WLAN IEEE 802.11a/b/g/n Indoor Coverage and Interference Performance Study

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Abstract—**An adequate wireless network plan is needed to replace the traditional wired LANs. A full coverage WLAN offers the flexibility to relocate people and equipment or to reconfigure and add more wireless devices to the network. Usually, an IEEE 802.11 variant is chosen based on their bandwidth and their coverage area. However, sometimes there are special cases where the best technology is not the newest one. In addition, suitable positioning of access points (AP) is crucial to determine the efficiency of the network. E.g. in the case where devices are going to transmit at a maximum of 1 Mbps, any choice is acceptable, but when it is required higher performance, other factors must be considered. In this paper, we compare IEEE 802.11a/b/g/n indoor environments to know what technology is better. This comparison will be taken in terms of RSSI, coverage area, and measuring the interferences between channels. These key factors must be optimum to have high performance in the WLAN. This study will help the researchers to choose the best technology depending of their deploying case, and we will see study the best variant for indoors.**

Keywords-WLAN; IEEE 802.11; Coverage; Interferences; Performance measurements.

I. INTRODUCTION

This paper is an extended version of the paper presented by S. Sendra et al. in [1].

One of the major issues in Wireless Local Area Network (WLAN) indoor environments is the multipath dispersion due to the influence of many signal reflectors and diffusions. Walls, floors and roofs attenuate the signal highly and provoke great variations in the mean received power. Even the furniture and the metallic structures of the walls and roofs have high impact because they enhance the scattering and diffraction. There has been many studies about the signal propagation in indoors [2][3]. Moreover, there are special challenges when designing WLANs in indoors [4].

Because the emitter and the receiver are close, the delay between echoes will enlarge the delay spread. But, temporal variations are slower because of the low mobility of the users. Temporal variations are mainly given by the presence of humans close to the antennas. Moreover, there are other features in indoor environments such as:

- Electromagnetic fields provided by electronic devices. Although the reflection and diffraction can be modeled, there are many things inside the building that introduce a certain grade of variability [3].
- Usually people walking in any corridor or facility close to the emitter or the receiver will cause significant variations [5].
- Because the distances are short, any variation of the direction of the antenna will imply high changes in the signal received.
- Metallic objects reflect the radio signal. The signal will not cross metallic walls and metallic objects will fade.
- Wood, crystal, plastic and bricks reflect part of the signal, but let pass the rest.
- The objects with high humidity have more signal absorption.

There are several indoor propagation models. They can be classified in empirical models (which are based on the measures taken and predict the signal loss), in deterministic models (that simulate the signal propagation in order to characterize the transmission channel), theoretical models, (which are based in the physical laws of the modeled medium) and stochastic models (they are modes which results have a probability distribution) [6]. The appropriate model must be chosen based in the design necessities. Empirical models are used in network design, while deterministic models are used for high precision applications. The first ones are less complex and need lower input parameters, but they do not predict instantaneous signal fainting [7].

The most well known models are the following ones:

- Log-Normal Shadowing Path Loss Model [8]
- Loss Model based in COST 231 [9]
- Linear Path Attenuation Model [10]
- Keenan-Motley Model [11]
- ITU-R Model [12]
- Dual Slope-Model [13]
- Multi-Wall Model [14]

Several authors have studied empirically each one of them providing their drawbacks and benefits.

But, when we are setting up a WLAN, it is not practical to model all wireless coverage area for each site where the access point is going to be placed, especially when we are talking about large extension areas [15]. Within the IEEE 802.11 standard [16], there are included several variants like IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and IEEE 802.11n. All of them provide different coverage areas, and even different signal strength inside the coverage area.

The standard uses the CSMA/CA protocol as the medium access method. It is a carrier sense multiple access with collision avoidance used to avoid collisions between wireless data packets. In Europe, the frequency ranges from 2.401 to 2.483 GHz is divided into 13 channels of 22 MHz wide, and spaced 5 MHz between them, where channel 1 is centered on 2.412 GHz and the channel 13 is located at 2.472 GHz.

Japan adds an additional channel 14, located 12 MHz above channel 13. In an IEEE 802.11 network, the participant significantly reduces the speed of the overall wireless network. Now we are going to introduce each IEEE 802.11 variant [17, 18].

A. IEEE 802.11a

IEEE 802.11a was approved in 1999. Although it was born in 1999, it did not begin to be marketed until 2001. This variant works in the 5 GHz band. Its architecture is based on two types of devices: the Access Points (APs), which are the base station for the wireless network, and the wireless clients, that can be mobile devices such as laptops, PDAs, and fixed devices such as desktops and workstations equipped with a wireless network interface.

IEEE 802.11a uses OFDM (Orthogonal Frequency Division Multiplexing) modulation with 52 subcarriers. This standard has a theoretical maximum speed of 54 Mbps, but the transmission rate decreases when the signal quality decreases. 54 Mbps could be changed to 48, 36, 24, 12, 9 and 6 Mbps. There are 52 subcarriers, 48 of them are used for the data transmission and 4 for pilot tasks, with a separation of 312.5 KHz. Each subcarrier may be modulated by BPSK (Binary Phase Shift Keying), QPSK (Quaternary Phase Shift Keying), 16-QAM (Quadrature Amplitude Modulation) or 64-QAM.

IEEE 802.11a provides 12 non-overlapping channels. As it uses the 5 GHz band, the signal has less interference than the other standards IEEE 802.11. But the equipment must be in the line of sight (LOS) to gain a better efficiency in communications.

B. IEEE 802.11b

The 802.11b standard was approved in 1999. IEEE 802.11b data are encoded using the Direct Sequence Spread Spectrum Signal (DSSS). This technology uses CCK (Complementary Code Keying) and QPSK modulation to achieve a maximum transfer raw rate of 11 Mbps. However, it cannot exceed 6 Mbps with TCP (Transmission Control Protocol) and 7 Mbps with UDP (User Datagram Protocol) theoretically.

The protocol can be used in point-to-multipoint or point-to-point topology with links over distances proportional to the features of the antennas and output power. Furthermore, if there is any problem with the signal quality, it is possible to transmit in 5.5, 2 or 1 Mbps, using redundant methods of data encryption.

First devices appeared very quickly because this variant was an extension to the DSSS modulation of the original standard. The higher speed and the low cost of the devices achieved a fast growth of this technology in the market.

C. IEEE 802.11g

IEEE 802.11g appeared in 2003. It is an evolution of IEEE 802.11b. It works on 2.4 GHz frequency band and it is compatible with IEEE 802.11b. Its theoretical transfer is 54 Mbps, although it is reduced to 22 Mbps when the receiver is some meters far from the AP in a real scenario. It uses 52 subcarriers.

The modulation scheme used in 802.11g is orthogonal frequency-division multiplexing (OFDM), such as in 802.11a, with data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. It reverts to CCK (like the 802.11b standard) for 5.5 and 11 Mbps and to DBPSK and DQPSK + DSSS for 1 and 2 Mbps respectively. In this standard, there is also a speed decrease according to the signal quality.

IEEE 802.11g suffers from the same interference as IEEE 802.11b in the already crowded 2.4 GHz range.

Because IEEE 802.11g uses the same radio signaling (CCK) as 802.11b, at the lower four IEEE 802.11g data rates, it is fully backward compatible with IEEE 802.11b. This enables IEEE 802.11b/g wireless networks to continue supporting only IEEE 802.11b enabled devices. IEEE 802.11g may seem to be the competence of 802.11a, but most products include both technologies because they are complementary.

D. IEEE 802.11n

While IEEE 802.11a/b/g WLANs provide adequate performance for today's networking applications, the wireless applications of next generation require higher data throughput and bigger coverage area. This variant sought to bring the transmission capacity of wireless data transmission at speeds of wired systems.

IEEE 802.11n is a proposed amendment to the IEEE 802.11-2007 standard [16] in order to significantly improve the network performance of the previous standards such as 802.11b and 802.11g. IEEE 802.11n is built based on previous standards of the 802.11 family, adding Multiple-Input Multiple-Output (MIMO) and binding of network interfaces (Channel Bonding). It also adds frames to the MAC layer.

It presents an increase of the theoretical maximum rate of 600 Mbps of data transfer. Currently it supports a PHY rate of 450 Mbps, using 3 spatial streams in a channel width of 40 MHz. Furthermore, IEEE 802.11n uses MIMO based on using multiple transmit and receive antennas to improve system performance. This technology requires a separated radio-frequency chain and an analog to digital converter for each MIMO antenna which increases the implementation costs compared to the systems without MIMO technology.

