Experimental Assessment of RRM Techniques in 5 GHz Dense WiFi Networks Using REMs

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Abstract—**The increasing acceptance of WiFi has created unprecedented levels of congestion in the unlicensed frequency bands, especially in densely populated areas. This results mainly because of the unmanaged interference and uncoordinated operation between WiFi access points. Radio Environment Maps (REM) have been suggested as a support for coordination strategies that optimize the overall WiFi network performance. In this context, the main objective of this experiment is to assess the benefit of a coordinated management of radio resources in dense WiFi networks at 5 GHz band, using REMs for indoor scenarios. It was shown that REMs can detect the presence of interfering links on the network or coverage holes, and a suitable coordination strategy can use this information to reconfigure Access Points (AP) channel assignment and re-establish the client connection, at a cost of diminishing the aggregate throughput of the network. The technique of AP hand-off was tested to balance the load from one AP to another. Using REMs, the Radio Resource Management (RRM) strategy could reconfigure the network to optimize the client distribution among available APs. Although the aggregate throughput is lower after load balancing, the RRM could increase the throughput of the overloaded AP.**

I. Introduction

Today's enterprises, public venues, and businesses of all types are looking for WiFi services to address an urgent need for wireless broadband connectivity. In this context, an important activity is the project, deployment and maintenance of WiFi networks, where capacity, stability and scalability are key design factors. As wireless traffic quickly grows, we expect more and more WiFi access points to be deployed. At this point, interference will be stronger and more unpredictable than traditional wide-area systems, and its management will emerge as one of the key technical challenges. Today's static planning and configuration of WiFi infrastructures requires intense manual work. The dynamic management of WiFi based on Radio Environment Maps (REMs) can potentially improve the wireless local access in a variety of scenarios and business cases. This concept can be introduced in outdoor public swimming pools, shopping malls and football stadiums which are amongst the most challenging locations to deploy a WiFi network. Recent studies have proposed algorithms to optimize the transmit power in multiple WiFi links with overlapping bands [1]. Moreover, the use of efficient of Radio Resource management strategies, supported by REMs, have emerged as a valid combination to optimize spectrum usage [2]. Recently, we conducted a set of experiments in a pseudo-shielded WiFi testbed on the 2.4 GHz Industrial, scientific and medical (ISM) band, to assess the benefit of a coordinated approach for interference management in dense WiFi networks, that make use of realistic Radio Environment Maps [3]. The objective of this paper is to extend this study further, and assess the advantages of RRM in dense WiFi networks in the 5 GHz ISM band. Besides interference management [4], we will also verify the potential of REMs for load balancing [5] and hole detection [6] in WiFi networks.

The paper is structured as follow: After the introduction, we describe the experimental setup in Section II, then Section III presents the experimental measurements and results, and the last section contains the conclusions and future work.

II. Experimental Setup

A. Architecture

The generic setup of the experiment shown in Figure 1 is based on the WiSHFUL software architecture (blue and orange blocks) and uses the UPIN,R and UPIHc interfaces [7]. The Global Control Program is the piece of software that implements the RRM algorithm and strategy that adapts the WiFi devices based on the local observed REM, which is built based on the spectrum sensors.

The RRM follows a strategy that maximizes the overall throughput of the WiFi network, by providing the optimal channel and transmit power to each network node [2].

The testbed setup consists of four major components as briefly explained in the following:

- A network of low-cost spectrum sensors (Wi-Spy USB dongle or any other low-cost device with spectrum sensing capabilities) placed on the field and that report spectrum and interference measurements.
- A REM builder module that computes the radio environmental maps based on the spectrum sensing measurements, the positions and configurations of access point (AP) radio transmitter, indoor propagation models and spatial interpolation algorithms.
- The radio resource manager that runs the algorithms and strategies to optimize the overall WiFi network in

