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Extended Study Regarding Sustained Transfer Rate for 802.11 Wi-Fi Communications With Partially Overlapped Channels Interference

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Abstract — **This paper extends the pervious studies of the authors on the 802.11 Wi-Fi Communication regarding the influence on the sustained transfer rate caused by the existence of the Partially Overlapped Channels (POCs) interference. The main influence in this situation is the reducing of the sustain transfer rate caused by increasing number of the rejected cell, lost cells and delayed packets. The maximum channel throughput is dramatically reduced in the presence of the adjacent and eventually co-channels interference. The usual solution to this problem is the increasing of the distance between the wireless access points or increasing of the channel spacing. Our study proposes a better solution combining those two methods. For achieving the optimum solution first we make the necessary studies regarding the physical distance influence and the channel spacing influence to the interference. For this goal the test bed solution was redesigned in order of achieving the optimum measurements for sustained transfer rate. Our contribution is related to the new perspective on the sustained transfer rate analysis and optimum parameter setup in the presence of the interference. The new data observations related to the maximum throughput, lost cells and average cell delays also could contribute to the optimum Wi-Fi coverage planning. Finally we made a personal interpretation of to the data measured in the laboratory.**

I. INTRODUCTION

In this paper demonstrate the importance of the interference caused by Partially Overlapped Channels (**POCs**) in reducing the maximum channel throughput. We create a more complex scenario related to physical distance and channel spacing between Access Points (**AP's**).

In order to reduce the interference effect the IEEE regulation forum extended the complexity of the standards proposing more suitable frequency band. Even using Multiple Input Multiple Output (**MIMO**) technologies for the wireless devices, it is more obvious than ever that the POCs will be the future for the intensive use of Industrial, Scientific and Medical (**ISM**). The 2.4 GHz is divided into 11 or 13 channels (country dependent regulations) with a 5 MHz frequency separation and 22 MHz channel bandwidth. Usually the differences between these standards consist in modulation techniques but the channel frequency allocation is similar.

The general approach in interference studies is related to co-channel, adjacent non-overlapped channel or adjacent partially overlapped channels interference. The authors make a different approach analyzing the maximum sustain rate for the channel. It is important because only in this situation the interference can cause the maximum effect.

The interference factor analysis is already approached in many papers, as [**1**], [**4**], [**5**].

An extended study was made by A. Mishra in [**4**] and he introduced a normalized factor Signal to Interference plus Noise Ratio (**SINR**). The parameter is extended by Yong Cui in [**5**] considering the distance an important factor besides the Adjacent Channel Interference (**ACI**).

Our paper's aim is to get for users an extended theoretical model and experimental results to obtain useful information regarding channel allocation and spatial reuse in conditions of the sustained traffic rates, by exploiting the data related to the site interference.

Our study demonstrates the interference influence on the wireless technologies when they are running in the same environment, showing major variations in performance.

II. GENERAL CONSIDERATIONS AND REMARKS

In this chapter we are making some general considerations regarding how POCs or co-channels do affect the signal. Co-channel interference is defined when Wi-Fi devices share the same channel, and take turns. Adjacent-Channel Interference (ACI) is defined when two networks partially overlap. Since they aren't sharing the same channel, they don't have rules to take turns. The only 1, 6 and 11 channels don't have interference (**Fig. 1**).

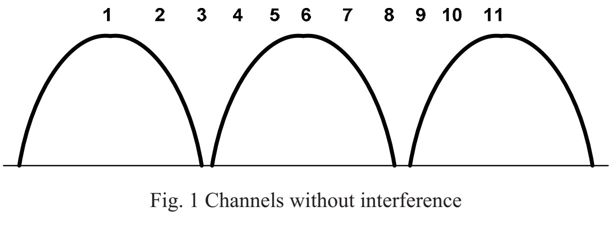

Fig. 1 Channels without interference

Co-channel interference is not really a classical interference it's more like cooperation. In IEEE 802.11 Standards a single channel is the medium for getting data across. For example, when AP1 connect on channel 6, client device and AP1 are talking to each other on channel 2. Now if AP2 devices on the same 6 channel transmit data at the same time, the transitions will interfere with each other and cause data corruptions. In order to avoid this situation, the IEEE 802.11 Standards impose complex signaling algorithms so any Wi-Fi device to share the same channel. In fact only one device can use the channel to transmit at any one time to prevent interference or collisions. Putting AP's within range of each other on the same channel in this way causes what is know as co-channel interference. Generally sharing a channel is could be better than partially overlapping.

