Experimental Assessment of WiFi Coordination Strategies Using Radio Environment Maps

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***Abstract*—The rapidly increasing popularity of WiFi has created unprecedented levels of congestion in the unlicensed frequency bands, especially in densely populated urban areas. This results mainly because of the uncoordinated operation and the unmanaged interference between WiFi access points. 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 for both 2.4 GHz and 5 GHz bands, using Radio Environment Maps (REM). This experiment has used the w-iLab.t test environment and the portable test-bed provided by iMINDS for indoor scenarios. It was shown that REMs can detect the presence of interfering links on the network (co-channel or adjacent channel interference), and a suitable coordination strategy can use this information to reconfigure Access Points (AP) channel assignment and re-establish the client connection. The coordination strategy almost double the capacity of a WiFi link under strong co–channel interference, from 6.8 Mbps to 11.8 Mbps, increasing the aggregate throughput of the network from 58.7 Mbps to 71.5 Mbps. However, this gain comes with the cost of a relatively high-density network of spectrum sensors, increasing the cost of deployment. The technique of AP hand-off was tested to balance the load form one AP to another, although the aggregate throughput is lower after load balancing. REMs are also capable of detecting coverage holes on the network, and a suitable Radio Resource Management strategy use this information to reconfigure the APs transmit power to re-establish the client connection and increase the throughput of the overloaded AP, at a cost of diminishing the aggregate throughput of the network. The insights coming out from this experiment helped to understand the opportunities and limitations of WiFi coordination strategies in realistic scenarios.**

***Index Terms*—*Radio Environment Map*; *Portable Radio Test-bed*; *Radio Resource Management*; *WiFi*; *Interference Management*; *Load Balancing*.**

I. INTRODUCTION

During the last fifteen years, the WiFi technology, as a last mile access to Internet, has experienced global explosion. Nowadays, the WiFi networks carry more traffic to and from end-user's terminals (PCs, tablets, and smartphones) than Ethernet and cellular networks combined. The success of this technology is owed to its introduction in unlicensed spectrum (ISM bands), which has furthermore allowed unprecedented innovation in the wireless technology. However, as the penetration of WiFi continues, the unlicensed bands are becoming overcrowded. Unpredictable user-deployed hot spots (smartphone) are a new source of interference and instability that can undermine the network performance. Moreover, many Internet of Things (IoT) devices also share the unlicensed spectrum with WiFi, which further increases the problem scale.

In fact, interference is a limit factor of WiFi densification; this is a result mainly because of the uncoordinated operation and the unmanaged interference between the WiFi Access Points (AP). In WiFi, each Access Point can only access locally available sensing information within single cell coverage. It cannot access global knowledge on a multi-AP network and the deployment environment, leading to a sub-optimal network configuration.

In this context, the design of the WiFi networks is complex because of the high-density of users and significant variability of capacity requirements that can be strongly dependent on location and time. The variability of the capacity demand can be faced by deploying a dynamic network infrastructure, in which WiFi access points can be switched on and off, can work on different bands, and can tune their coverage range from the network status and QoS requirements.

This paper is organized in five sections. After the introduction, the second section describes the background and the motivation of the work. In Section III, we describe the test-beds and define the setup environment of the experiments. The fourth section presents the experimental results with different measurements and scenarios. Conclusions and future work are drawn in Section V.

II. BACKGROUND

Recently, we conducted a set of experiments in a pseudo-shielded WiFi test-bed, to assess and verify the benefit of a coordinated approach for interference management in dense WiFi networks on the 2.4 GHz ISM band, which make use of realistic Radio Environment Maps (REM) [1]. Other research work also supports that the REM of the target coverage area is an important input for interference management and coordination strategies [2]; Other studies have recently demonstrated the potential economic value of WiFi coordination in dense indoor experiments [3] or proposed a secured framework to achieve optimal RRM in residential networks, using distributed channel assignment algorithm [4]. Thus, the use of efficient of Radio Resource Management (RRM) strategies, supported by REMs, have emerged as a valid combination to optimize spectrum usage [5].

The REM is a dataset of spectrum occupancy and interference levels computed based on raw spectrum measurements, propagation modeling and spatial interpolation algorithms [6]. Radio Resource Management (RRM) algorithms can use REMs to optimize the overall network performance.

In [1], we experimentally verified that a coordinated approach of the RRM of channel frequency and power, combined with the use of REMs, can increase the performance of WiFi networks in dense deployment scenarios. To extend this study further, the main objective of this experiment is to assess the benefit of a coordinated approach in dense WiFi networks also in the 5 GHz ISM band, using realistic Radio Environment Maps and an implementation-oriented approach in two wireless environments: the pseudo-shielded test-bed w-iLab.t, and a common office building. Besides interference management, we will also verify the potential of REMs for load balancing and hole detection in WiFi networks. An important performance metric is the gain in terms of average throughput, comparing the coordinated approaches with the legacy uncoordinated approach. We are interested in measuring the average capacity gain, when using market available and low-cost spectrum sensors in very dense indoor scenarios. The results of this experiment are very useful from a business perspective and industrial research, to realize if the actual coordination gain is sufficient enough to justify the investment in the sensing and the signaling infrastructure needed to implement a WiFi coordination scheme in realistic scenarios [6].

III. Experimental Setup and Architecture

This section defines and describes in detail the setup environment. The experiments were divided in two distinct phases:

- Phase 1: Assessment of WiFi coordination in dense indoor scenario using the w-iLab.t test-bed, at 2.4 GHz.
- Phase 2: Assessment of WiFi coordination in dense indoor scenario (two floor building) using a portable test-bed, at 2.4 GHz and 5 GHz.

For each of the two phases, we ran several experiments:

- Intra-network co-channel interference;
- Intra-network adjacent-channel interference;
- Non-overlapping (optimal) channels assignment;
- Channel reallocation triggered by external interferences;
- Load balancing;
- Hole detection.

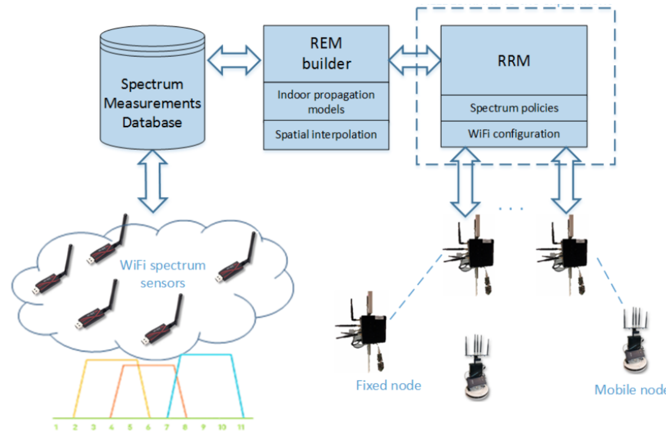


Fig. 1. Generic Setup diagram for the experiment.

A. Setup architecture

The setup diagram of the demonstrator, depicted in Figure 1, encompasses four major components, as briefly explained in the following:

- A network of spectrum sensors (energy detectors) that report spectrum measurements to a database.
- A REM builder module that computes the radio environmental maps based on measurements stored in the spectrum database, the positions/configurations of radio transmitters (AP), indoor propagation models and spatial interpolation algorithms.
- The RRM that optimizes the overall WiFi network in terms of channel and power allocation based on the REM.
- WiFi APs that receive the configuration settings and reports performance metrics to the RRM module.