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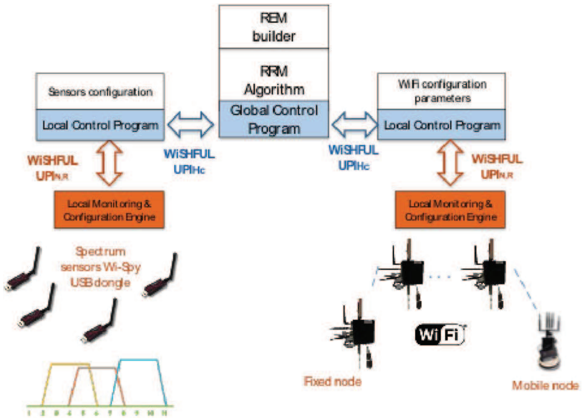


Fig. 1. Generic Setup diagram for the experiment.

terms of channel, bandwidth (i.e. operating mode IEEE 802.11a/b/g/ac) and power allocation.

- WiFi access points that get the configuration settings from the RRM module and report performance metrics to the RRM module. The WiFi configuration and performance metrics reporting will be done through the software interfaces UPIs (Unified Programme Interfaces) provided by WiSHFUL for the IEEE 802.11 hardware platform.

B. *Testbed*

The w-iLab.t testbed (Ghent - Belgium) is a pseudo-shielded environment with more than 50 reconfigurable radio nodes. Figure 2 shows the testing area and the locations of the nodes. We have selected 5 equidistant links in a Client - Server configuration, represented by arrows. The distance between adjacent links is 6 m, and for each link, the distance between the client and the server (AP) is 3.6 m. Each node has one embedded PC (ZOTAC) with two wireless IEEE 802.11 a/b/g/n cards (Spartklan WPEA-110N/E/11n), one Gigabit LAN, and a Bluetooth USB 2.0 Interface and a ZigBee sensor node. The red arrow represents the interfering link with a separation of 6 m between client and AP nodes and 3.6 m from Link 3 and Link 4.

After reserving the nodes, the java-based framework jFed [8] is used to remotely configure the testbed nodes. jFed is also used to activate all 12 nodes, select a disk image for each node, and SSH into the nodes. Three additional nodes were used as omf [9] and oml [10] servers and WiSHFUL controller.

C. *REM builder*

The REM is a dataset of spectrum occupancy computed based on raw spectrum measurements, propagation modelling and spatial interpolation algorithms.
There are several methods to compute REMs available on the literature, with different interpolation approaches and based on time and space spectrum measurements. One of the most commonly used methods is the Inverse Distance Weighted Interpolation (IDW) [11]. Despite the "bull's eyes" effect, this method is relatively fast and efficient, and present good properties for smoothing REM. We have implemented a modified version of IDW method to decrease the sensitiveness to outlier measurements, which calculates the interpolated values using only the nearest neighbour's points.
To compute the REM, the exact position of each radio node on the w-iLab.t testbed area is defined as shown in Figure 2. REMs are computed using Matlab to facilitate the integration with the RRM algorithms, also implemented in Matlab.

III. Experimental Measurements and Results

We ran five different experiments:

- Experiment 1: Considering full co-channel interference between links;
- Experiment 2: Considering non-overlapping channels assignment between links;
- Experiment 3: Channel reallocation triggered by co-channel interference;
- Experiment 4: Load balancing;
- Experiment 5: Hole detection.

Each experiment is structured in four steps:

1) Get spectrum measurements for the WiFi frequency channels in use;
2) Compute the REMs based on spectrum measurements and interpolation algorithms;
3) Measure the throughput of the radio links during 100 seconds, and record the mean value after 50 trials;
4) Apply the RRM strategy, e.g., reconfigure the channel allocation or (and) transmitted power.

A. *Experiment 1 - Considering full co-channel interference*

All APs are configured with the same channel 40 (5200 MHz). The aim is to have a worst-case reference scenario in terms of co-channel interference. All 5 links are sequentially configured with transmit power of 0, 7 and 15 dBm. Using a client-server configuration for each link, the Iperf4 tool [12] reports the measured throughput to the wishful controller, who gathers all the information from measurement files, parses and stores it in a database.
The average values of the measured throughput for each link and the aggregated throughput of the WiFi network are computed and shown in Table I. As expected, the low values of link's throughput are due to the strong co-channel interference that limits the overall performance of the network. This effect is even more pronounced with low transmit power (0 dBm). Note that this is a worst-case reference scenario in terms of co-channel interference.