The inSSIDer application marks partially overlapping networks and sharing networks with different colors (Fig. 2).

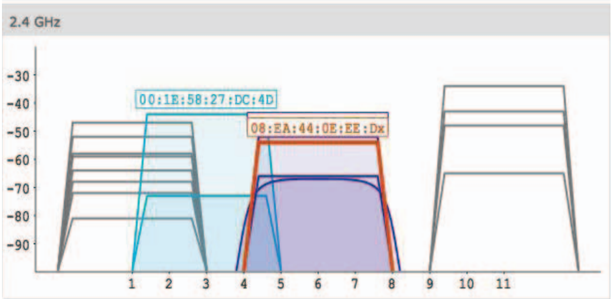

Fig. 2 Channels without interference

Channel overlap causes the data to be corrupted and have to be re-transmitted, which in turn can cause all types of issues.

Data corruption or loss will increase layer 2 retransmissions and cause many more problems with your wireless network. Remember channels 1, 6 and 11 are the only channels that do not overlap each other so stick to those (Fig. 1).

III. Testing Bad Configurations and Scenarios

Our study is going to be focused on the 2.4 GHz spectrum, part of the ISM spectrum, where the use is allowed without government license, according to regulations that limit the transmitted power. We are going to study the Wi-Fi network in the IEEE 802.11g Standards. We will search how throughput of the transmission on adjacent channels affects the transmission of our working signal and how the data rate is reduced in the conditions of the sustained traffic rate.

The main disadvantage of this IEEE 802.11 Standard is that there are only 3 non-overlapping channels and there is interference from the overlapping channels. The IEEE 802.11g Standard includes the use of OFDM (Orthogonal Frequency Division Multiplexing). The advantages of OFDM are that it is very robust against the multipath propagation (resistant to selective fading). This feature enables to reduce the inter-symbols interference and provides high transmission data rates.

For the interference factor analysis, previously defined in the literature [**1**], [**4**], [**5**], we must describe the minimum testing bed architecture.

The first step is defining of the reference model (Fig. 3). The reference model consists in one AP and 2 laptops. The PC1 laptop is connected to AP via cable and the PC2 is using a wireless connection. On the PC1 is installed the Jperf server application and on the PC2 is setup as work station. In this case only one wireless connection is involved.

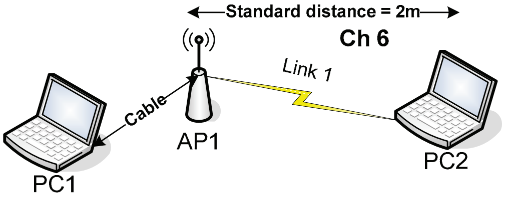

Fig. 3 Reference testing bad architecture

The goal is to determine the maximum throughput of the channel 6 in condition of interference less. The results are presented in Table 1.

TABLE 1. TEST RESULT FOR REFERENCE TEST BET

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	18.44	1.79	1.10%
2	100	18.51	1.36	0.88%
3	100	18.44	1.93	1.20%
4	100	18.24	2.03	0.87%
5	100	18.55	1.61	0.88%
Average	100	18.44	1.74	0.98%

The main observation to the data presented in the above table is that even in the non interference conditions the maximum throughput of the channel 6 is around 18.4 Mb/s.

The second step is defining of the general case the configuration. The configuration is the following: 2 access points (AP1 and AP2) and 4 laptops (PC1, PC2, PC3 and PC2) as in Fig. 4.

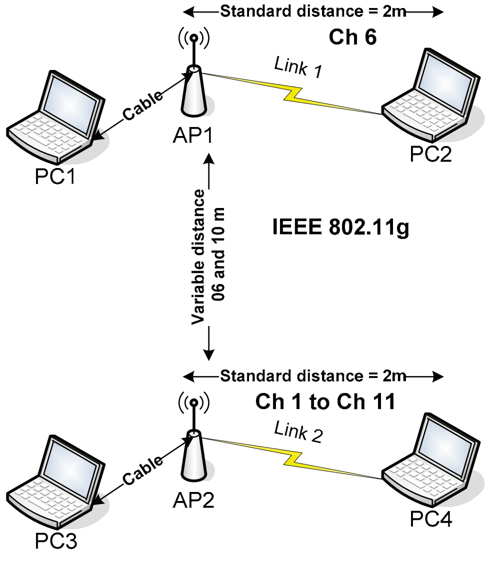

Fig. 4 Testing bad architecture and configuration

The access points used are "*Tenda W316R*" wireless routers and the network card of the laptop is "*Qualcomm Atheros AR5BWB222*".