B. Test-bed and resources allocation

Besides the available WiFi hardware, both portable and w-iLab.t test-bed offers several software tools to setup, control and gather radio measurements. We used the java-based framework jFed [7] to configure the test-bed nodes. jFed is also used to activate nodes, install the Operating System, and SSH into the nodes. OMF6 [8] controls all the experiments, using scripts written with OMF Experiment Description Language (OEDL) [9], which is based on the Ruby programming language. The experiment description with OMF6 is structured in two main steps:

1) First, we declare the resources to be used in the experiment, such as applications, nodes, and related configurations, such as Wi-Fi channels and transmitted power;
2) In the second step, we define the events that triggers the experiment's execution, and the tasks to be executed.

The Iperf traffic generator tool [10] generates data for each link using a client – server configuration. All links parameters are recorded during 100 s for all experiments. This ensures that the radio signals for the links under test are on the air and stable. The measurements data are extracted during the experiment using OML [11]. OML is a stand-alone tool that parses and reports all the measurements to a database (SQLite3 or PostgreSQL) installed on the experiment controller server of the test-bed.

1) Phase 1 – w-iLab.t test-bed: All experiments took place in a shielded environment in the w-iLab.t test-bed (Ghent – Belgium), a cognitive-radio test-bed for remote experimentation [12]. The nodes are installed in an open room (66 m by 21 m) in a grid configuration. Figure 2 shows the testing area and the locations of the nodes, represented by black numbered circles. Each node has one embedded PC (ZOTAC) with two wireless IEEE 802.11 a/b/g/n cards (Spartklan WPEA–110N/E/11n), a spectrum sensor (Wi-Spy USB spectrum analyzer), one Gigabit LAN, and a Bluetooth USB 2.0 Interface and a ZigBee sensor node [13].

We have selected 5 equidistant links in a client – server configuration, represented by a black arrow in Figure 2. The distance between adjacent links is 12 m, and for each link, the distance between the client node and the AP node is 3.6 m. The red arrow represents the interfering link, with a separation of 12.5 m between nodes.

2) Phase 2 – Portable test-bed: The second phase of the experiment took place on a building at the School of Technology – Polytechnic Institute of Castelo Branco. The building is 60 m by 25 m wide. The building is divided in two floors, as depicted in Figure 3(a) (Floor 0) and Figure 3(b) (Floor 1). The walls are 20 cm thick and built with clay bricks and concrete, and the separation floor is made of 50 cm thick reinforced concrete. A staircase give access to both floors as depicted on the bottom left corner of both figures. Each WiFi node has one Intel NUC Embedded PC (NUC), with a wireless IEEE 802.11 a/b/g/n Qualcomm Atheros AR928X (PCI-Express), a spectrum sensor (Wi-Spy USB spectrum analyzer) and one Gigabit LAN interface.

Two radio links were installed on Floor 0:

- Link 2 connects NUC8 (client) and NUC7 (AP). The nodes are located next to the ceiling of a corridor, with Line of Sight (LOS) condition between nodes (Figure 3(a)). The distance between nodes is 8.5 m.
- Link 3 connects NUC6 (client) and NUC3 (AP). As already explained before, NUC6 is located on Floor 0, below NUC3. The dashed line from NUC3 and NUC6 represent the best propagation path between nodes, through the staircase between Floor 0 and Floor 1. The distance between NUC7 and NUC6 is 13.4 m.

Three radio links were installed on Floor 1:

- Link 4 connects NUC1 (client) and NUC2 (AP). The nodes are located on separated rooms with no Line of Sight (NLOS) between nodes (Figure 3(b)). The distance between nodes is 9.6 m.
- Link 1 connects NUC5 (client) and NUC4 (AP). The nodes are located on a corridor with LOS between nodes (Figure 3(b)). The distance between nodes is 9.5 m.
- Link 3 connects NUC6 (client) and NUC3 (AP). NUC6 is located on Floor 0, below NUC3. The dashed line from NUC3 and NUC6 represent the best propagation path between nodes, through the staircase between Floor 0 and Floor 1.

The distance between NUC2 and NUC3 is 12 m.

C. Radio Environment Map builder

The REM is a dataset of spectrum occupancy computed based on raw spectrum measurements, propagation modeling and spatial interpolation algorithms.

There are several methods to compute REMs available on the literature, with different interpolation approaches and based on space and time spectrum measurements. One of the most commonly used methods is the Inverse Distance Weighted Interpolation (IDW) [6]. Despite the "bull's eyes" effect, this method is relatively fast and efficient, and presents good properties for smoothing REM. To decrease the sensitiveness to outlier measurements, we have implemented a modified version of IDW method, which calculates the interpolated values using only the nearest neighbor's points.

To compute the REM, the exact position of each radio node on the w-iLab.t test-bed 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.

D. RRM coordinating strategies

The RRM optimizes the overall WiFi network configuration in terms of channel, and power allocation based on the information provided by the REM. The adopted RRM strategies during the experiments are the following [2]:

- Strategy 1: Allocate the WiFi links to disjoint, non-overlapping bands and use minimum possible transmit power for each WiFi link;
- Strategy 2: Optimize the transmit power of multiple WiFi links, when interference is detected.

IV. Measurements

After describing the setup architecture and the test-bed resources, we will explain the experimental measurement campaigns. Each set of measurement aims at studying the influence of measurable interference characteristics on the throughput of the WiFi network under study. The process was structured in four steps:

1) Spectrum measurements from the spectrum sensors in all WiFi frequency channels;
2) Compute the REMs based on spectrum measurements and IDW algorithm;
3) Measure and record the throughput of the radio links;
4) Apply the coordination strategy, e.g., reconfigure the channel allocation or the transmitted power of each APs.

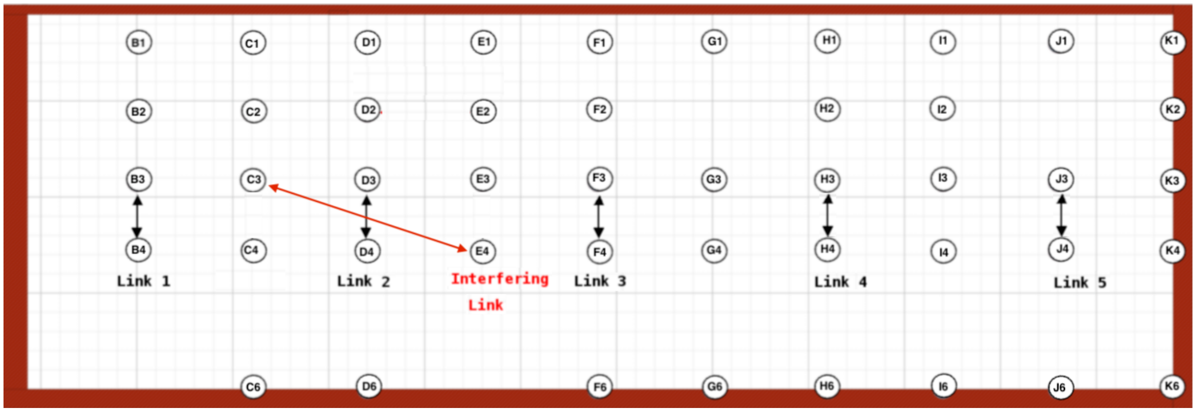
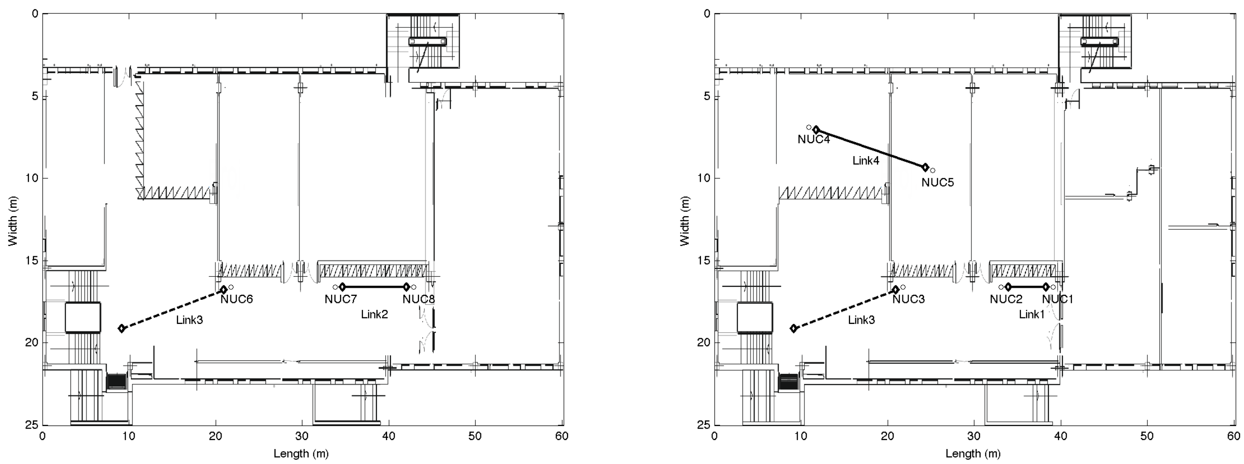


