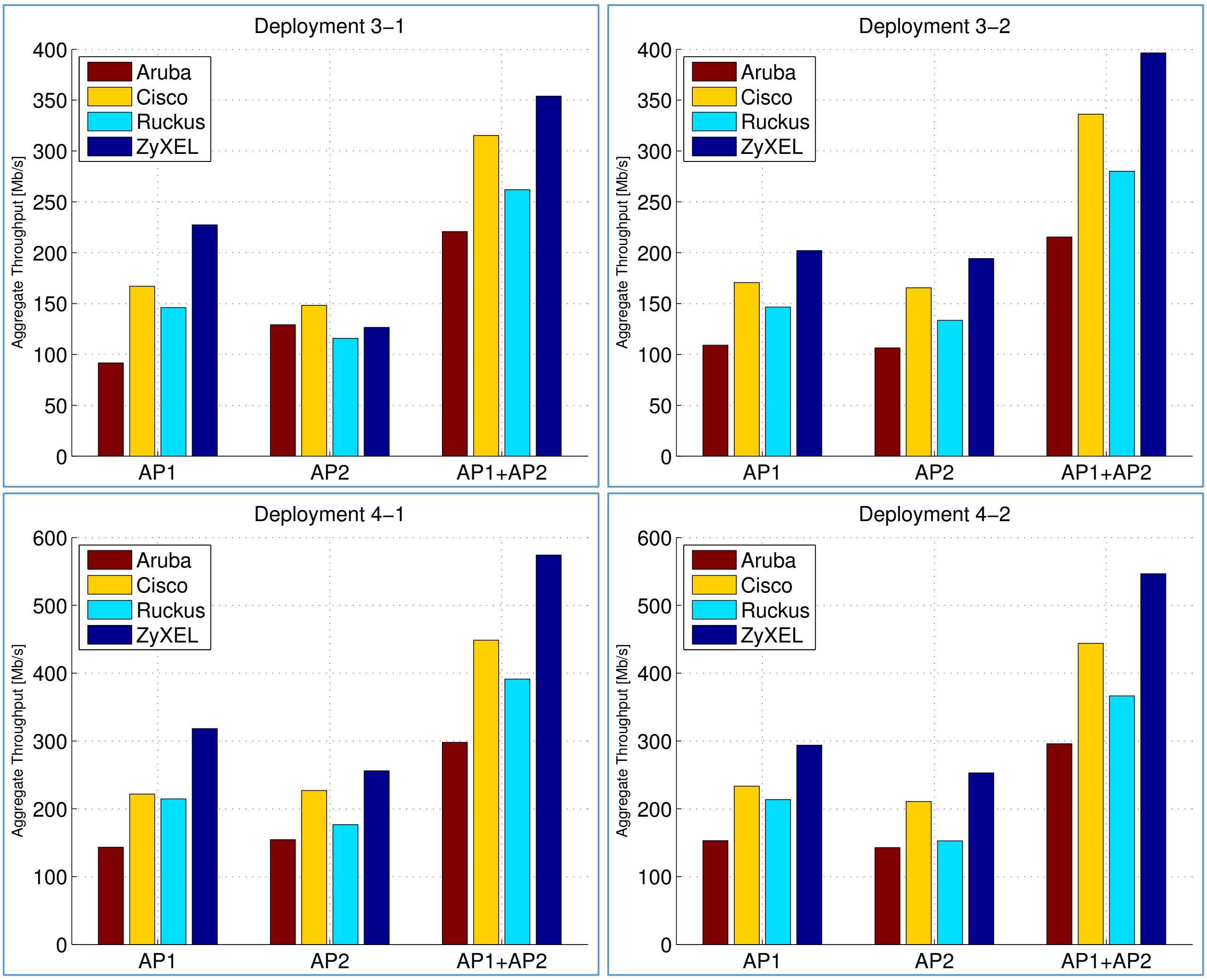


Figure 9 Aggregate throughput delivered by each AP and aggregate per deployment: AP transmission power set to 23dBm for ZyXEL and Ruckus, 17dBm for the others.

Finally, we compute the average gain by considering all the eight deployments: the overall gain achieved by ZyXEL in this case is 75% with respect to the reference and 45% with respect to Ruckus.