The laptops are connected one with each other using the AP routers. The radio performance parameters are influenced by the functioning of the AP2 in the proximity and in the same frequency range (ISM). The variation factor is related to the spatial distance between the AP's and the channel spacing.

IV. MATHEMATICAL MODEL DESCRIPTION

In order to determine more precise the real influence of the AP2 equipment we must make some observations regarding channel parameters as they are defined in the IEEE standards [**2**] and also considered in [**3**].

Paper [**1**] investigates the interference influence on throughput making the general assumption that the devices fulfill the transmission mask [**2**] depicted in Fig. 5 and the modulated signal can be assumed to be filtered like in Fig. 6

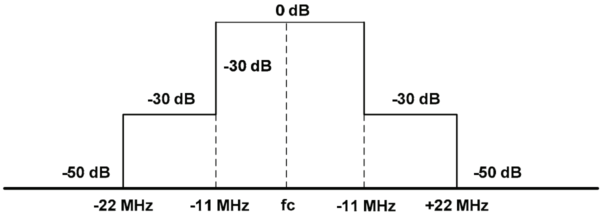

Fig. 5 Channel mask according IEEE Standard 802.11 [**2**]

The Fig. 5 allows evaluating the possibility of efficient using of the ISM in the presence of the POCs [**2**], [**3**].

For practical reasons it is necessary to investigate the mutual influence of the adjacent channels in diverse scenarios.

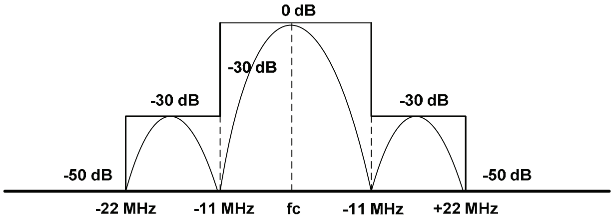

Fig. 6 Transmitter channel using filter

The main assumption of the IEEE standards is that the communication must be made considering partially overlapping, as it is clearly depicted in Fig. 7.

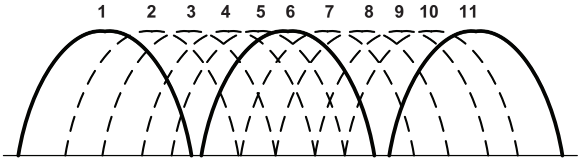

Fig. 7 Spectrum allocation in ISM 2.4 GHz [**2**]

The quantification of interference caused by ACI could be defined by the interference factor as [**1**]:

$$I_{u,i}(F)=\int_{-\infty}^{+\infty}P_{Em}(f)\cdot P_{\mathrm{Rec}}(f-F)\,df \tag{1}$$

where: $P_{Em}(f)$ is the transmitted signal power distribution, $P_{\mathrm{Rec}}(f)$ is the receiver band-pass filter's response and $F=\left|F_u-F_i\right|$ is the amount of the overlap between the two frequencies (transmitter/receiver).

Usually, in order to have a good communication, according to [**1**] and [**3**], the system must fulfill two conditions: (**a**) the communication signal to be greater than the receiver sensitivity and (**b**) the signal to noise ratio in the presence of interference (Signal to Interference plus Noise Ratio = SINR) to be greater than a threshold.

In order to evaluate the interference factor $I_{u,i}$, we must create the equivalent scheme of the test bed architecture from Fig. 1, as depicted in Fig. 8.

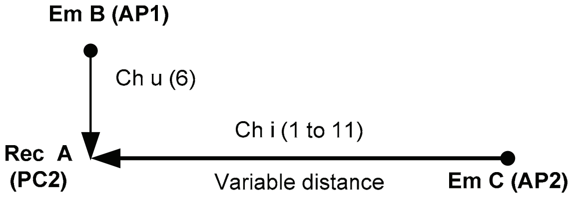

Fig. 8 SINR test bed equivalent scheme

For practical reasons we will consider the noise level negligible versus interference level, so the SNIR factor will become SIR (Signal to Interference Ratio) factor. The SIR factor can be determined analytically using:

$$SIR=\frac{P_{\mathrm{Rec}}\{B\rightarrow A\}}{P_{\mathrm{Rec}}\{C\rightarrow A\}} \tag{2}$$

The power received from a transmitter in the theory of propagation is determined by the relationship:

$$P_{\mathrm{Rec}}=\frac{P_{Em}\cdot G_{Em}\cdot G_{\mathrm{Rec}}\cdot\lambda^{2}}{(4\cdot\pi)^{2}\cdot d^{2}\cdot L} \tag{3}$$

where: P_{Rec}, P_{Em} (G_{Rec}, G_{Em}) are respectively reception/transmission powers (antennas gains), λ wavelength of the operating frequency, L loss factor due to propagation and d distance between transmitter and receiver.