Fig. 2. w-iLab.t test-bed environment (Phase 1): Distance between AP and client is 3.6 m for Links 1, 2, 3, 4 and 5, and 12.5 m for the Interfering Link.



(a) (b)

Fig. 3. Portable test-bed (Phase 2): (a) Floor 0 of the building, with the location of Link 2 (NUC7 and NUC8). Link3, represented with a dashed line, connects NUC6 and NUC3, installed on Floor 1; (b) Floor 1 of the building, with the location of Link 1 (NUC1 and NUC2) and Link 4 (NUC4 and NUC5). Link 3, represented with a dashed line, connects NUC3 and NUC6, located on Floor 0.

A. Phase 1 – w-iLab.t test-bed

1) Estimation of the path-loss propagation model: Having a suitable propagation model is a key element to build good REMs, therefore before running the experiments, we have measured the path loss between the clients and the APs in the w-iLab.t test environment to estimate the propagation model parameters. Since most of the nodes are in Line–of–Sight (LoS) and relatively closed to each other, as shown in Figure 2, we have considered a Free Space Path Loss (FSPL) model:

$$L = n\left(10log_{10}\left(d\right) + 10log_{10}\left(f\right)\right) + 32.45\,(\text{dB}) \qquad (1)$$

Where L is the path loss in dB, d is the distance in meters, f is the frequency in GHz and n is the path loss exponent, which is 2 in the FSPL model. The path-loss measurement process was implemented as follows:

1) Setup one node as an AP with 5 dBm transmit power (P_{Tx}) on WiFi Channel 1 ($f = 2.412$ GHz), and all the other nodes as clients.
2) For each client:
   - Measure the Received Signal Strength Indication (RSSI) of the AP, denoted as P_{Rx}.
   - Measure the distance d between the client and the AP.
3) Setup a different node as AP and the remaining nodes as clients.
4) Repeat steps 1), 2) and 3).

The blue dots on Figure 4 represent the results of the measurement campaign.

Considering Friis transmission equation, $L = P_{Tx}\,(\text{dBm}) - P_{Rx}\,(\text{dBm})$, combined with (1), we compute an estimate of the path loss exponent n [14],

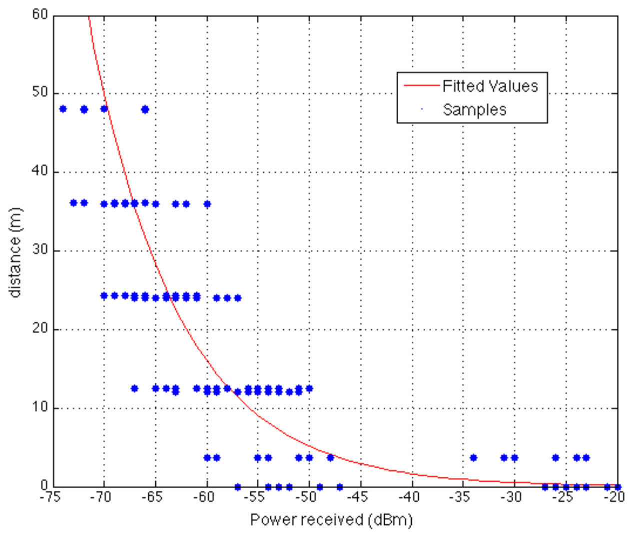


Fig. 4. RSSI measurement campaign (blue dots) and corresponding fitting curve (red line).

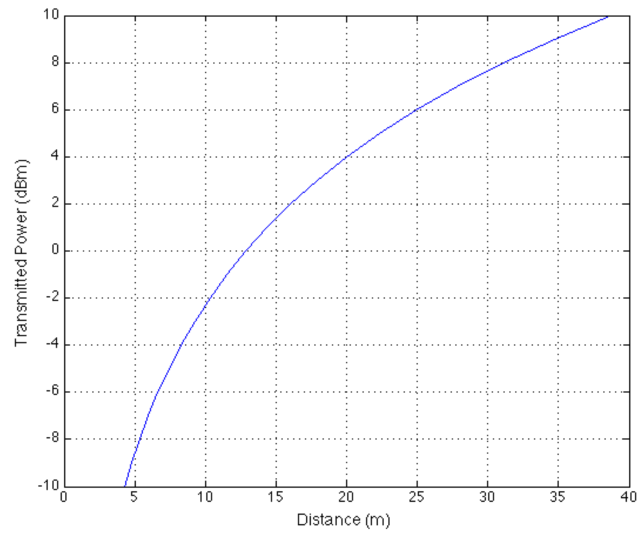


Fig. 5. Transmit power as a function of the distance, for -65 dBm received power baseline.

$$P_{Tx} - P_{Rx} = n\left(10log_{10}\left(d\right) + 10log_{10}\left(f\right)\right) + 32.45$$
$$\Leftrightarrow \tag{2}$$
$$n = \frac{P_{Tx} - P_{Rx} - 32.45}{10log_{10}\left(d\right) + 10log_{10}\left(f\right)}$$

Using (2) with the Fitting Toolbox provided by Matlab and the measured RSSI (P_{Rx}), the value of n was found to be 2.097, with a 95% confidence bounds $[2.084, 2.109]$. This experimentally determined value corresponds to what we are expecting for a LoS scenario. The red curve in Figure 4 shows the result of the fitting process.

Appropriate AP power levels are essential to maintaining a coverage area, not only to ensure correct (not maximum) amount of power covering an area, but also to ensure that excessive power is not used, which would add unnecessary interference to the radiating area. Transmitted power can be minimized to reduce interference among the APs.

Considering a typical baseline signal strength of -65 dBm for the WiFi received signals coming from adjacent cells, using (1) and n = 2.097, we have computed the optimal transmit power as a function of the distance, as depicted in Figure 5. This study is important to setup the initial APs transmit power to ensure a suitable cell coverage. Considering that 12 m is the separation between adjacent WiFi cells in the experiment set-up (Figure 2), the APs transmit power are set at 0 dBm, unless otherwise noted in the following experiments.

2) Experiment 1 – Assessment of the channel distribution influence on the throughput: The aim of this experiment is to assess the influence of channel distribution on the throughput, and verify the worst-case reference scenario in terms of intra–network co-channel interference, e.g., when all APs assigned to the same channel (Channel 1 – 2.412 GHz).