B. *Experiment 2 - Considering non-overlapping channels assignment*

For this experiment, the APs are configured with non-overlapping channels 40, 44, 48 and variable transmitted power 0 dBm, 7 dBm and 15 dBm. This channel configuration is the baseline for the following Experiments, unless otherwise noted. Links 1 and 4 are configured to use channel 40 (5200 MHz). Links 2 and 5 use channel 44 (5220 MHz) and Link 3 uses channel 48 (5240 MHz).

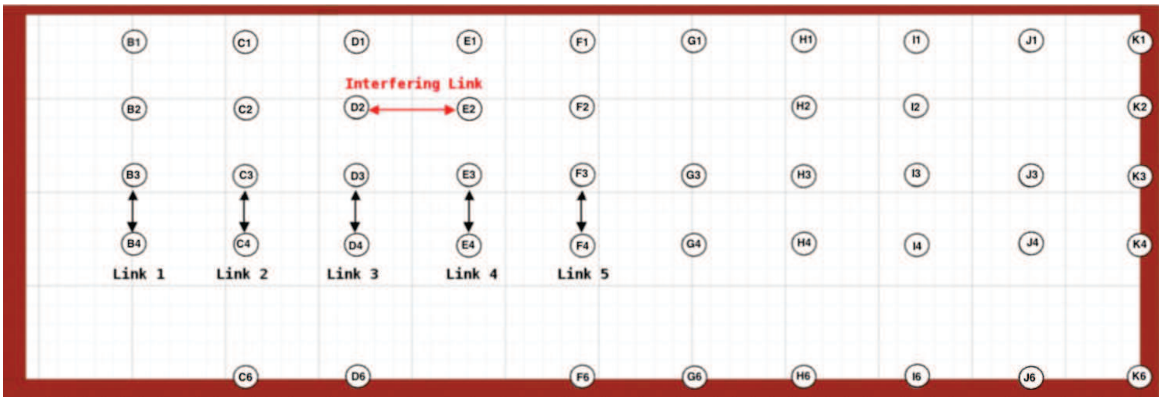


Fig. 2. W-iLab.t testbed environment: Links 1, 2, 3, 4 and 5 are 3.6 m length, Interfering Link is 6 m length.

TABLE I. THROUGHPUT RESULTS FOR EXPERIMENT 1.

Exp. 1	Ch.	Throughput (Mbps) $P_{Tx} = 0$ dBm	$P_{Tx} = 7$ dBm	$P_{Tx} = 15$ dBm
Link 1	40	2.51	8.12	5.68
Link 2	40	0.65	1.80	5.84
Link 3	40	0.94	0.68	5.91
Link 4	40	0.45	0.80	5.86
Link 5	40	3.16	10.04	4.70
Aggregated Throughput (Mbps)		**7.70**	**21.45**	**27.99**

The measured throughput presented in Table II shows the advantage of using no-overlapping channels in the WiFi planning. With a transmitted power of 0, 7 or 15 dBm on each AP, the measured aggregated throughput is approximately three times higher than the value measured in Experiment 1, for the same power. The aggregate throughput is proportional to the transmitted power, but this increase will also bring higher intra-network interference between Link 1 and Link 4, and between Link 2 and Link 5.

TABLE II. THROUGHPUT RESULTS FOR EXPERIMENT 2.

Exp. 2	Ch.	Throughput (Mbps) $P_{Tx} = 0$ dBm	$P_{Tx} = 7$ dBm	$P_{Tx} = 15$ dBm
Link 1	40	1.13	13.36	15.03
Link 2	44	2.41	3.94	14.87
Link 3	48	21.18	29.53	29.44
Link 4	40	2.46	2.60	15.05
Link 5	44	3.03	10.00	12.54
Aggregated Throughput (Mbps)		**30.22**	**59.43**	**86.94**

C. Experiment 3 - Channel reallocation triggered by co-channel interference

The initial setup for Experiment 3 has a non-overlapping channels allocation identical to Experiment 2, with an additional interference Link configured at Channel 48 and a transmit power of 15 dBm, located at 7 m from Link 3 client node, as depicted in Figure 2.