Table 1 summarizes the main characteristics of the four variants of the IEEE 802.11 standard.

The success of the standard has caused density problems related to crowding in urban areas. So, some issues must be studied such as interference, coverage and used bandwidth in each IEEE 802.11 variant. In our previous work, presented in a conference [1], we carried out coverage measurements of several devices that were capable to work in different IEEE 802.11 variants. In addition, the number of lost packets, bandwidth and throughput when there are interferences, for each IEEE 802.11 variant were measured. In this paper, we have added, on the one hand, some coverage measures that were not performed in the previous work and, on the other hand, we have taken more measurements of lost packets, bandwidth and throughput for each IEEE 802.11 variant. The results will be the mean values for each variant.

Table 1. Technology comparison.

	IEEE 802.11a	IEEE 802.11b	IEEE 802.11g	IEEE 802.11n
Frequency band	5.7 GHz	2.4 GHz	2.4 GHz	2.4 / 5 GHz
Average Theoretical speed	54 Mbps	11 Mbps	54 Mbps	600 Mbps
Modulation	OFDM	CCK modulated with QPSK	DSSS, CCK, OFDM	OFDM
Channel bandwidth	20 MHz	20 MHz	20 MHz	20 / 40 MHz
Coverage radius	35 m	38 m	38 m	75 m
Unlicensed spectrum	Yes (it depends on countries)	Yes	Yes	Yes (it depends on countries)
Radio Interference	Low	High	High	Low
Introduction cost	Medium-Low	Low	Low	High-medium
Device cost	Medium-Low	Low	Low	Medium
Mobility	Yes	Yes	Yes	Yes
Current use	Medium	High	High	High
Security	Medium	Medium	Medium	High

In this paper, we are going to show the empirical coverage area and the signal strength inside the coverage area. This let us know which is the technology that provides better coverage features, but, in this case (compared with reference [1], we will take more measures in order to extract more reliable conclusions. Moreover, we are going to compare the interferences between neighboring channels for each technology in order to know the number of available channels that can be used to plan the wireless network.

The remainder of this paper is organized as follows. Section II shows the related work on WLAN coverage designs. This section is separated in two parts. The first part shows indoor coverage studies and the second part shows papers related with performance measurements such as interferences, bandwidth and throughput. The test bench where our measurements have been performed is shown in Section III. Section IV presents the coverage measurements performed and the graphs obtained for each device, working in different IEEE 802.11 variant. Section V shows the measurements of the interferences between channels for each variant. It shows the graphs of lost packets, bandwidth and throughput when there are interferences. Finally, Section VI concludes the paper and gives our future work.

II. Related Work

In the literature, there are some works related with performance test and interference calculations. However, very few people have worked with physical devices to obtain real values.

A. Related works of indoor coverage.

There have been many studies of indoor coverage for single-transmitter and single-receiver protocols, like IEEE 802.11a, IEEE 802.11b and IEEE 802.11g [6]. Others use the measurements obtained from the signal level of a group of access points to perform the channel planning while avoiding interference [15]. There are some that locate clients by using the signal strength received by several access points [5]. IEEE 802.11 infrastructure has the advantage of being available in numerous indoor environments, and is deployed in densities that allow for the possibility of positioning with meter level accuracy.

As IEEE 802.11 networks are widely deployed, there has been a significant amount of work about planning IEEE 802.11n wireless networks. In such networks, the use of Multiple-Input Multiple-Output (MIMO) transmission scheme changes the expected behavior of signal level due to its multiple antenna use, exploiting physical phenomena such as multipath propagation to increase the transmission rate and reduce the error rate.

Foschini [19] derives theoretically that for the same SNR a 2x2 MIMO channel can hold twice the amount of bandwidth than using a single transmission and receiving antenna. As shown in [20] even further gain can be expected by the use of larger arrays of antennas in both reception and transmission.

Most of the recently published papers have modeled the MIMO channel matrix with independent and identically distributed Gaussian entries, which is an idealistic assumption, especially for indoor scenarios. More realistic MIMO channel models can be generally divided into three classes: ray-tracing, scattering and correlation models [21]. Anyway, for indoors need very large simulation time and complexity for trying to provide a good prediction of the channel behavior. On the other hand, correlation-based models don't provide detailed information about coverage, which could be needed for applications like indoor positioning [22].

There are still a few indoor IEEE 802.11n channel measurements reported in the literature. Simulation methods of these channels based on direct measurements are even fewer. At the 5 GHz band, for example, the publicly available IEEE TGn models [23] are the most convenient tools for MIMO channel simulations. However they have their own limitations; e.g., they are based on single-input single-output (SISO) channel models presented in [20] which do not reflect accurately the multipath propagation channel.

Another work that studies the coverage is presented by E. Amaldi et al. in [24]. This paper describes the optimization models with hyperbolic and quadratic objective functions. The authors propose heuristic methods that combine greedy and local search phases, and show the need of appropriate planning models and procedures that are specific to WLANs. The authors suppose that the system affects to the coverage planning process, and the incidence of overlapping regions should be taken into account in the planning procedure (beside of all the other optimization parameters). The computational results show that their heuristics provide near-optimal solutions within a reasonable amount of time.

Finally, in [25], J. N. Davies et al. measure the IEEE 802.11n signal level in a real building, but they don't make any comparison with IEEE 802.11a or IEEE 802.11g.

B. Related works of interferences.

From the IEEE 802.11 WLAN interference side, Nicolescu [26] proposed a model for interference in dense wireless networks that enables a low complexity procedure to collect the interference map and can be used to predict the damage from several simultaneous interferers. Unfortunately measurement of the interference map faces asymmetries in the card and channel behavior, which make the complexity still prohibitive for dense multiple card networks, requiring direct measurements in indoor deployments. Also, Fuxjäger et al. [27] show that the assumption of perfect independence between non-overlapping channels does not always hold in practice, by means of simple experiments with commercially available hardware, and found that the level of interference varies with physical distance, concurrent link-load, modulation rate, frame size, transmission power, receiver sensitivity and design, antenna patterns, etc., calling also for more direct measurements.

J. Padhye et al. present in [28] an interference measurement-based study between links in a static, IEEE 802.11, multi-hop wireless network. Then, the authors propose a simple empirical estimation methodology that can predict pair wise interference using only measurements. These tests are based on heuristics methods where the wireless links are defined by their packet loss rate. They state that this methodology could be applicable to any wireless network that uses omni-directional antennas.

Related to interference and throughput measures in WLAN, J. Jun et al. present in [29] an accurate formula to estimate the throughput in IEEE 802.11 networks, for several variants (802.11, 802.11b, 802.11a), in the absence of transmission errors and for various physical layers, data rates and packet sizes. The authors cite some applications where it is very important to know the maximum throughput in order to design them correctly. Theoretical Maximum Throughput can be used to facilitate optimal network provisioning, for example, in multimedia applications. It can influence the topological distribution of the nodes in the case of ad-hoc networks.

Although analytical studies and network simulations may provide valuable insights of the WLANs' operation, they cannot predict the actual performance of practical implementations with high accuracy. Moreover, measurements obtained from file transfer operations are also limited by the need to specify the processor type, processor speed and the network operating system. B. Bing presents in [30], an experimental study to characterize the behavior in terms of throughput and response time of two commercial AP under different degrees of network load. They are WavePOINT, from Lucent Technologies, and Spectrum24, from Symbol Technologies. The tests showed important characteristics such as throughput and response time under various network loads. The author also shows that the length of a data frame and the wireless bit rate also affects to the WLAN's transmission capabilities. But, the performance of an IEEE 802.11 WLAN is generally unaffected by the type of frame and the use of reservation frames such as RTS and CTS.

III. The Scenario Description

In this section, we describe the scenario where the measures have been taken and the hardware and software used to perform our research.

A. Place of measurement

In order to do the measures, we have sought a wide enclosure with an area of 91 m^2, with a length and a width of 12.5 m by 6.68 m. This building is made with walls of different thickness and materials. We have tried to find a scenario that was made from different materials, as can be found in common houses.

Fig. 1 shows the plane of garage. It has rectangular base, divided into two parts by a wall of 9 cm of thick: the garage (left) and the kitchen (right). The enclosure of the staircase is made of bricks with high consistency. All these walls have a layer of plaster and paint on both sides. The bathroom is made with hollow bricks of 9 cm. These walls are covered by ceramic tiles. All external walls are double with a thermic and acoustic insulation of polystyrene. Fig. 1 also shows the APs placement. In red we can see AP, which has been used for the coverage measurements test bench. In green we can see AP1 and AP2, which have been used for the interference test bench. Their placements have been decided randomly in order to avoid having equidistant placements.