The average values of the measured throughput for each link and the aggregated throughput of the WiFi network are 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. Note that this is a worst-case reference scenario in terms of co-channel interference.

TABLE I. THROUGHPUT RESULTS FOR EXPERIMENT 1.

Experiment 1	Channel Number	Throughput (Mbps) $P_{Tx} = 0$ dBm
Link 1	1	5.25
Link 2	1	4.02
Link 3	1	3.93
Link 4	1	3.86
Link 5	1	5.28
Aggregated Throughput (Mbps)		**22.34**

3) Experiment 2 – Considering non-overlapping channels assignment: With this experiment, all APs are configured with non-overlapping channels: Channel 1 (2.412 GHz), Channel 6 (2.437 GHz) and Channel 11 (2.462 GHz). The measured throughput presented in Table II clearly shows the advantage of using non-overlapping channels in the WiFi planning. With a transmitted power set to 0 dBm on each APs, the measured aggregated throughput is 71.50 Mbps, i.e., more than three times higher than the value in Experiment 1 (22.34 Mbps). However, if the transmitted power P_{Tx} is increased to 5 dBm, the aggregate throughput decreases to 66.05 Mbps, because of the higher co-channel interference between Link 1 and Link 4, and between Link 2 and Link 5. Note that according to [1], with 5 dBm, the APs have 22 m coverage radius. This channel configuration is the baseline scenario for the following measurements of Phase 1.

4) Experiment 3 – Channel reallocation triggered by co-channel interference: The setup for Experiment 3 has the same

TABLE II. THROUGHPUT RESULTS FOR EXPERIMENT 2.

Experiment 2	Channel Number	Throughput (Mbps) $P_{Tx} = 0$ dBm	Throughput (Mbps) $P_{Tx} = 5$ dBm
Link 1	1	13.27	12.16
Link 2	11	11.76	10.50
Link 3	6	21.54	21.56
Link 4	1	12.57	11.18
Link 5	11	12.36	10.65
Aggregated Throughput (Mbps)		**71.50**	**66.05**

TABLE III. THROUGHPUT RESULTS FOR EXPERIMENT 3.

Experiment 3	Channel Number	Throughput (Mbps) P_I=0dBm	Throughput (Mbps) P_I=7dBm	Throughput (Mbps) P_I=15dBm
Before RRM strategy				
Link 1	1	12.12	12.30	12.3
Link 2	**11**	**6.80**	**7.08**	**6.98**
Link 3	6	21.59	21.63	21.61
Link 4	1	11.27	11.23	11.07
Link 5	11	6.88	6.83	6.75
Aggregated Throughput (Mbps)		**58.67**	**58.96**	**58.70**
After RRM strategy				
Link 1	6	13.27	13.12	13.10
Link 2	**1**	**11.76**	**11.62**	**11.56**
Link 3	6	21.53	21.55	21.61
Link 4	11	12.57	12.73	2.70
Link 5	1	12.37	12.41	12.40
Aggregated Throughput (Mbps)		**71.47**	**71.43**	**71.38**

non-overlapping channels allocation as in Experiment 2, with an additional interference Link active at Channel 11, placed next to Link 2, as depicted in Figure 2. Three different interference power levels (P_I) were applied during the experiment $\{0, 7, 15\}$ (dBm). The computed REMs at Channel 11 for different interference link's power are shown in Figure 6(a). 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). The yellow dots are due the "bull's eye" effect typical of the IDW interpolation algorithm and should be discarded. By observing the REMs, we can detect not only Link 2 and Link 5, but also the extra radio activity coming from the interfering link. Note that the detection of this interfering link will trigger the coordination strategy in the WiFi network.

The results from Table III show an overall network throughput decrease, compared with the results from Experiment 2, mainly due to the interference from the interfering link on Link 2 and Link 5. However, the results indicate that the variation on the power level of the interferer does not have a strong impact on the aggregate throughput.

From the REM information, the coordination strategy reallocates the WiFi channels among the APs, to avoid strong co-channel interference. The REM for Channel 11, depicted in Figure 6(b), shows a clear spatial separation between the interference source and Link 4.

TABLE IV. WEIGHTING FACTOR ACCORDING TO THE FREQUENCY SPACING BETWEEN CHANNELS.

n	**Frequency Spacing (MHz)**	**Weight (dB)**
1	5	0
2	10	-10
3	15	-19.5
4	20	-28
5	25	36.5

Table III shows a significant throughput increase from 58 Mbps to 71 Mbps thanks to the coordination strategy. The aggregate throughput is now close to the values obtained with Experiment 2, i.e., without any interference Link. Once again, the results indicate that the variation on the power level of the interferer does not have a strong impact on the aggregated throughput.

5) Experiment 4 – Channel reallocation triggered by adjacent channel interference: With this experiment, we want to understand how the WiFi network is affected by strong adjacent channel interference and how effective is the coordination strategy under such circumstances. The interfering link is set to operate on Channel 10, while Link 2 uses Channel 11. In the case of adjacent channel interference, the REM generated for channel X must take into account the power received from adjacent channels $X \pm n \in \mathbb{N}$, weighted according to the spectral mask of the filter present at the WiFi receiver [15]. The weighting factors of the transmit mask are listed in Table IV and represented in Figure 7. Note that each WiFi channel is 22 MHz wide, but the channel separation is only 5 MHz. As an example, the power of the 4^{th} adjacent-channel should be reduced by 28 dB to be correctly used in the computation of the REM.

The results from Table V show an overall network throughput decrease, compared with the results obtained from Experiments 3 and 4. This result shows that the first adjacent-channel interference leads to a higher throughput degradation than a co-channel interference (no–interference: 71.5 Mbps, co–channel interference: 58.6 Mbps and adjacent–channel interference: 56.7 Mbps). Once again, the results also indicate that the variation on the power level of the interferer does not have a strong impact on the aggregate throughput.

6) Experiment 5 – Automatic power control to overcome co-channel interference: The aim of this experiment is to understand if automatic power control is a good strategy to overcome co-channel interference. The setup of the network under test has five links using non-overlapping channels, with an additional co–channel interference link in Channel 11. The RRM strategy in this experiment keeps the same channel assignment of each link and increases the power of the victim link (Link 2). The transmitted power increases in steps of 5 dB, from 0 to 15 dBm. The remaining APs of the network under test remains at 0 dBm, and the interfering link is set to transmit 5 dBm in Channel 11. The measured throughput is listed in Table VI.

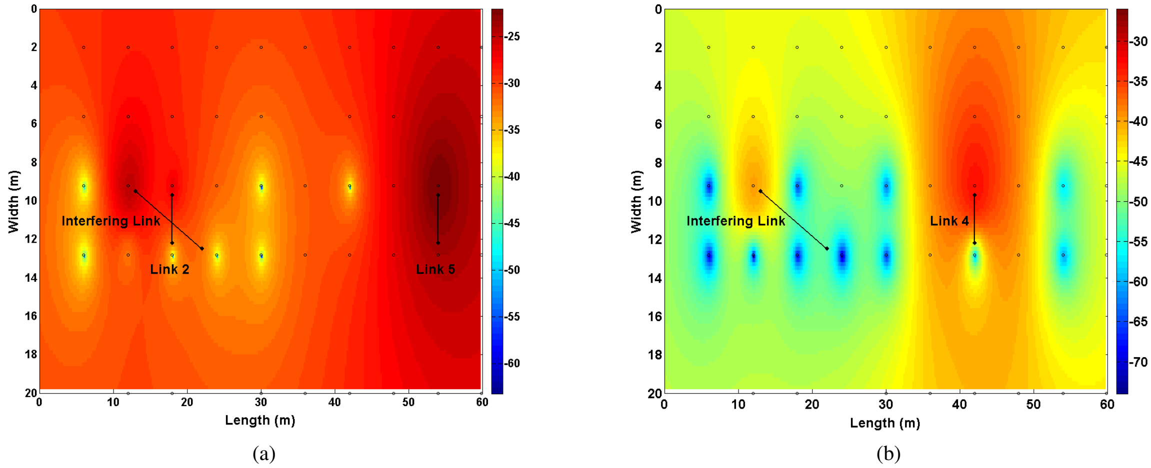


Fig. 6. Measurement 3. (a): REMs with Link 2, Link 5 and Interferer Link at Channel 11 with 0 dBm; (b): REMs with Link 4 and Interferer Link at Channel 11 with 0 dBm. Color bar in dBm.