The computed REM during Experiment 3 at channel 48 is shown in Figure 3a. A REM uses the spectrum measurements from the Received Strength Signal Indicator (RSSI) files and the IDW interpolation algorithm, with a 10 cm grid. The color gradient represents the computed power in dBm for a channel at location (x, y). The location of the nodes is added as an additional layer (black circles), with the links represented with a black arrow. The yellow dots are due to the ”bull's eye” effect typical of the IDW interpolation algorithm and should be discarded.

By observing the REM is possible to detect not only Link 3 AP activity, but also the extra radio signal activity coming from the interfering link AP. Note that the detection of this interfering link will trigger the RRM strategy in the WiFi network.

The results from Table III shows an overall network throughput decrease, compared with the results from Experiment 2, mainly due to the interference from the interfering link on Link 3.

TABLE III. THROUGHPUT RESULTS FOR EXPERIMENT 3 BEFORE CHANNEL REASSIGNMENT.

Exp. 3	Ch.	Throughput (Mbps) $P_{Tx} = 0$ dBm	$P_{Tx} = 7$ dBm	$P_{Tx} = 15$ dBm
Link 1	40	1.38	12.20	15.06
Link 2	44	3.41	3.11	14.67
Link 3	**48**	**12.44**	**15.05**	**14.97**
Link 4	40	3.09	2.36	15.10
Link 5	44	2.96	8.93	15.20
Aggregated Throughput (Mbps)		**23.29**	**41.64**	**72.43**

As shown in Figure 3a, the REM allows the detection of the interfering link in channel 48. The RRM strategy implemented in this scenario reallocates the WiFi channels among the APs, to avoid the strong co-channel interference. Links 1 and 5 are reconfigured for channel 48, Link 2 and Link 4 are now using channel 44 and Link 3 uses channel 40. The REM for channel 48, depicted in Figure 3b, shows a clear spatial separation between the interference source and Links 1 and 5, even when the interferer transmits 15 dBm.