B. Hardware used in the test bench

Four APs of different brands and models have been used. All of them are capable to working in different wireless technologies of IEEE 802.11 a/b/g/n (depending on the model). The models used are described below:

- Linksys WRT320N: It is a small device that is able to work in IEEE 802.11a/b/g/n standard variants. It works at frequencies of 2.4 GHz and 5GHz. It has three internal antennas, needed to work in IEEE 802.11n. Its RF power (EIRP) is 17 dBm.
- Dlink DWL-2000AP+: It works on IEEE 802.11g. It can be configured to work as a wireless AP, as a point to point bridge with another access point, as a wireless bridge point to multi-point or as a wireless client configured. Its output power is 16 dBm.
- Cisco Aironet 1130AG: It has been built to provide wireless coverage in offices and workplaces for their services. It is designed to be hung on the wall in a vertical position and it can works in IEEE 802.11a/g but it is also compatible with 802.11 b. It output power in IEEE 802.11a is 17 dBm, and its output power in IEEE 802.11g is 20 dBm.
- Linksys WRT54GL: This device is capable of working in the variants IEEE 802.11b/g, therefore, is only capable of emitting at a frequency of 2.4 GHz. It has 2 external antennas, which are used to correct the multipath effect. His RF power (EIRP) is approximately 18 dBm.
- Linksys WUSB600N: This is a wireless USB interface device that has been used as the capture device for all Laptops and PCs used in the test bench. This wireless card is able to capture IEEE 802.11a/b/g/n signals. It has a transmitting power of 16 dBm in all variants and its receiver sensitivity is approximately -91 dBm.

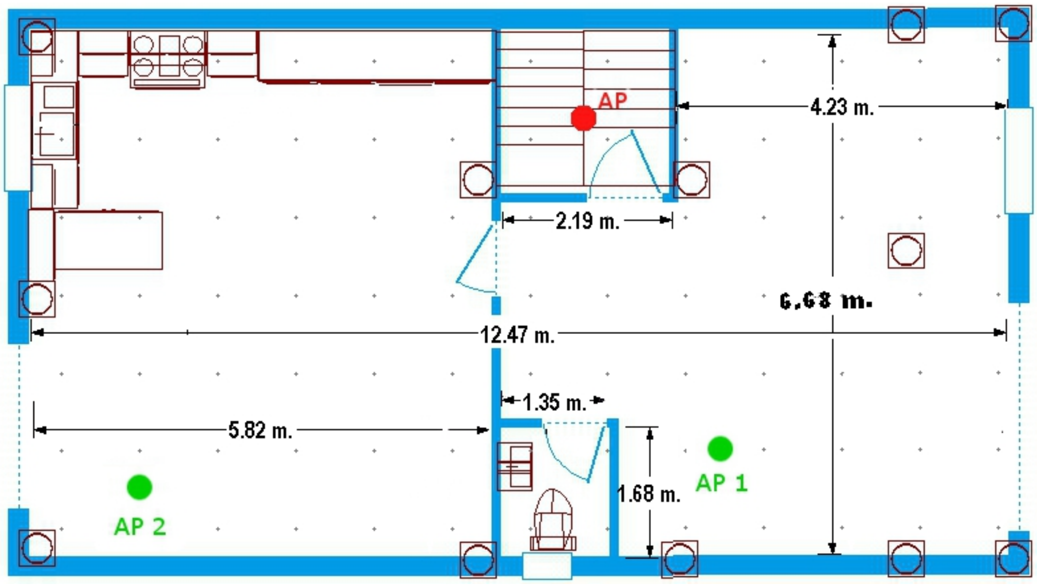

Figure 1. Scenario and APs situation.

In order to take the coverage measurements, we have used a laptop with dual core processor at 1.67 GHz per core and 1 GByte of RAM. In addition, two desktop PCs with an AMD 1700MHz CPU and 1 GByte of RAM memory have been used to take the interference measurements.

C. Software used

This subsection describes the software used to perform our test bench.

- InSSIDer is a freeware that can detect wireless networks and manage, in a graphics mode, the intensity of these signals. This program let us detect all wireless networks in the test area on the computer screen and lists all of their details: SSID, MAC address, channel, Radio Signal Strength Indicator (RSSI), type of network, security, speed and signal intensity and allows monitoring the signal quality via a chart using the received RSSI [31].
- MS-DOS commands. The MS-DOS shell presents some utilities and commands, which allow checking the status of the network connection.
- Net Meter monitors the network traffic used by all network interfaces [32]. It displays in real-time graphical and numerical downloading and uploading bandwidth rates.

IV. COVERAGE MEASUREMENTS

This section describes the strategies carried out to do the coverage measurements and the measures obtained.

A. Process to gather the coverage measurements

First we measured the wireless coverage offered by each device, working on various wireless technologies. These signal values depend mainly, on the losses suffered due to the walls traversed and the multipath effect.

In order to perform this work, we draw a grid in the garage floor. It allowed us to take measurements of all devices in the same place. The position of the measure points is seen in Fig. 1. The equidistant points shown in the figure are separated 1m from each other.

Each access point has been located in the stairwell (marked in red on Fig. 1), at a height of 50 cm of the floor. The signal power levels received at each measure point is collected by a laptop running the application software InSSIDer. The used capture device was a WUSB600N wireless card for all computers in order to avoid adding some sort of error taking the measurements. The laptop was located at a height of 50 cm above the ground.

B. Results of coverage measures

In Fig. 2, we can see the legend used for all coverage graphics. All values shown are measured in dBm, with an absolute error of 1dBm.

Fig. 3 shows the level of coverage obtained with Linksys WRT320N when it is configured to work only in 802.11a. As the figure shows, the best coverage is located in the stairwell. The signal is propagated out of the walls of the stairwell to the outer walls. Then, there signal strength is quickly decreased with some low peaks in the coverage area.

Fig. 4 shows the coverage obtained with the Cisco Aironet 1130AG when it is configured to work only in 802.11 a. This device presents the lowest signal level. This may be due to the antenna radiation direction (we place all the devices in the same position, independently of the placement of the antenna inside of them).

Fig. 5 shows the level of coverage obtained with Linksys WRT320N configured to work only in 802.11b. In this case, the best coverage is located in the staircase, but the signal is decreased quickly as it is propagated to the garage. The kitchen area has a lower signal level than the garage.

Fig. 6 shows the level of coverage obtained with the Linksys WRT54GL configured to work only in 802.11b. It has been the device that provides higher signal strength in the coverage area.

Fig. 7 shows the level of coverage obtained with the Linksys WRT320N configured to work only in 802.11n. Although there is high signal strength close to the access point, there are suddenly low values in the coverage area.

Fig. 8 shows the level of coverage obtained with the Dlink DWL-2000AP configured to work only in 802.11 g. This device presents the highest signal levels in almost all the garage surface, and the kitchen's area.

Fig. 9 shows the level of coverage obtained with the Cisco Aironet 1130AG configured to work only in 802.11 g. This device is the one that presents the lowest signal level. This may be due to the antenna radiation direction (we place all the devices in the same position, independently of the placement of the antenna inside of them).

Fig. 10 shows the level of coverage obtained for the Linksys WRT320N configured to work only in 802.11g. As we can see, when it is working in IEEE 802.11b, its coverage is better than in IEEE 802.11g . It is even more significant in closest distances.

Fig. 11 shows the coverage obtained with the Linksys WRT54GL when it is configured to work only in 802.11g. It has been one of devices that provides the lowest higher signal strength in the coverage area.

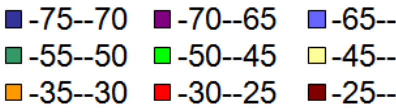

Figure 2. Colour legend.

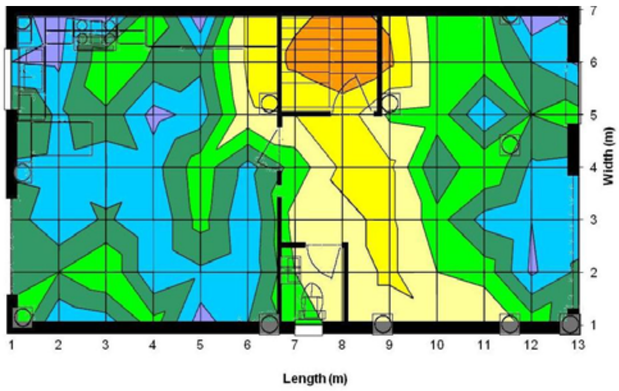

Figure 3. Coverage to Linksys WRT320N in 802.11a.