Replacing the notations in equation (**3**), we obtain for the link 1:

$$P_1=\frac{P_{Em}\{B\}\cdot G_{Em}\{B\}\cdot G_{\mathrm{Rec}}\{A\}\cdot\lambda_{\{B\rightarrow A\}}^{2}}{(4\cdot\pi)^{2}\cdot d_{\{B\rightarrow A\}}{}^{2}\cdot L} \tag{4}$$

Similarly, for link 2, we have the next expression of the received power:

$$P_2=\frac{P_{Em}\{C\}\cdot G_{Em}\{C\}\cdot G_{\mathrm{Rec}}\{A\}\cdot\lambda_{\{C\rightarrow A\}}^{2}}{(4\cdot\pi)^{2}\cdot d_{\{C\rightarrow A\}}{}^{2}\cdot L}\cdot I_{u,i} \tag{5}$$

where: $I_{u,i}$ is the channel interference factor between useful and disruptive emission channel, $P_1=P_{rec}\{B\rightarrow A\}$ and $P_2=P_{rec}\{C\rightarrow A\}$.

For both above equations the antenna gains are considered equal, in order to simplify the calculation of the interfering factor. We can also make the assumption that the powers of the two transmitters are equal in the case of similar equipment:

$$P_{Em}\{B\} = P_{Em}\{C\} \tag{6}$$

Also, the propagation factor L is identical to both relationships so that we can have the signal interference ratio SIR as:

$$SIR = \frac{1}{I_{u,i}} \cdot \left(\frac{d_i}{d_u}\right)^2 \cdot \left(\frac{f_i}{f_u}\right)^2 \tag{7}$$

For the laboratory tests we can take into account the special situation:

$$d_{\{B \to A\}} = d_{\{C \to A\}} \tag{8}$$

According to IEEE Standard 802.11, the difference between the two channels is 5MHz (each having 22MHz bandwidth), so two non-overlapping channels are at a minimum distance of $n \cdot 5\,\mathrm{MHz}$, 25 MHz without overlap is considered a deviation from an adjacent channel (ACI) and then:

$$f_i = f_u + k \cdot 5\,\mathrm{MHz} \quad k = \overline{1,4} \tag{9}$$

$$\frac{S}{I} = \frac{1}{I_{u,i}} \cdot \left(\frac{f_u + k \cdot 5\,\mathrm{MHz}}{f_u}\right)^2 \tag{10}$$

According to Shannon's theory, channel capacity is:

$$C = B \log_2\left(1 + \frac{S}{N}\right) \tag{11}$$

In our case the noise is negligible compared to the interference and considering values measured in the laboratory we can build an estimate using average values $I > N + 80\,\mathrm{dB}$, so that Shannon's relationship becomes:

$$C = B \log_2\left(1 + \frac{S}{I}\right) \tag{12}$$

Following the above logical chain, the signal to interference ratio can be estimated using the next equation:

$$\frac{S}{I} = 2^{\frac{C}{B}} - 1 \tag{13}$$

Replacing in equation (**10**) we can estimate the interference factor as:

$$I_{u,i} = \frac{1}{2^{\frac{C}{B}} - 1} \cdot \left(\frac{f_u + k \cdot 5\,\mathrm{MHz}}{f_u}\right)^2 \tag{14}$$

The k factor has values form 1 to 4 according to the nature of the overlapping in the IEEE 802.11 allocation.

V. EXPERIMENTAL DATA AND RESULTS

All the measurements in our test were made using testing bed depicted in Fig. 4 The maximum reachable data rate between AP1 and PC2 is determined in condition of interference from the AP2 equipment, which is transmitting data in adjacent channels to the desired signal channel.