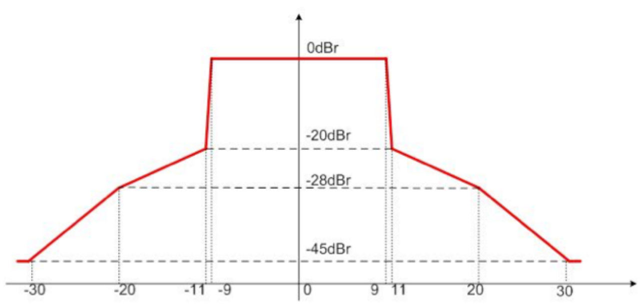


Fig. 7. IEEE transmit mask (IEEE Std. 802.11-2007).

TABLE VI. THROUGHPUT RESULTS FOR EXPERIMENT 5 AFTER AUTOMATIC POWER CONTROL.

Exp. 5	Ch.	Throughput (Mbps) P_2=0dBm	Throughput (Mbps) P_2=5dBm	Throughput (Mbps) P_2=10dBm	Throughput (Mbps) P_2=15dBm
Link 1	6	12.30	12.32	11.47	11.43
Link 2	**11**	**7.08**	**3.84**	**6.88**	**6.97**
Link 3	6	21.63	21.33	21.52	21.39
Link 4	1	11.23	11.12	11.60	11.64
Link 5	11	6.83	9.60	6.90	6.83
Aggregated Throughput (Mbps)		**58.96**	**58.13**	**58.39**	**58.26**

The results suggest that, despite the increase of transmitted power on Link 2, the overall throughput remains low and approximately constant (roughly 58 Mbps), therefore, power increase alone does not overcome the degradation caused by strong co-channel interference. The WiFi coordination strategy investigated in Experiment 3 is much more effective, leading to an aggregated throughput of 71 Mbps.

TABLE V. THROUGHPUT RESULTS FOR EXPERIMENT 4.

Experiment 4	Channel Number	Throughput (Mbps) P_I=0dBm	Throughput (Mbps) P_I=7dBm	Throughput (Mbps) P_I=15dBm
Before RRM strategy				
Link 1	1	12.17	12.23	12.11
Link 2	**11**	**4.63**	**3.84**	**4.04**
Link 3	6	21.37	21.33	21.23
Link 4	1	11.17	11.12	11.27
Link 5	11	7.22	9.60	8.96
Aggregated Throughput (Mbps)		**56.57**	**58.13**	**57.60**
After RRM strategy				
Link 1	6	8.12	8.14	8.16
Link 2	**1**	**7.72**	**7.75**	**7.76**
Link 3	6	21.53	21.51	21.55
Link 4	11	12.08	11.97	12.2
Link 5	1	11.82	11.06	11.16
Aggregated Throughput (Mbps)		**61.13**	**60.43**	**60.83**

B. Phase 2 – Portable test-bed

For the indoor propagation model used to create all REMs, beside the relative position and distance between NUCs, we also consider the following parameters on the algorithm:

- Wall penetration Losses: 5 dBm
- Floor penetration Losses 18 dBm
- Height of each floor: 5 m

All experiences were conducted for both 2.4 GHz and 5 GHz frequency bands.

1) Experiment 1 – Full co-channel interference: In this first experiment, all APs (NUC2, NUC3, NUC4 and NUC7) are configured to transmit at Channel 6 (2.437 GHz). The objective is to have a worst-case reference scenario in terms of co-channel interference, and to verify the influence of walls and floor on the overall performance of the network.

REMs are produced based on the measured RSSI on each client and for each AP. Figure 8 represents the REM computed for Experiment 1, taken at Channel 6 and 17 dBm transmit power. 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) along with the corresponding link (black lines).

On the first floor (Figure 8(b)), the uniform red color on the REM is the evidence of a high-power level transmitted at Channel 6. The walls between Link 4 and Link 3 or Link 1 have little influence on the propagation of the signal, and cannot avoid co-channel interference. On the other floor (Figure 8(a)), the REM shows the position of the single AP present on that floor (NUC7 - Link 2). The high color contrast suggests that the influence of other APs located on the first floor is low, mainly caused by the presence of a thick floor.

The throughput for each link is computed at different transmitted powers and frequency bands, and the aggregated throughput results are presented in Figure 9 (solid lines). As expected and from the analysis of the REMs, all links from the first floor (Link 1, 3 and 4) are strongly interfering with each other. This effect is more visible when the transmitted power is 17 dBm.

For lower transmit powers, in particular between 0 and 5 dBm, the clients are outside or on the edge of the coverage area of the AP, which cause a low throughput. This is particularly evident for Link 3, as shown in Table VII, with a client on one floor and the AP on the other. This effect is even more evident for the 5 GHz band measurements.

The only link that present good results in the single link located on Floor 0 (Link 2). At 2.4 GHz, this link present higher throughput values, but as the transmit power is increased the throughput decreases due to co-channel interference with the other links. At 5 GHz, where the coverage area is lower for the same transmit power, better throughput results are attained at any transmit power, exception made at 14 dBm, probably due to bad measurement procedures.

2) Experiment 2 – Considering no-overlapping channels assignment: On the second experiment, all APs (NUC2, NUC3, NUC4 and NUC7) are configured with no-overlapping channels and variable transmit power between 0 dBm and 17 dBm. Both 2.4 GHz and 5 GHz frequency bands are tested.

The results shown in Table VIII are consistent with the strategy applied on this experiment, even for Link 3, with a client on one floor and the AP on the other. The increase of the aggregate throughput presented in Figure 9 (dashed lines) reflects the advantage of a coordinated approach. As an example, for the 2.4 GHz frequency band, and compared with the previous Experiment 1, the aggregated throughput has increased from 6.31 Mbps to 49.64 Mbps when transmit power is 17 dBm. For the 5 GHz frequency band and the same transmit power, the aggregated throughput has increased from 28.29 Mbps to 99.77 Mbps.

3) Experiment 3 – Channel reallocation triggered by co-channel interference: Experiment 3 setup is a WiFi network composed by three Links (Links 1, 2 and 3), with a channel distribution following a no-overlapping strategy. Link 4 is used as an external interferer with a constant transmit power of 17 dBm and set to the same frequency channel as Link 3. The objective is to trigger the RRM algorithm to reconfigure the channel distribution, based on REMs.

According the frequency band in use during each experiment, the initial channel distribution is:

- Link 1: Channel 11 or Channel 44
- Link 2: Channel 1 or Channel 36
- Link 3: Channel 6 or Channel 40
- Link 4: Channel 6 or Channel 40 (Interferer)

As an example, from the RSSI measurement on each client, the computed REM at Channel 6 is shown in Figure 10. By observing the REMs on both floors, it is possible to detect not only Link 3 activity on Channel 6, but also the extra radio signal activity coming from the interfering Link 4.