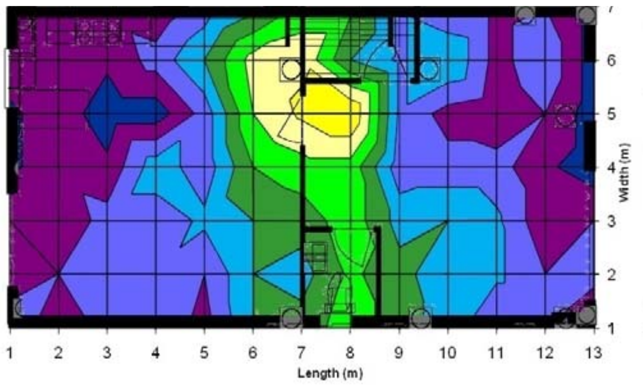

Figure 4. Coverage to Cisco aironet 1130AG in 802.11a

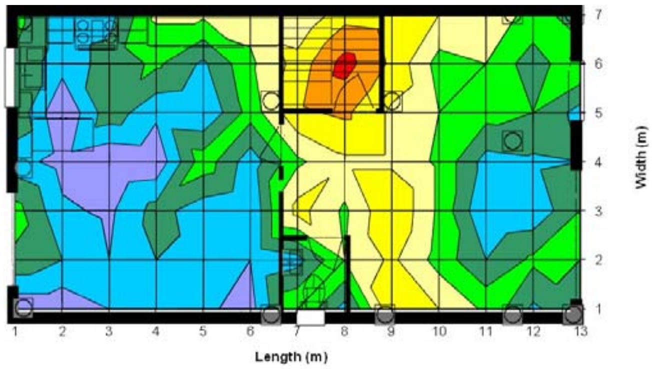

Figure 5. Coverage to Linksys WRT320N in 802.11b.

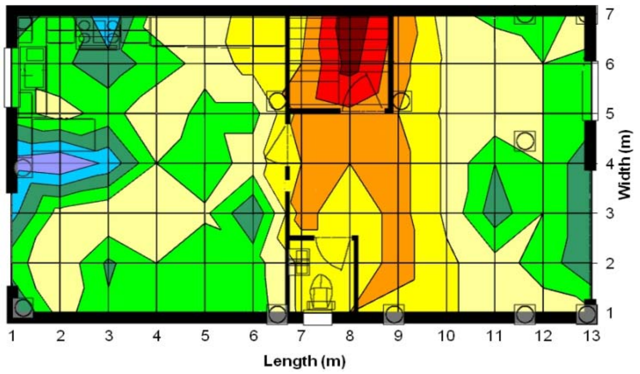

Figure 6. Coverage to Linksys WRT54GL in 802.11b.

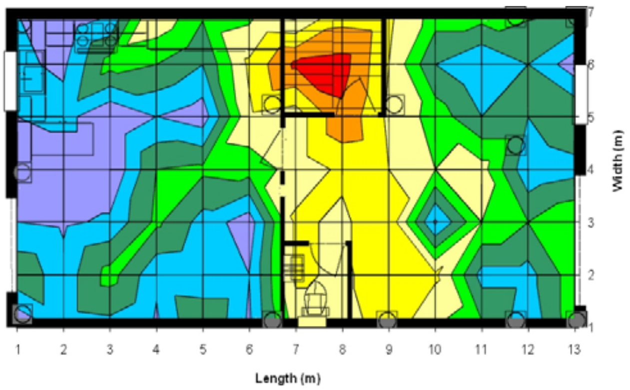

Figure 7. Coverage to Linksys WRT320N in 802.11n.

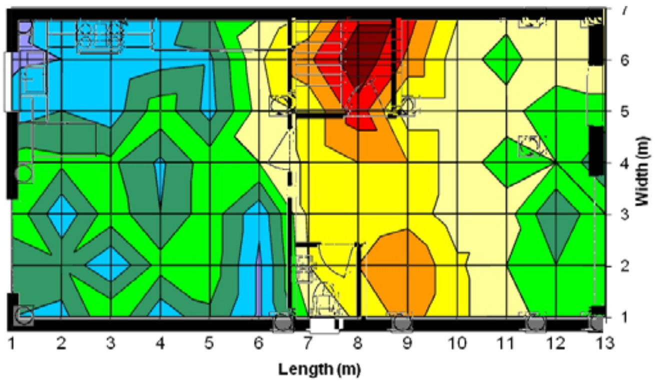

Figure 8. Coverage to Dlink DWL-2000AP in 802.11g.

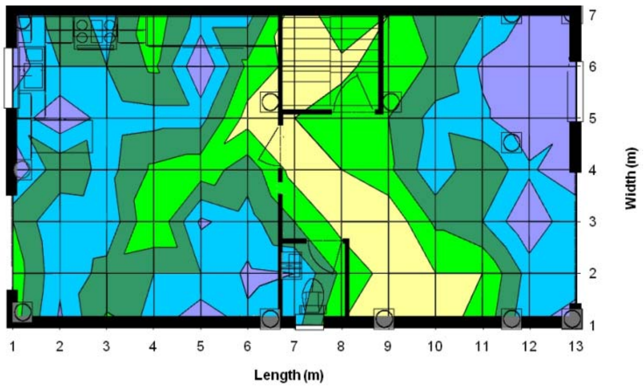

Figure 9. Coverage to Cisco Aironet 1130AG in 802.11g.

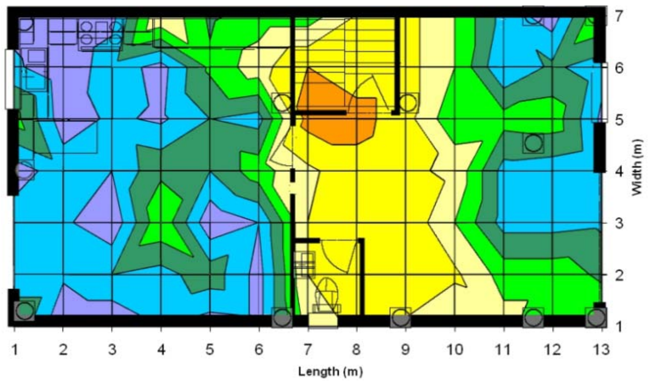

Figure 10. Coverage to Linksys WRT320N in 802.11g.

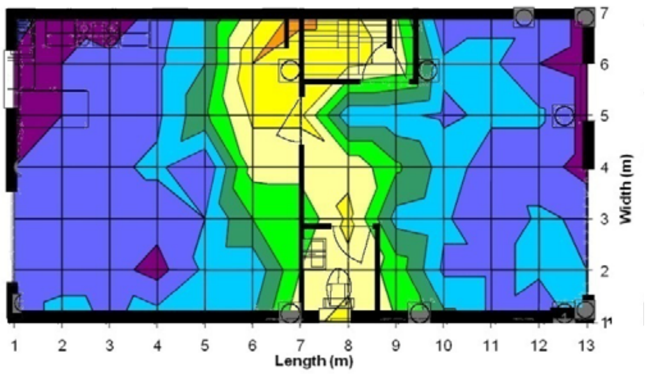

Figure 11. Coverage to Linksys WRT54GL in 802.11g

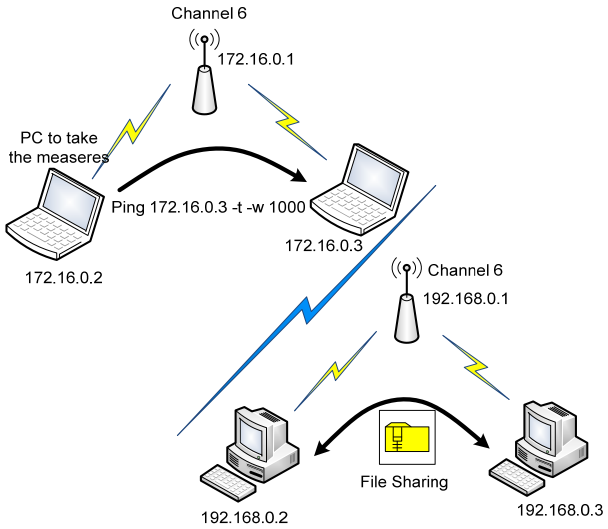

Figure 12. Network topology.

V. INTERFERENCE MEASUREMENTS

This section describes the process used to make the interference measurements. It also shows the topology of PCs and APs.

A. Scenario

In this test, we have used four PCs and two APs of the same brand and model. Fig.1 shows the location of AP1 and AP2 (marked in green). These sites are chosen to ensure that there are walls between the two small wireless networks.