The measured data are presented in the following tables:

TABLE 2. Test result for Ch 4 at 06 m distance

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	9.34	1.87	1.50%
2	100	10.85	1.44	1.40%
3	100	11.77	1.26	1.60%
4	100	11.41	1.53	2.80%
5	100	11.09	1.66	1.90%
Average	100	10.89	1.55	1.84%

TABLE 3. Test result for Ch 4 at 10 m distance

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	11.65	1.50	0.24%
2	100	12.35	1.94	0.28%
3	100	12.43	16.19	0.44%
4	100	11.90	1.28	0.26%
5	100	12.57	1.39	0.25%
Average	100	12.18	4.46	0.29%

TABLE 4. Test result for Ch 5 at 06 m distance

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	9.50	2.27	0.22%
2	100	9.35	1.93	0.17%
3	100	12.01	1.58	0.30%
4	100	11.00	1.89	0.24%
5	100	10.92	1.54	0.48%
Average	100	10.56	1.84	0.28%

TABLE 5. Test result for Ch 5 at 10 m distance

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	11.14	1.38	0.20%
2	100	9.79	1.41	0.28%
3	100	9.92	6.39	0.13%
4	100	10.20	5.16	0.21%
5	100	9.36	2.03	0.26%
Average	100	10.08	3.27	0.22%

TABLE 6. Test result for Ch 6 at 06 m distance

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	12.77	1.27	0.47%
2	100	12.78	1.69	0.47%
3	100	12.77	1.57	0.48%
4	100	12.88	1.53	0.60%
5	100	12.93	1.45	0.91%
Average	100	12.83	1.50	0.59%

TABLE 7. Test result for Ch 6 at 10 m distance

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	13.20	1.58	0.41%
2	100	13.00	1.18	0.18%
3	100	12.96	1.74	0.18%
4	100	13.37	1.32	0.30%
5	100	13.05	1.18	0.38%
Average	100	13.12	1.40	0.29%

TABLE 8. TEST RESULT FOR CH 7 AT 06 M DISTANCE

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	7.71	1.45	0.41%
2	100	5.70	1.35	0.22%
3	100	6.99	1.40	0.72%
4	100	6.20	1.41	0.41%
5	100	4.38	1.42	0.32%
Average	100	6.20	1.41	0.42%

TABLE 9. TEST RESULT FOR CH 7 AT 10 M DISTANCE

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	13.28	1.60	0.28%
2	100	13.06	1.73	0.25%
3	100	13.68	1.83	0.61%
4	100	13.88	1.96	0.25%
5	100	13.94	1.54	0.17%
Average	100	13.57	1.73	0.31%

TABLE 10. TEST RESULT FOR CH 8 AT 06 M DISTANCE

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	9.27	1.47	0.81%
2	100	10.63	1.06	0.63%
3	100	9.79	1.61	0.63%
4	100	10.54	1.33	0.55%
5	100	9.11	1.09	0.95%
Average	100	9.87	1.31	0.71%

TABLE 11. TEST RESULT FOR CH 8 AT 10 M DISTANCE

No.	Running Time[s]	Throughput [Mb/s]	Jitter [ms]	Lost packets
1	100	12.92	16.42	0.37%
2	100	13.11	1.49	0.49%
3	100	13.04	1.33	0.34%
4	100	12.69	16.26	0.22%
5	100	13.46	1.77	0.22%
Average	100	13.05	7.45	0.33%

In order to measure the data rate we will use Jperf application [7], which is able to determine the maximum throughput between two computers.

For each configuration we setup 2 parameters: physical distance and channel separation. The distance parameter has 2 values 6 meters and 10 meters. The channel separation was setup to cover the POCs around the channel 6, we started from channel 4 and end to channel 8.

For each pair parameters (distance and channel separation) we have made 5 experiments with 100 s durations.

In Fig. 9 is presented values for POCs interference with AP2 situated at 6 m distance from AP1 according to SINR determined in the equation (10).

All the measurement was made in the real conditions with existing of other equipment in the proximity. For the future we will use an anechoic chamber in order to avoid the uncontrolled interference to appear.

The Wi-Fi equipments used are commercially ones with few controllable parameters. For the next set of tests we will use more flexible equipments. The main parameter witch must be controlled is the power level of the equipment.

After finishing shifting the interference through every channel (Ch 4 to Ch 8), we have changed the distance between PC2 and AP2 to 10 meters and repeated the hole process

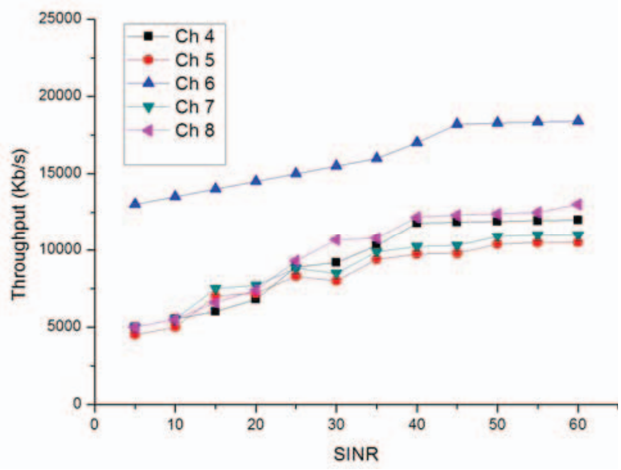

Fig. 9 Data results with POC interference from 6 m

. In Fig. 10 is presented values for POCs interference with AP2 situated at 10 m distance from AP1 according to SINR determined in the equation (10).