Figure 11 (solid lines) shows the measured throughput for each link at 2.4 GHz and 5 GHz band, when the transmit power of Links 1, 2 and 3 is swept form 0 dBm to 17 dBm. The bold line presents the computed aggregate throughput of

TABLE VII. THROUGHPUT RESULTS FOR EXPERIMENT 1 WITH THE PORTABLE TEST-BED.

Experiment 1 Portable test-bed	Channel Number	Throughput (Mbps) P_I=0dBm	Throughput (Mbps) P_I=8dBm	Throughput (Mbps) P_I=17dBm
2.4 GHz				
Link 1	6	0.16	4.68	2.77
Link 2	6	13.66	4.32	1.59
Link 3	**6**	**0**	**0.45**	**0.58**
Link 4	6	3.98	9.74	1.37
Aggregated Throughput (Mbps)		**56.57**	**19.19**	**6.31**
5 GHz				
Link 1	48	20	0	0
Link 2	48	27.25	27.34	28.27
Link 3	**48**	**0.01**	**0**	**0**
Link 4	48	0	0	0.02
Aggregated Throughput (Mbps)		**47.26**	**27.34**	**28.29**

TABLE VIII. THROUGHPUT RESULTS FOR EXPERIMENT 2 WITH THE PORTABLE TEST-BED.

Experiment 2 Portable test-bed	Channel Number	Throughput (Mbps) P_I=0dBm	Throughput (Mbps) P_I=8dBm	Throughput (Mbps) P_I=17dBm
2.4 GHz				
Link 1	6	0.21	11.37	18.17
Link 2	11	0	16.87	9.63
Link 3	**1**	**0**	**0.06**	**5.69**
Link 4	11	2	11.19	16.15
Aggregated Throughput (Mbps)		**2.21**	**39.49**	**49.64**
5 GHz				
Link 1	36	20.47	29.4	29.5
Link 2	40	0	20.47	29.23
Link 3	**44**	**0.3**	**8.84**	**20.36**
Link 4	48	0	10.39	20.68
Aggregated Throughput (Mbps)		**20.77**	**69.1**	**99.77**

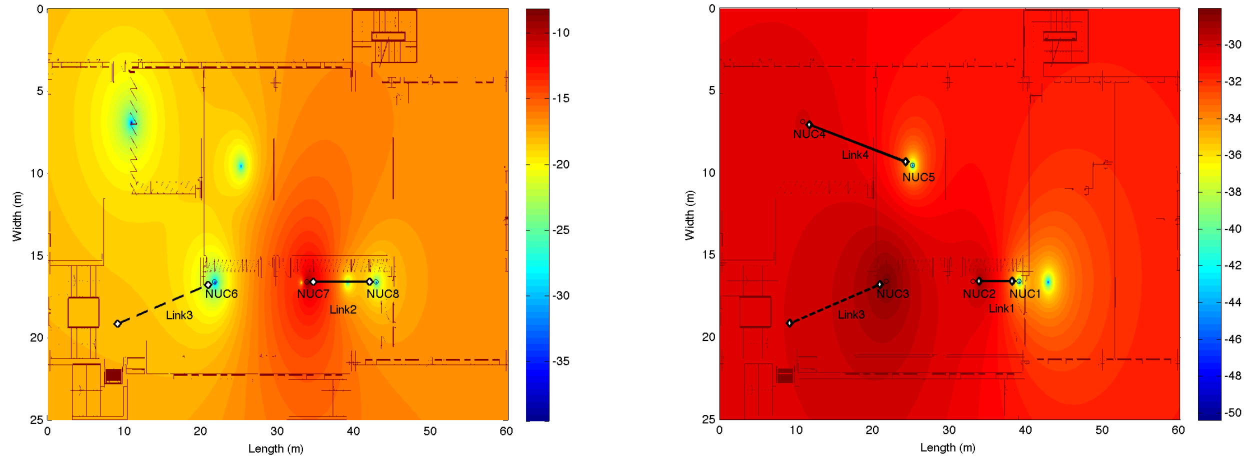


Fig. 8. REMs computed during Experiment 1 for Links 1, 2, 3 and 4, at Channel 6 and 17 dBm transmit power: (a) Floor 0; (b) Floor 1.

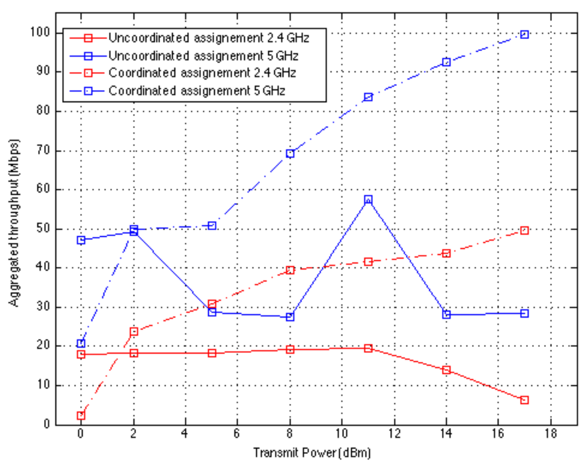


Fig. 9. Aggregated throughput at 2.4 GHz (red lines) and 5 GHz (blue lines) for the uncoordinated approach (solid lines) and coordinated approach (dashed lines).

the network.

As the transmit power increases, so does the aggregated throughput of the network, to a maximum of 19.36 Mbps for 14 dBm (2.4 GHz band) and 67.04 Mbps for 8 dBm transmit power (5 GHz band). As the transmit power increases further, so does the overall co-channel interference of the network mainly at Channel 6 (or 40), causing the throughput to drop.

As shown in Figure 10, the REM allows the detection of the interfering link. With this information, and by setting an appropriate threshold for the minimum throughput on each link, the RRM strategy reallocates the WiFi channels among the APs to avoid the strong co-channel interference. Thus, after the RRM strategy is applied, the network channel reassignment is as follow:

- Link 1: Channel 1 or Channel 36
- Link 2: Channel 6 or Channel 40
- Link 3: Channel 11 or Channel 44
- Link 4: Channel 6 or Channel 40 (Interferer)

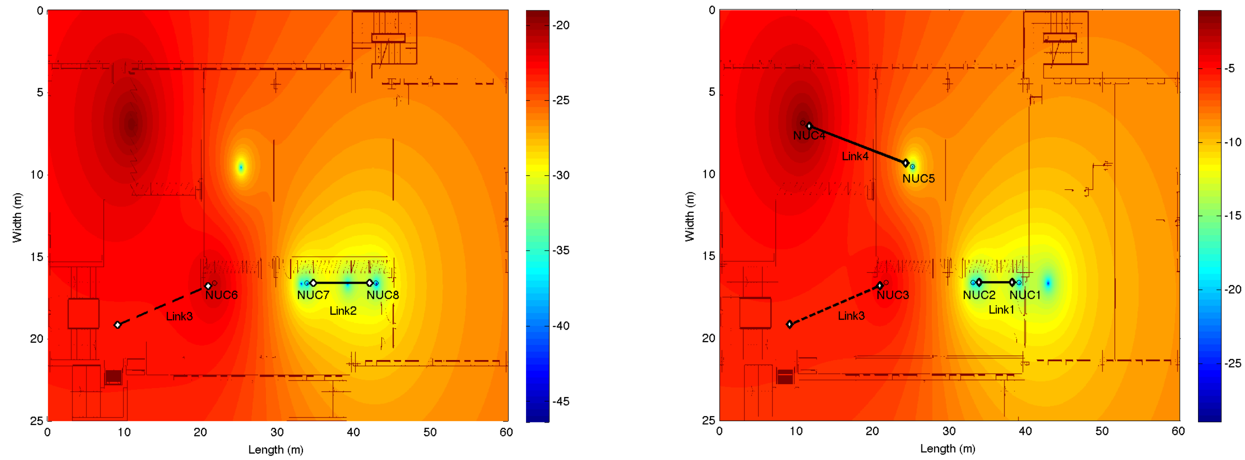
After the RRM channel reassignment, throughput measurements shown in Figure 11 have significant increase from 19.36 Mbps to 46.9 Mbps on the 2.4 GHz band, and from 67.94 Mbps to 79.97 Mbps on the 5 GHz band, thanks to the RRM strategy based on REM. The aggregate throughput is now close to the values obtained with Experiment 2, i.e., without any interference Link.