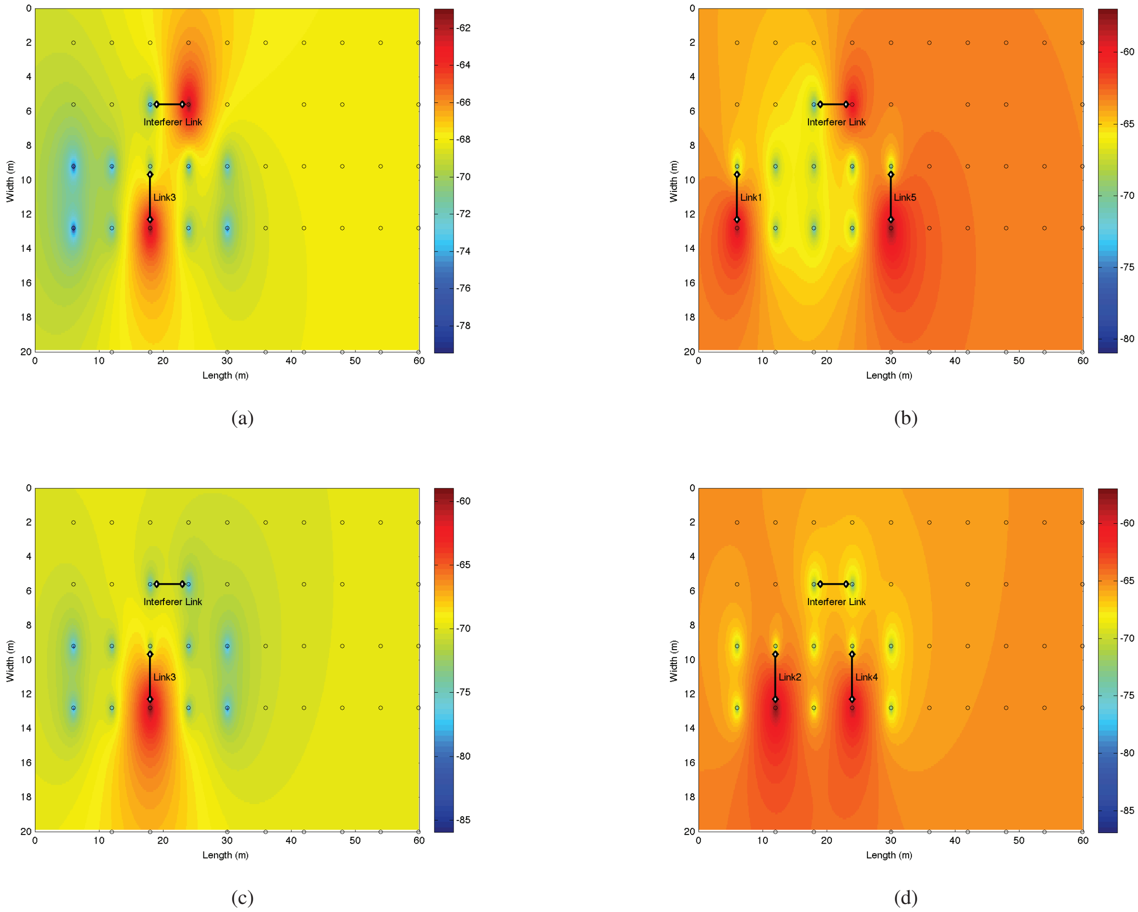


Fig. 3. REMs for Experiment 3 before RRM strategy: (a) Link3 at Channel 48 with 0 dBm EIRP. Interferer Link at Channel 48 and 15 dBm. REMs for Experiment 3 after the RRM strategy: (b) Channel 48; (c) Channel 40 and (d) Channel 44.

Table IV shows an overall throughput increase because of the RRM strategy. With 7 dBm transmit power, the aggregate throughput is now closer to the values obtained with Experiment 2, i.e., without any interference Link.

TABLE IV. THROUGHPUT RESULTS FOR EXPERIMENT 3 AFTER CHANNEL REASSIGNMENT.

Exp. 3	Ch.	Throughput (Mbps) $P_{Tx} = 0$ dBm	$P_{Tx} = 7$ dBm	$P_{Tx} = 15$ dBm
Link 1	48	0.81	2.04	10.08
Link 2	44	2.45	7.79	13.90
Link 3	**40**	**15.66**	**25.77**	**29.21**
Link 4	44	1.58	14.62	15.59
Link 5	48	4.54	6.88	7.32
Aggregated Throughput (Mbps)		**25.03**	**59.10**	**76.10**