First, we used channel 6 for both wireless devices. Then, we configured different IP networks in order to perform our test. Now we are able to measure the effects of the interference generated by another network working in the same channel. In order to take the measurements, we changed the working channel in one device while the other remained fixed. The measurements were taken for each channel until there was a difference of 5 channels. With the collected data, the average value of lost packets, throughput and bandwidth was estimated. This let us know the behavior of each variant based on the number of overlapping channels.

Fig. 12 shows the topologies. The PCs are situated at a distance of approximately 1 m from the AP which is associated to. A large file is transmitted between the computers associated to the AP2. Meanwhile, measurements of the packet loss, throughput and bandwidth consumed are carried out in the Wireless Network of the AP1.

In order to present our results, we have grouped the collected data of the variants IEEE 802.11 b/g/n (all of them work at 2.4 GHz) in the same figures, because the distribution channels were the same, while IEEE 802.11a, which works at 5GHz, was displayed in separate figures.

The measures were made with all devices under test, working on different variants. Later, we computed the average value of lost packets, throughput and bandwidth.

B. Lost Packets

Based on the physical properties of radio-frequency signals, when we have two frequency components, represented in the same spectral domain, the interference should be low (which results in fewer lost packets), because overlapping spectra is lower. But, in the following simulations we have found that the measurements do not always follow this behavior.

In order to know the lost packets, a ping is transmitted between the PCs associated to AP1. We fixed the maximum time to 1000 milliseconds. After this time, the packet will be considered lost. We choose a small time, because it is a small network, without a large number of intermediate devices that may introduce delays. Measurements were taken during 3 minutes in each the devices.

The obtained results as a function of the amount of channel separation are shown in the following figures.

Figure 13 shows the number of lost packets for IEEE 802.11 b/g/n, when both devices are working on the same channel. As we can see b variant has higher number of lost packets (around 44%) than g variant, while devices working in IEEE 802.11n do not have lost packets.

Figure 14 shows the number of lost packets for IEEE 802.11 b/g/n, where there is one channel between them. In this case, b variant records around 55% of lost packets and g variant has lost 42%. IEEE 802.11n does not have lost packets.

Fig. 15 shows the number of lost packets for IEEE 802.11 b/g/n, where there are two channels of separation. The number of lost packets, when the devices operate in IEEE 802.11b/g variants, was between 42 and 46%. In this case, IEEE 802.11n variant has 1% of lost packets.

Fig. 16 shows the number of lost packets for IEEE 802.11 b/g/n, when there are three channels of separation. The number of lost packets for IEEE 802.11b/g was between 40 and 44% and the IEEE 802.11n variant does not have lost packets.

Figure 17 shows the number of lost packets for IEEE 802.11 b/g/n, when there are four separation channels. As we can see the IEEE 802.11b variant has a higher number of lost packets (around 42%) than the IEEE 802.11g variant (around 37%). While IEEE 802.11n, does not have lost packets.

Figure 18 shows the number of lost packet for IEEE 802.11 b/g/n, when there are five separation channels. The number of lost packets for IEEE 802.11b/g was between 38 and 42%, and IEEE 802.11n didn't report lost packets.

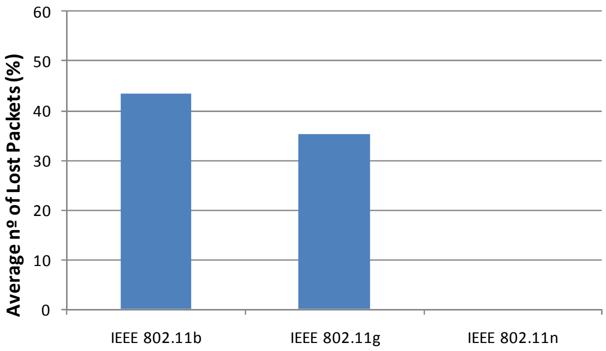

Figure 13. Lost packets with overloaping channels.

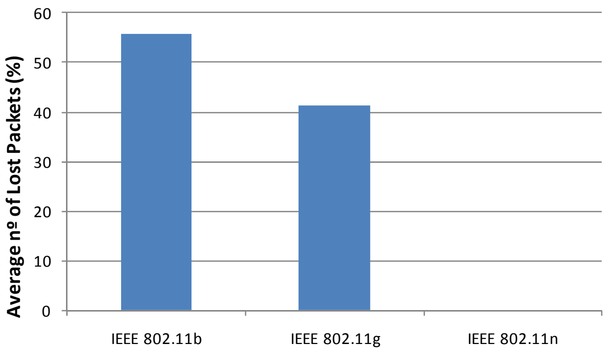

Figure 14. Lost packets with one channel of difference.

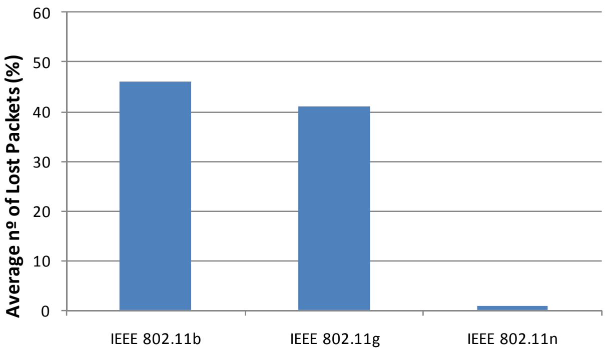

Figure 15. Lost packets with two channels of difference.

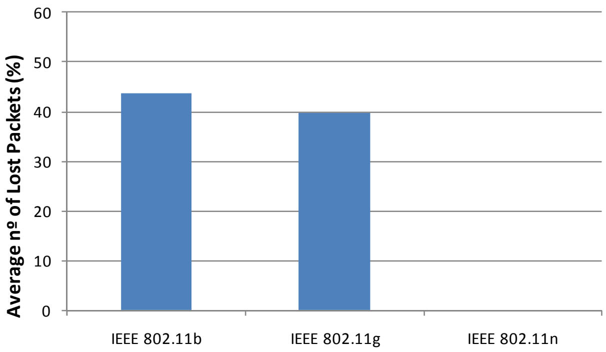

Figure 16. Lost packets with three channels of difference.

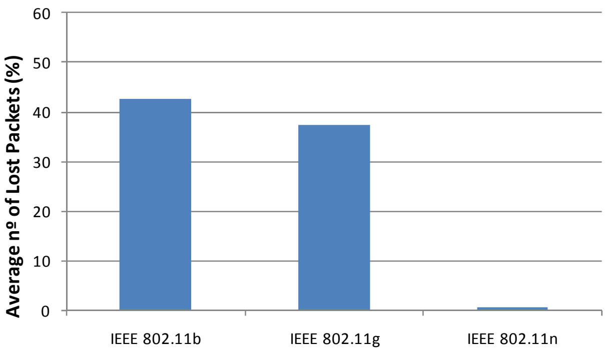

Figure 17. Lost packets with four channels of difference

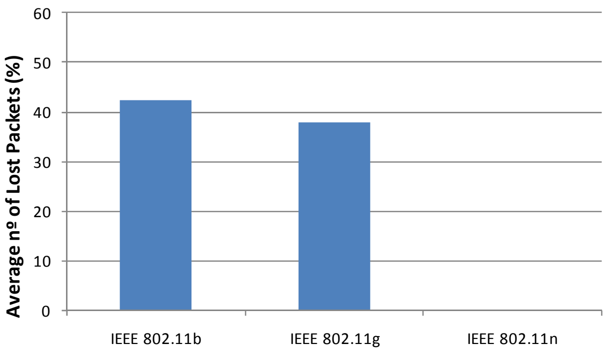

Figure 18. Lost packets with five channels of difference.

The measurements show that devices operating under the IEEE 802.11n variant does not have lost packets, while the IEEE 802.11b and IEEE 802.11g variants could have 40% of lost packets (depending on the amount of separation channels). This is mainly because IEEE 802.11n uses MIMO technology, where both transmitter and receiver have multiple antennas reducing the interferences. Generally, in traditional wireless transmission the signal is affected by reflections, causing self-degradation and therefore data loss. MIMO takes advantage of physical phenomena such as multipath propagation to increase the transmission rate and reduce the error rate. That is, MIMO increases the spectral efficiency of wireless communication system through the use of the space domain.