4) Experiment 4 – Hole detection: This experiment is aimed at detecting coverage holes on the network, based on REMs, and implement a RRM algorithm to increase the transmit power of adjacent APs next to the clients with poor or non-existent connection with their former AP. The initial setup consists of 4 NUCs located on Floor 1, with the following configuration:

- NUC2: Access Point 3; Channel 6; 0 dBm transmit power
- NUC5: Access Point 2; Channel 1; 16 dBm transmit power
- NUC4: Access Point 1; Channel 11; 13 dBm transmit power
- NUC3: Client connected to Access Point 2; Channel 1; 17 dBm transmit power

After 100 s, Access Point 2 (Link 1) is disconnected and the client loses connection and the corresponding throughput drops to zero. The RRM algorithm implements a series of actions to ensure that the client reconnects:

- Compute REM of the APs;
- Detect the absence of AP2 transmit signal on Channel 1;
- Increase the transmit power of adjacent Access Points (AP1 and AP3) up to 16 dBm, so the client may discover one or both APs, and connect to one of them.



(a) (b)

Fig. 10. REMs computed from Experiment 3 with the portable test-bed for Links 3 and 4, at Channel 6 and 17 dBm transmit power: (a) Floor 0; (b) Floor 1.

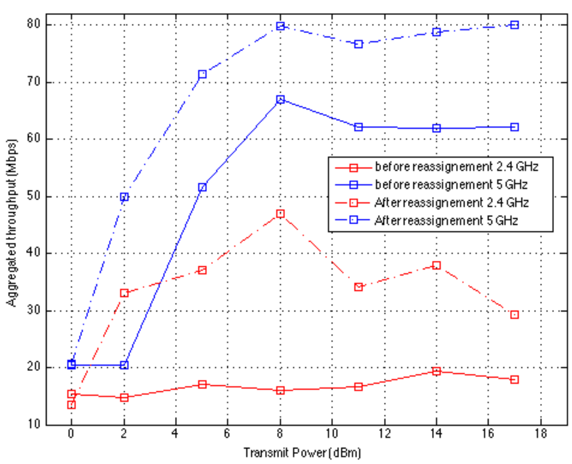


Fig. 11. Aggregated throughput at 2.4 GHz (red lines) and 5 GHz (blue lines) with the presence of an interfence Link, before (solid lines) and after (dashed lines) the coordinated RRM approach.

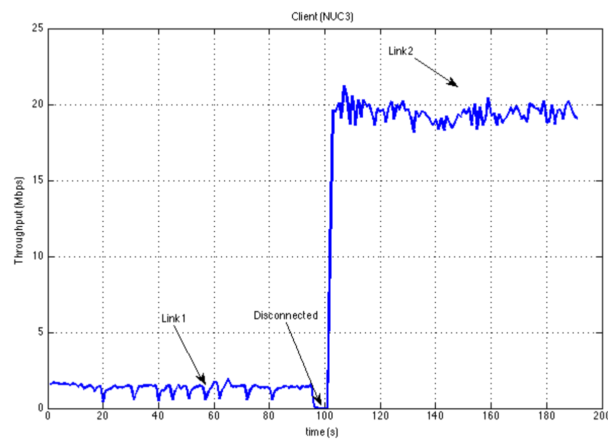


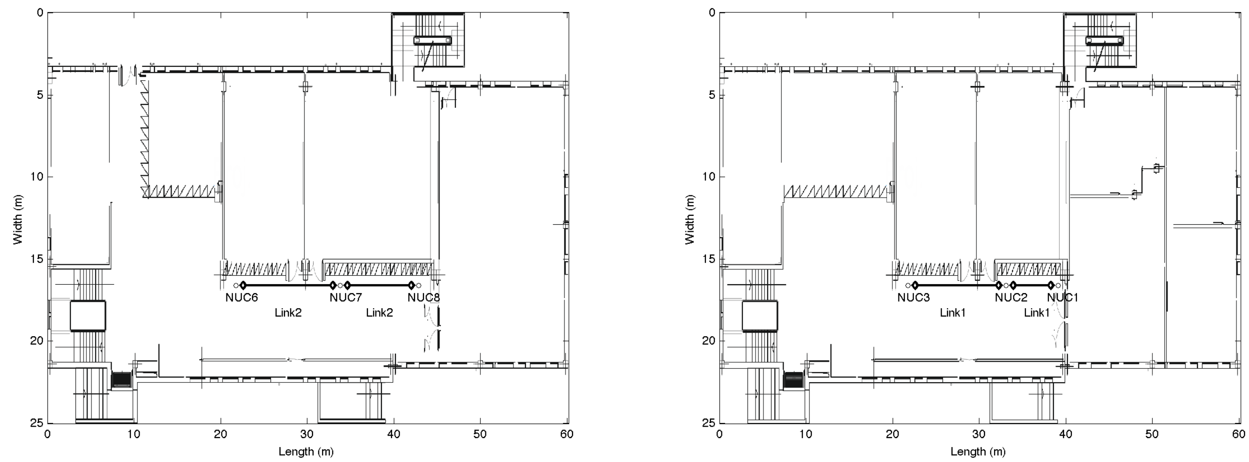
Fig. 12. Throughput of the network client (NUC3) – before (Link 1) and after (Link 2) hole detection.

Compared with the previous state, the RRM decision is to increase the transmit power of adjacent AP1 (NUC4) and AP3 (NUC2) next to the client node with poor or non-existent connection. This action gives to the former Link 1 client the option to select and connect to the best AP available, based on RSSI (AP3 – NUC2 in this experiment). Figure 12 shows the throughput evolution of the client node during the experiment. Initially connected to Link 1, the mean throughput was 1.7 Mbps. After losing connection with AP2, the new connection with AP3 (Link 2) was set with a mean throughput of 19.4 Mbps.

5) Experiment 5 – Characterization of the building floor as a WiFi barrier: In this experiment, the objective is to verify the potential of a building floor as an effective barrier between WiFi Links in a co-channel scenario.

As depicted on Figure 13, the setup consists of two NUCs configured as APs, using the same frequency channel (11 on the 2.4 GHz band or 48 on the 5 GHz band), located on different floor, but on the same vertical alignment. Each AP has two clients connected to it. The floor is made of concrete, 50 cm thick.

From the measurement campaign at 2.4 GHz, the building floor is not efficient in blocking the radio signal from crossing the concrete structure and interfering with the other WiFi link. For Link 1, the power level of the AP located on Floor 0 suffers an attenuation of 10 dB when crossing to Floor 1. For Link 2 AP, located on Floor 1, the signal has no attenuation, when crossing from Floor 1 to Floor 0. However, at 5 GHz, the building floor introduce 20 dB attenuation on both links, when the radio signal crosses the building floor. However, the



(a) (b)

Fig. 13. Network configuration for Experiment 5 with the portable test-bed. (a) Floor 0 with Link 2 and (b) Floor 1 with Link 1.

signal level from Link 2 is more pronounced than the signal from Link 1 on the other floor.