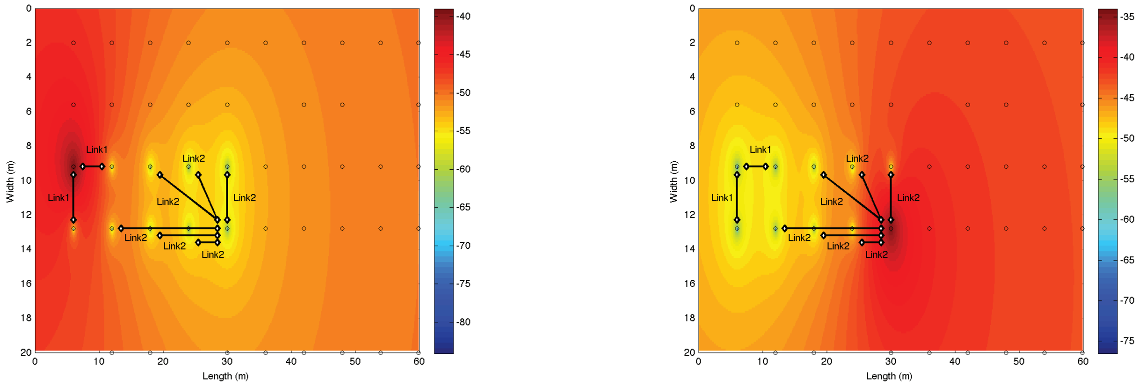
D. Experiment 4 - Load balancing

Client load balancing is a technique to distribute wireless traffic more efficiently among wireless access points. The most usual types of client load balancing are AP hand-off or frequency hand-off. During Experiment 4, the RRM algorithm can select both AP Hand-off or frequency hand-off technique combined with REM information, to select the best channel / transmit power. The initial network was configured per the distribution in Figure 4a and 4b. Node B3 is the AP for Link 1, with two clients (nodes B4 and C3). The AP was configured with 10 dBm transmitting power, 54 Mbps bandwidth and set to channel 40.

Node F4 is the AP of Link 2, and nodes F3, E3, E4, D3, D4 and C4 are the clients. The AP was configured with 16 dBm transmitting power, 54 Mbps bandwidth and set to channel 44. In Figure 4, the REMs show a higher intensity map for channel 44 (Figure 4b), as compared with the figure for channel 40 (Figure 4a), since Link 2 AP has a higher transmit power than Link 1 AP.

The RRM algorithm used for access point hand-off wireless load balancing, involves the following:

- Use REM maps information to check for channel activity and relative power of each AP.
- If the throughput of an AP falls below a threshold (5 Mbps for example), then the clients with the weakest



(a) (b)

Fig. 4. REM before load balancing for: (a) Link 1 (Channel 40) and (b) Link 2 (Channel 44).

RSSI signals are signalled by the RRM to drop off and join another AP.

The mean throughputs on Link 1 and Link 2 are presented in Table V. The result shows that Link 2 is overloaded and the throughput (3.24 Mbps) falls below the predefined threshold. Aggregated throughput is higher than 18 Mbps, since Link 1 is less busy, with only two clients.

TABLE V. Throughput results for Experiment 4.

Exp. 4	Link 1	Link 2	**Aggregated Throughput**
Channel	40	44	**(Mbps)**
Without load balancing			
Number of clients	2	6	
Throughput (Mbps)	15.03	3.24	**18.27**
With load balancing			
Number of clients	4	4	
Throughput (Mbps)	7.24	5.23	**12.97**

When the RRM algorithm is applied to the network, two clients are dropped off Link 2 and joins Link 1 AP. The transmit power for both AP is now 13 dBm, and the channel distribution remains the same.

E. Experiment 5 - Hole detection

This experiment is aimed at detecting coverage holes on the network, based on REMs, and then implement a RRM strategy to increase the transmit power of adjacent APs next to the clients with poor or non-existent connection with their former AP.

Initially, the AP of each link is set to transmit power at 10 dBm. Links 1 and 4 are configured at channel 40, Links 2 and 5 at channel 44, and Link 3 at channel 48. Table VI shows that the overall throughput is 87.42 Mbps in these conditions.

The next step was to shut down the AP of Link 3, leaving the corresponding client without a connection. When the new REM is computed for channel 48 (Link 3), the RRM algorithm use this map to detects the absence of a signal from Link 3 AP, and reconfigure adjacent APs to increase their transmit

TABLE VI. Throughput results for Experiment 5 before hole detection.