In IEEE 802.11b and IEEE 802.11g variants there is a slight tendency to record fewer lost packets when the channel separation is an even number than when there is an odd channel of separation. These losses can be approximated in both cases by a fifth degree polynomial with high accuracy. In particular, taking the measurements gathered, IEEE 802.11b follows expression 1:

$$y = 0.09x^5 - 1.14x^4 + 5.5x^3 - 12.98x^2 + 14.54 + 35.25 \quad (1)$$

And IEEE 802.11 g follows expression 2:

$$y = 0.35x^5 - 4.95x^4 + 25.96x^3 - 59.43x^2 + 0.31x + 43.5 \quad (2)$$

Where x is the separation between working channels and y represents the value in % of lost packets.

In order to test the performance of IEEE 802.11a variant we used two different devices. The first one was Cisco Aironet 1130AG working in IEEE 802.11a, which uses dynamic frequency selection (DFS). This system does not allow us to select different channels (such as we did in IEEE 802.11 b/g/n). The other device was the WRT320N working in IEEE 802.11a, which only works in the channels 36, 40, 44, 48. Although in the 5GHz frequency band, devices could work theoretically with 8 non-overlapping channels simultaneously, this device only allows us to work with 4 non-overlapping channels. Then, we estimated the average bandwidth for each device when there are no overlapping channels. The results are represented in fig. 19.

As fig19 shows, WRT320N working in IEEE 802.11a presents five times less packet loss than the Cisco Aironet 1130AG device (which has around 40%).

C. Throughput and Bandwidth consumption measurements

In order to measure the bandwidth offered by each technology, we performed the following test. First, 2 PCs were associated to the AP2 and were transmitting large files consuming all the bandwidth available in this network. Then, there were 2 PCs associated to the AP1, which were transmitting a large file too. The Net Meter captured the consumed bandwidth in one of these PCs. The measures are carried out during 3 minutes.

The result of the average bandwidth consumed by each IEEE 802.11 variant for different the number of separation channels is shown in the following figures.

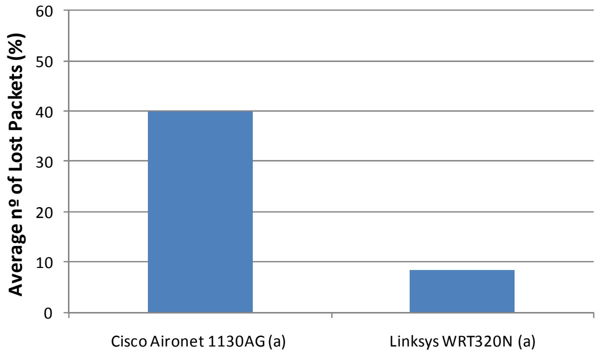

Figure 19. Lost packets with non overlapping channel

This average has been estimated taking into account the measurements taken from all devices for each variant.

Fig. 20 shows the bandwidth consumed for IEEE 802.11b/g/n, when both devices are working in the same channel. As we can see, IEEE 802.11b variant has approximately an average of 3Mbps, while IEEE 802.11g and n variants, provide around 10-12 Mbps.

Fig. 21 shows the bandwidth for IEEE 802.11b/g/n, when there is one separation channel. In this case, the IEEE 802.11b variant shows a mean bandwidth of 2Mbps and IEEE 802.11g and n variants provide approximately 11Mbps.

Fig. 22 shows the bandwidth for IEEE 802.11b/g/n, when there are two separation channels. The average bandwidth values for IEEE 802.11g and n are between 10-11Mbps. Furthermore, IEEE 802.11b is using an average bandwidth of 2.5Mbps.

Fig. 23 shows the bandwidth for IEEE 802.11b/g/n, when there are three separation channels. In this case, IEEE 802.11g variant has higher bandwidth (11Mbps) than the IEEE 802.11n variant (10Mbps). IEEE 802.11b variant has an average value of 3Mbps.

Fig. 24 shows the bandwidth for IEEE 802.11b/g/n, when there are four separation channels. We can see that IEEE 802.11b variant has an average value of 3 Mbps, while IEEE 802.11g variant has 10.5 Mbps and IEEE 802.11n variant has 12 Mbps.

Fig. 25 shows the bandwidth for IEEE 802.11b/g/n, when there are five separation channels. The IEEE 802.11b variant maintains its average value around 3 Mbps, while IEEE 802.11g/n variants have their average values very close to 10Mbps.

As it happens in lost packets measurements, there is a trend in the bandwidth consumption that is related to the separation of the working channels. On the one hand, IEEE802.11n and b variants, present higher mean values when the separation between the working channels is even, while IEEE802.11g variant, has its maximum values when the number of separation channels is odd.

Fig. 26 shows the bandwidth for IEEE 802.11a variant when channels are not overlapped. As we can see, both devices show a similar average bandwidth, with an average value of 11.4 Mbps.

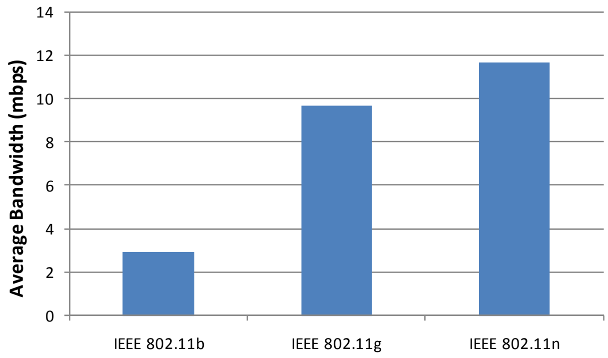

Figure 20. Average bandwidth with overloaping channels.

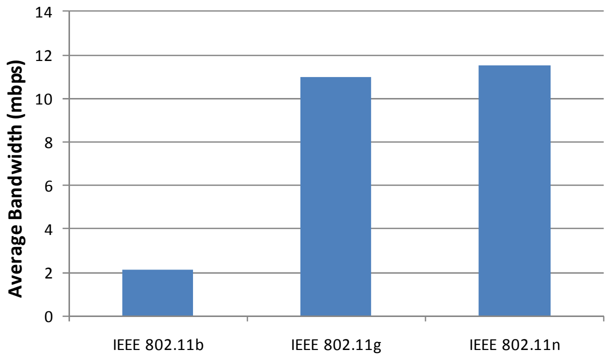

Figure 21. Average bandwidth with one channel of difference.

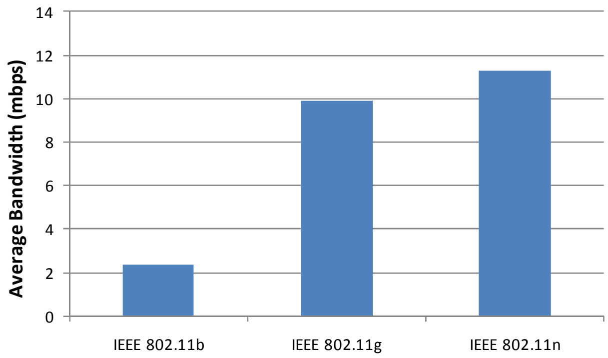

Figure 22. Average bandwidth for two channel of difference.

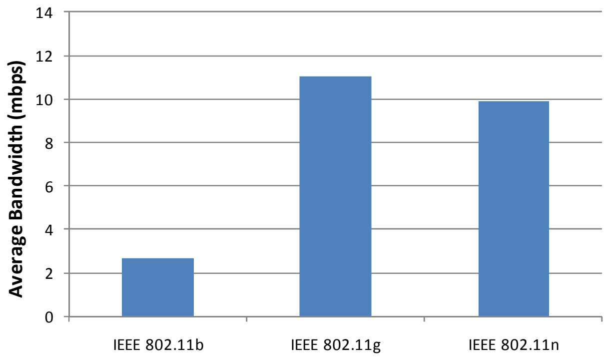

Figure 23. Average bandwidth for three channel of difference.

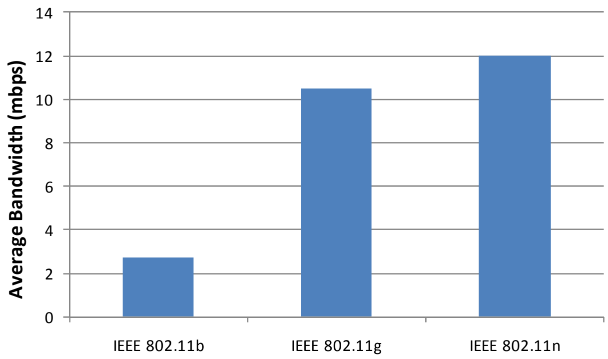

Figure 24. Average bandwidth for four channel of difference.