The aggregated throughput computed and represented on Figure 14 shows that the building floor is not efficient in blocking the radio signal from crossing the concrete structure and interfering with the other WiFi Link at 2.4 GHz. The aggregate throughput decreases from 19.4 Mbps to 3.5 Mbps as the transmit power increases, since co-channel interference between Links becomes stronger. However, Link 2 presents higher throughput, as the co-channel interference from Link 1 is lower.

At 5 GHz, the aggregate throughput increases from 16.7 Mbps to 24.6 Mbps as the transmit power increases, which indicates that co-channel interference between links has diminutive influence on the aggregated throughput. Thus, the presence of concrete walls and floor can be used by the coordination strategy to improve the channel distribution on the 5 GHz band and increase the network capacity.

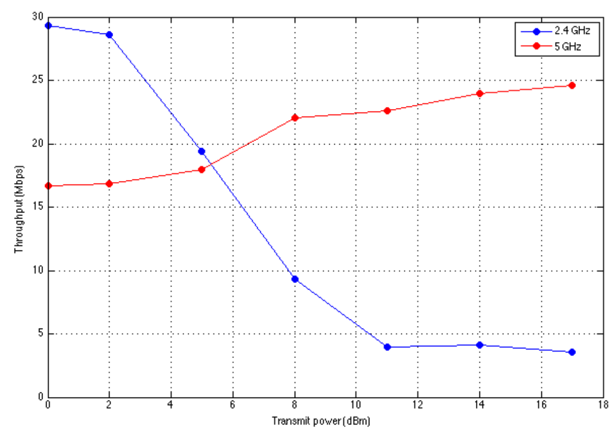


Fig. 14. Throughput of the radio signal crossing through a concrete floor, as a function of the AP transmit power.

V. CONCLUSION

This paper presented the testing of WiFi coordination strategies that exploits information from Radio Environment Maps, based upon several exploratory measurement campaigns in a pseudo-shielded test-bed environment and in a real environment using a portable test-bed. Several scenarios were tested: Uncoordinated channels assignment, optimal coordination, interference mitigation, automatic power control, hole detection and load balancing.

The overall performance of the WiFi network depends on a smart channel allocation. As an example, for the network under test in the pseudo-shielded test-bed environment, we've got an aggregated throughput of 22.3 Mbps in a full co-channel interference scenario and 71.5 Mbps using a configuration of non-overlapping channels. It was shown that based on the observation of REMs, it is possible to detect the presence of interfering links (co-channel and first adjacent channel). First adjacent-channel interference leads to a higher throughput degradation than a co-channel interference with the same power level (no-interference: 71.5 Mbps, co-channel interference: 58.6 Mbps and adjacent-channel interference: 56.7 Mbps). The coordination strategy that automatically reallocates WiFi channels to avoid channel overlapping is very beneficial (e.g., the aggregated throughput goes from 58.7 Mbps to 71.5 Mbps, the link under interference goes from 6.8 Mbps to 11.8 Mbps). However, in case of strong co-channel interference, the strategy of automatically increase the power level of the victim link, when keeping the same channel allocation, does not bring any gain in terms of measured throughput. With the portable test-bed in a real environment, The RRM that automatically reallocates WiFi channels to avoid channel overlapping from an external interferer is also very beneficial. At 5 GHz, the aggregated throughput goes from 62 Mbps to 79.97 Mbps, the link under interference goes from 3.15 Mbps to 20.7 Mbps.

Moreover, it was shown that a building's concrete floor that separates two WiFi networks using the same channel, act as an effective barrier at 5 GHz, but not on the 2.4 GHz band. Thus, the presence of concrete walls and floor can be used by the coordination strategy to improve the channel distribution and increase the network capacity. Increasing the transmit power on the first case (e.g., 5 GHz band) leads to a higher throughput (from 16.71 Mbps to 24.62 Mbps), while for the second case (e.g., 2.4 GHz band) decreases the aggregate throughput (from 19.36 Mbps to 3.54 Mbps).

For the RRM to be effective, several sensor nodes (energy detectors) are needed to create a REM with enough spatial resolution. The additional hardware required for spectrum sensing, inter–cell signaling and REM building may increase the investment by 50 %, when compared to an uncoordinated WiFi network. However, by implementing a coordinated management of radio resources, the overall throughput in WiFi network was increased more than 200 %, even in the presence of interfering links.

The results coming out from this experiment may have a clear impact in telecommunication companies and WiFi service providers, helping to understand the opportunities and limitations of WiFi coordination strategies in realistic scenarios. We will use the insights form this experiment in dense WiFi outdoor scenarios, to assess the benefit of a coordinate management of radio resources. In particular, WiFi coordination in shopping malls, football stadiums or swimming pool complexes are amongst the most challenging locations to deploy a WiFi network because of the huge crowds in close proximity to each other and the near universal use of smartphones by today's customers and sport fans.

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REFERENCES

[1] R. Dionisio, T. Alves, and J. Ribeiro, "Experimentation with radio environment maps for resources optimisation in dense wireless scenarios," in *7th International Conference on Advances in Cognitive Radio - COCORA 2017*, Apr 2017, pp. 25–30.

[2] L. P. Qian, Y. J. Zhang, and J. Huang, "Mapel: Achieving global optimality for a non-convex wireless power control problem," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1553–1563, March 2009.

[3] D. H. Kang, "Interference Coordination for Low-cost Indoor Wireless Systems in Shared Spectrum," Ph.D. dissertation, KTH, School of Information and Communication Technology (ICT), Communication Systems, CoS, 2014.

[4] S. Zehl, A. Zubow, M. Döring, and A. Wolisz, "ResFi: A secure framework for self organized Radio Resource Management in residential WiFi networks," in *2016 IEEE 17th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, June 2016, pp. 1–11.

[5] V. Rakovic, D. Denkovski, V. Atanasovski, and L. Gavrilovska, "Radio resource management based on radio environmental maps: Case of Smart-WiFi," in *2016 23rd International Conference on Telecommunications (ICT)*, May 2016, pp. 1–5.

[6] M. Pesko, T. Jarvonic, A. Kosir, M. Stular, and M. Mohorcic, "Radio Environment Maps: The Survey of Construction Methods," *KSII Transactions on Internet and Information Systems*, vol. 8, no. 11, pp. 3789–3809, November 2014.

[7] iMinds. (2017, November) jFed – Java-based framework for testbed federation. [Online]. Available: http://jfed.iminds.be

[8] (2017, November) OMF–6. [Online]. Available: https://github.com/mytestbed/omf

[9] (2017, November) OEDL – OMF Experiment Description Language. [Online]. Available: http://www.crew-project.eu/portal/oedl-explained

[10] (2017, November) Iperf, The TCP/UDP bandwidth measurement tool. [Online]. Available: http://iperf.fr/

[11] (2017, November) OML. [Online]. Available: https://wiki.confine-project.eu/oml:start

[12] S. Bouckaert, W. Vandenberghe, B. Jooris, I. Moerman, and P. Demeester, *The w-iLab.t Testbed*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 145–154.

[13] (2017, November) w-iLab.t. [Online]. Available: http://doc.ilabt.iminds.be/ilabt-documentation/wilabfacility.html

[14] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[15] E. G. Villegas, E. Lopez-Aguilera, R. Vidal, and J. Paradells, "Effect of adjacent-channel interference in ieee 802.11 wlans," in *2007 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, Aug 2007, pp. 118–125.