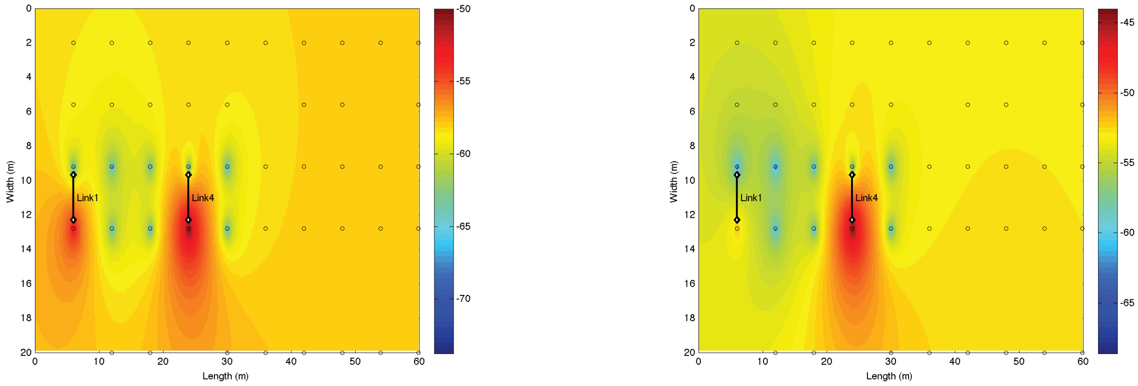
Exp. 5	Channel	Throughput (Mbps) $P_{Tx} = 10$ dBm
Link 1	40	15.02
Link 2	44	14.56
Link 3	48	29.42
Link 4	40	15.00
Link 5	44	13.41
Aggregated Throughput (Mbps)		**87.42**

power. For that scenario, the transmit power from Links 2 and 4 AP's are increased to 16 dBm. The REMs computed for this scenario are presented in Figure 5b. The computed REM after the RRM decision clearly shows the increased transmit power from Link 2 and Link 4 AP's, as compared to the initial configuration presented in Figure 5a.

This action gives to the former Link 3 client the option to select and connect to the best AP, based on RSSI (AP 4 in this experiment). From Table VII, the overall throughput obtained with that decision is now 47.87 Mbps, lower than in the previous conditions (Table VI). However, the RRM algorithm managed to connect all clients, even with the loss of one AP, at the cost of an overall throughput reduction. The resulting throughput for Link 3 and Link 4 is 4.22 Mbps and 5.73 Mbps, respectively, with an aggregate throughput of 9.95 Mbps. Although the resulting aggregate throughput is lower than before, the traffic load is now efficiently distributed between both APs.

TABLE VII. Throughput results for Experiment 5 after hole detection.

Exp. 5	Channel	Throughput (Mbps) $P_{Tx} = 16$ dBm	$P_{Tx} = 10$ dBm
Link 1	40	-	9.76
Link 2	44	15.14	-
Link 3 Link 4	40	9.95	-
Link 5	44	-	13.02
Aggregated Throughput (Mbps)		**47.87**	



(a) (b)

Fig. 5. REM for Experiment 5: (a) before AP 3 switch-off and (b) after AP 3 switch-off.

IV. Conclusion

The performance of a WiFi network depends on smart and assertive RRM techniques. As an example, for the network under test in the w-iLab.t testbed on the 5 GHz band, we got an aggregated throughput of 28 Mbps in a full co-channel interference scenario and 86.9 Mbps, using a configuration of non-overlapping channels.

The spatial interpolation algorithm IDW is suitable to compute REMs for large indoor areas. It was shown that based on the observation of REMs, it is possible to detect the presence of co-channel interfering links in the network.

The RRM that automatically reallocates WiFi channels to avoid channel overlapping from an external interferer is very beneficial. On the 5 GHz band, the aggregated throughput with the w-iLab.t testbed goes from 72.4 Mbps to 77.1 Mbps, the link under interference goes from 14.8 Mbps to 29.2 Mbps.

It was shown that REMs are capable of detecting coverage holes on the network, and a suitable RRM strategy can use this information to reconfigure the AP transmit power to re-establish the client connection, but at the cost of diminishing the aggregate throughput of the network, from 87.4 Mbps to 47.9 Mbps.

The technique of AP hand-off was tested to balance the load form one AP to another. Using REMs combined with additional inputs, the RRM strategy could reconfigure the network to optimize the client distribution among available APs. Although the aggregate throughput is lower after load balancing (from 18.3 Mbps to 12.97 Mbps), the RRM could increase the throughput of the overloaded AP, from 3.2 Mbps to 5.7 Mbps.

Overall, we conclude that a RRM strategy increases the capacity of links under strong interference, and can overcome networks hole coverage or unbalanced cells, however this gain comes with the cost of a relatively high dense network of spectrum sensors (each AP has it own sensor), increasing the cost of deployment.

Acknowledgment

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