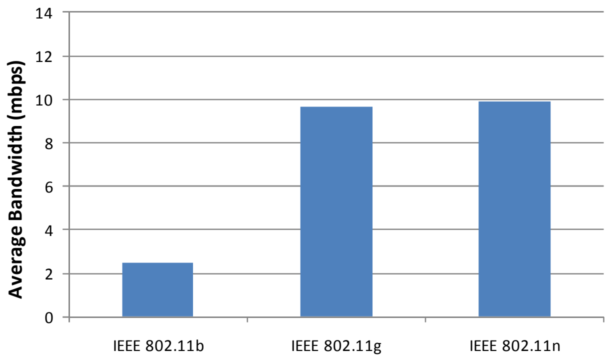

Figure 25. Average bandwidth for five channel of difference.

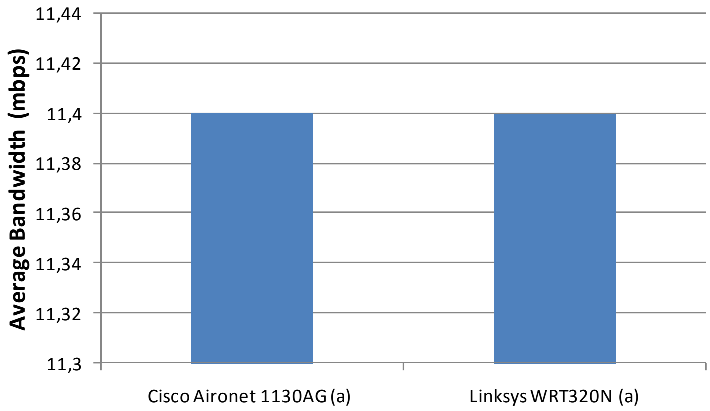

Figure 26. Average bandwidth when there are no overlapping channels in IEEE 802.11 a variant.

Finally, in order to see the use of the link capabilities for each IEEE 802.11 variant, we have measured the average throughput. These values have been obtained by dividing the average bandwidth consumption by the theoretical bandwidth of the IEEE 802.11 variant. It provides us the percentage of throughput consumption for each variant. For the IEEE 802.11n variant, we have used 320 Mbps as a reference to compute the percentage, because the used devices were limited to this speed. The results of the throughput average, as a function of the distance between channels, are shown in the following figures:

Fig. 27 shows the throughput average of IEEE 802.11b/g/n, when both devices are working in the same channel. IEEE 802.11b variant has an average throughput of 27%, meanwhile IEEE 802.11g variant maintains its average value around 18% and IEEE 802.11n variant has an average value of 4%.

Fig. 28 shows the average throughput of IEEE 802.11b/g/n variants, when there is a separation of one channel. In this case, IEEE 802.11b/g variants show values around 20% and IEEE 802.11n maintains its average value in 4%.

Fig. 29 shows the average throughput of IEEE 802.11b/g/n variants, when there are two separation channels. Again, IEEE 802.11n variant shows the lowest value, while IEEE 802.11g has its average value around 18% and the IEEE 802.11b version presents an average throughput of 22%.

Fig. 30 shows the average throughput of IEEE 802.11b/g/n, when there are three separation channels. In this case, IEEE 802.11b and g have increased their average values, locating them between 21% and 24%, but IEEE 802.11n has an average throughput of 4%.

Fig. 31 shows the average throughput of IEEE 802.11b/g/n, when there are four separation channels. The IEEE 802.11b variant has a throughput around 24.5% and IEEE 802.11g variant presents an average value of 19%. IEEE 802.11n variant maintains its value.

Fig. 32 shows the average throughput of IEEE 802.11b/g/n, when there are five separation channels. In this case, all values have decreased slightly. They have 22.5% for IEEE 802.11b, 17% for IEEE 802.11g and 3% for EEE 802.11n.

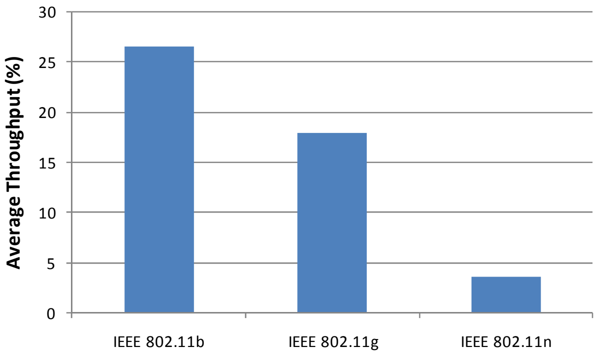

Figure 27. Average throughput with overloaping channels.

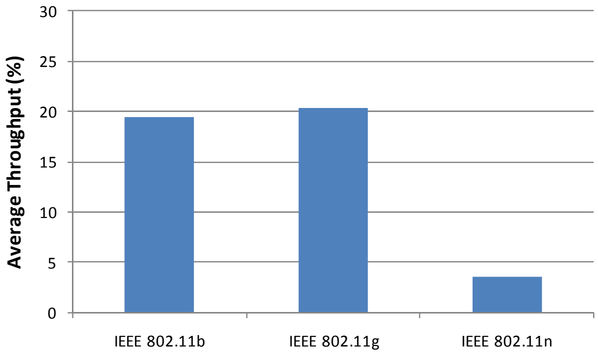

Figure 28. Average throughput with one channel of difference.

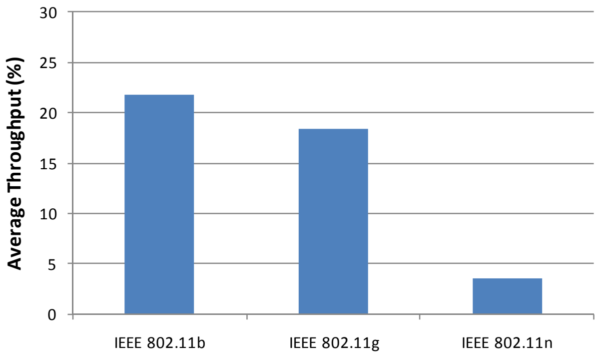

Figure 29. Average throughput with two channels of difference.

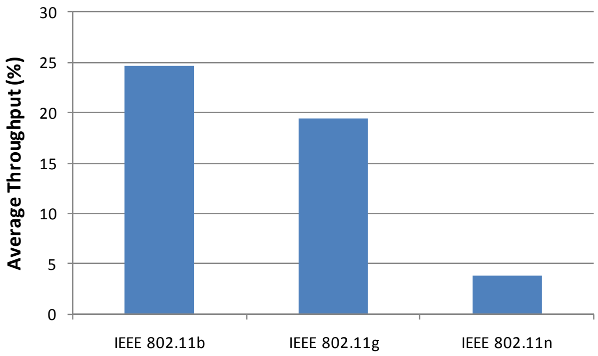

Figure 30. Average throughput with three channels of difference.

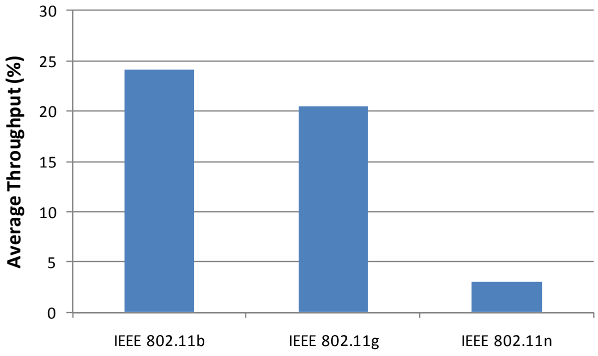

Figure 31. Average throughput with four channels of difference.

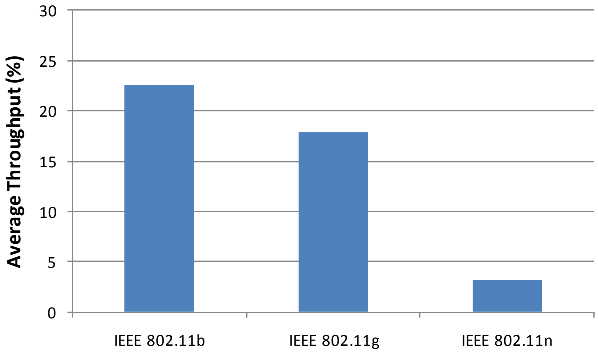

Figure 32. Average throughput with five channels of difference

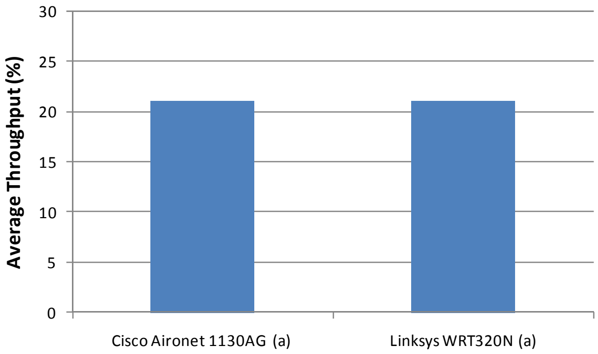

Figure 33. Average throughput with non overlapping channels

In general, we can see similar effects in all figures. The IEEE 802.11 variant that has lower average throughput is IEEE 802.11n, which in no case exceeds 5%. In IEEE 802.11g, the average throughput values is around 20%, while the variant that best uses its available bandwidth is IEEE 802.11b, which has average values very close to 25% of its total capacity.