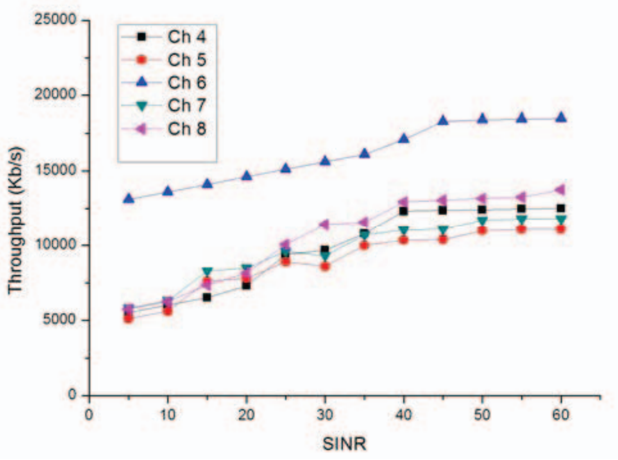

Fig. 10 Data results with POC interference from 10 m

We have worked in an open air environment, so the only attenuation was caused by the distance.

We can observe from the above figures that when the distance between PC2 and AP2 is fixed, the throughput between AP1 and PC2 increases as the number of separation channels grow up. We can also observe that for any single channel where the interference is transmitted, the throughput between AP1 and PC2 increases when AP2 is moved farther away from PC2.

We also can find in Fig. 10 that when the separation distance is short, the link 1 (desired signal) does not achieve the maximum reachable data rate, an issue less considered in [**4**].

Another important aspect is that if the distance is enough big, although we have the interference of an overlapping channel we can reach the maximum data rate.

Based on the last observation and results, it is worth to study in the future which is the minimum necessary distance from which it is possible to obtain the maximum reachable data rate in link 1, so one could consider that there is no interference (we will call this distance interference range). This means to extend the results from Fig. 9 and Fig. 10 to some scenarios where the distance is also variable, as a parameter.

Optimizing the network (reducing the interference influence) leads to a reduction of errors caused by interference and this way reducing the IP packets retransmissions, which eventually will improve the “air” (wireless) traffic and then throughput.

For future work we intend to extend, depending on the available hard/software, the implementation of the proposed general model and algorithm, with the PISA phase, eventually working to an integration software and if necessary improving the algorithms, based on simulation/experimental results.

VI. CONCLUSIONS

The extended use of WLAN applications produces a high density of access points and a lot of interfering signals that decrease the networks performance.

Through this paper we have presented a theoretical model and an experimental approach to obtain useful information regarding channel allocation and spatial reuse in conditions of the intense traffic, by exploiting the data related to the site interference.

The performed experiments allowed to observe how the interfering signals, in a diversity of spectrum scenarios, could affect the desired signal.

The results proved that not only co-channel and adjacent channel interferences affects our signal, but also non-overlapping signals can influence the desired signal and reduce the performance if the power level of the interfering signal is enough high [**11**], [**12**], [**16**].

These results have confirmed the increasing impact of interference on performance, as the jamming channel is closer to channel 6 where the desired signal is operating and the distance is smaller.

In addition, we have determined how smart planning of the operating channel versus the observed interference spectrum configuration can reduce the amount of interference impact and eventually improve Wi-Fi network performance. We have also proposed an alternative way to avoid interferences, without changing the channels (desired or jamming), which consists on getting out of the jamming signal’s interference range, after estimating this range.

A paper important result and conclusion is that a combination of both methods can allow avoiding an important part of the incoming interference.

The presented families of graphs could be used to extend the observations and practical conclusions, providing also a base to continue the study as we above mentioned, in order to refine the results and eventually correct the theoretical model.

There are more related papers to our work [**13**], [**14**], [**15**], [**17**], for a more precise determination of the interference factor we must create in the future an even more complex environment to simulate the sustained transmission related to SINR.

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