For IEEE 802.11a variant, the average throughput measures are shown in fig. 33. Both devices have a similar average throughput (approximately 21%).

In this case it is clear that the interference highly affects the performance of the wireless network variant. IEEE 802.11a, IEEE 802.11b and IEEE 802.11g have higher throughput than IEEE 802.11n, (which average values are between 21% and 25%).

VI. Measurement Discussion

Throughout this work we have performed different test benches in order to characterize the behavior of wireless signals in indoor environments. These tests have allowed us to check some statements realized by some papers related to this issue. We have also seen some other issues.

Moreover, we analyzed the frequency spectrum between 2.4 and 2.5 GHz, which includes all channels used in IEEE 802.11 b/g/n. Because of their physical properties, we could think that if there is no overlap between channels, there should not be any interference between them. But our results did not reflect this fact. In [27], authors show in their simulation that non-overlapping channels do not have interference. In fact, their tests were different from ours. They analyzed these losses depending on the distance between nodes. Despite of this fact, the conclusions are similar. As we have seen, the devices working at 2.4 GHz register fewer lost packets due to interference, when the channels are fully overlapping (Fig. 27), than when there is one channel of separation between the devices (Fig. 28). We also see that the number of lost packets, maintaining approximately the same value when there are 3 channels of separation (Fig. 30), when there are 4 (Fig. 31) or 5 channels (fig.35). In the last two cases, the number of lost packets should be very low or zero, since the overlap between the spectral is virtually nonexistent. In this case, after having performed different tests, we state that there is a slight tendency to register fewer lost packets when the channel separation is an even number than when the channel separation is an odd number. These measurements enabled us to characterize this behavior to a fifth degree polynomial with a correlation value close to the unity.

Moreover, we can extrapolate the analysis about the number of lost packets to the bandwidth measurements, where the behavior is identical. That is, when the channel separation is an even number, there is a greater bandwidth than when the channel separation is an odd number. This fact corresponds to the values of lowest packet losses. Therefore, although we have shown that non-overlapping channels does not mean less interference level, the analysis shows that a greater number of lost packets corresponds to a lower useful bandwidth in the network.

Some published papers define the throughput, as the volume of information that traverses the network over time. And others define the throughput as the channel performance. We have taken the second meaning of this concept. It relates the amount of information flowing through the channel and the theoretical maximum capacity offered by technology. Another factor that draws the attention of this analysis is that despite of the packet losses registered in IEEE 802.11n is low; the value of throughput and channel performance is quite low. As we can see in [33] the theoretical maximum throughput and data rates for IEEE 802.11 networks in a and b variants are different compared with real throughput and data rates.

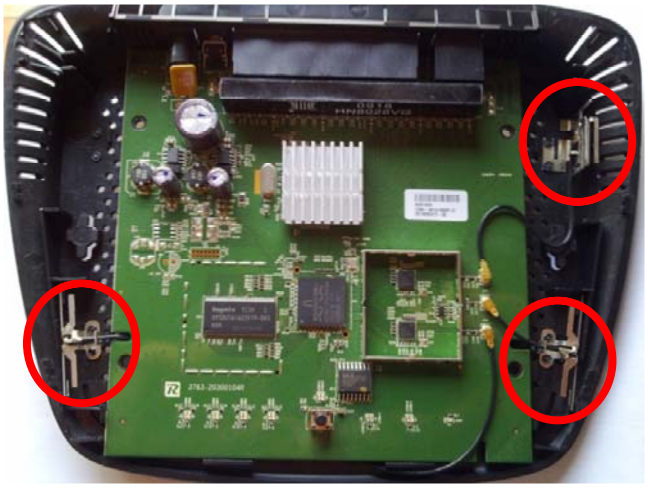

Figure 34. Internal view of WRT320N

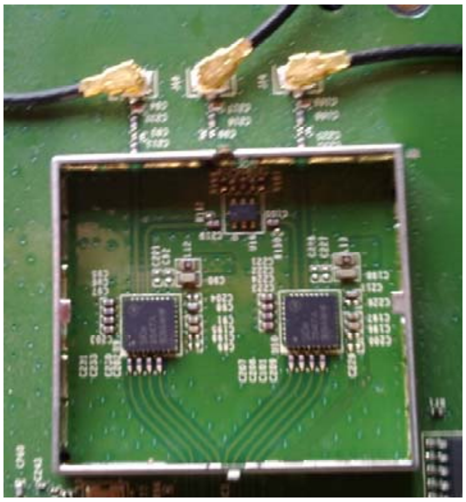

Figure 35. Integrated circuits for WRT320N

Although this phenomenon has been seen in the 4 variants measured, the n variant is the one that has the biggest difference among its theoretical value and real value. In order to analyze this, first we have analyzed the hardware characteristics of wireless device. In this case, WRT320N has 3 antennas, as shown in Fig. 34, and it should use the 3 antennas in order to work in IEEE 802.11n with MIMO.

However, as we can see in Fig. 35, only two out of three antennas are controlled by the SE2547A circuit. It allows a dual stream for both antennas. A review of this device is shown in a specific forum of wireless technology [34]. There are also other cases where the devices only work with 2 antennas, enabling a maximum effective flow rate of 315 Mbps compared to the 600 Mbps specified in the standard. In addition, the theoretical maximum data rate specified in the WRT320N datasheet is 320Mbps.

Moreover, the USB device used as a receiving interface is WUSB600N. It has 2 internal antennas and when it works in IEEE 802.11n, MIMO is also used. The network performance operating under IEEE 802.11n standard should be better than the other analyzed standards because the technology used (that is MIMO) allows it. Therefore, the most probable cause of the discrepancy between the number of lost packets and the information flowing through the channels is due to the hardware characteristics and the low performance of one of the two devices.

We demonstrated that this behavior is also observed in other variants. Other authors also analyzed IEEE 802.11 a and b theoretically [33] and observed this behavior.

VII. CONCLUSION

In this paper, we have measured the signal strength inside the coverage area of several WLAN variants (concretely in the IEEE 802.11a/b/g/n).

On the one hand, the measurements have been carried out under specific conditions, inside a house with a particular form and size. We chose an isolated place, free of wireless signals, in order to not having distorted results. We were pursuing accurate measurements. On the other hand, a specific antenna has been used, with a particular sensitivity. May be the same experiment performed in other conditions, may vary the results slightly. However, due to the results and other previous tests we had made, we believe that the results obtained are a good sign of the technology behavior. Similar results would be obtained under the same conditions

We can see that in the closest zones, the best technologies have been IEEE 802.11b and IEEE 802.11n, while the worst ones have been IEEE 802.11g and IEEE 802.11a. The one with highest signal strength in larger distances has been IEEE 802.11b and the worst ones have been IEEE 802.11g and IEEE 802.11n.

We have also measured the interferences between neighboring channels for each variant. We have observed different effects. On the one hand, we observed that the hypothesis, which told us that if we increase the separation of working channels, we should record lower losses, so it would not be always true. May be this effect happens because the measurements have been taken in closed zones, and the signal reflections may affect to the received signal strength. We think that this is a key factor when we are going to set up an IEEE 802.11 WLAN. Moreover, we have proved that packet looses have a fifth degree polynomial function of the channel separation (it matches this function almost exactly).

In general, although we have seen that the hardware used is more significant in the packet loss than the chosen IEEE 802.11 variant, we think that the variants IEEE 802.11b and IEEE 802.11g seem to be better for installations in closest zones.

Because there is an increasing number of wireless devices, and the presence of wireless networks working under the IEEE 802.11 technology is increasing, the likelihood to create interference is greater.

In a future work we will use the studies we have done in order to estimate the best position for a wireless sensor device inside a network, based on the received signal strength and the frequency interferences, in order to avoid having random sensor placements.

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