

Frequency Assignment and Capacity of WLANs in the Home Environment

Allocation de fréquences et analyse de la capacité des réseaux WLANs en environnement résidentiel

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Abstract-Interference in the 2.45 GHz frequency band is one of the main limitations of WLAN performance. This paper presents a comprehensive study about WLAN frequency planning in the home environment with adjacent cell interference. It is proved that, with only 13 overlapping channels, the 802.11b/g global throughput can be dramatically reduced in the case of deployment in a multi-storey building. The usual frequency plans, restricted to the 1-6-11 or 1-5-9-13 channels, are not recommended. It is important to consider all channels to get the best performance. This paper confirms that WLANs in the 5 GHz frequency band outperform the 802.11b/g capacity.

Index Terms—HF radio propagation, home environment, radio spectrum management, WLAN.

Résumé—Les interférences dans la bande 2,45 GHz sont l'une des principales limites aux performances des réseaux locaux sans fils. Cet article présente une étude complète concernant la planification des fréquences des systèmes WiFi en environnement résidentiel en présence d'interférences dans les cellules voisines. Il est montré qu'avec seulement 13 canaux recouvrant le débit utile des systèmes 802.11b/g peut être considérablement réduit pour les utilisations en contexte multi-étages de type immeubles. Les plans de fréquences usuels limités aux canaux 1-6-11 ou 1-5-9-13 ne sont pas recommandés. Dans ce cas, il est important de considérer l'ensemble des 13 canaux pour obtenir les meilleures performances. Cette étude confirme également que les réseaux locaux WiFi dans la bande de fréquences 5 GHz surpassent le 802.11bg en termes de capacité.

Mots clés—Propagation radio HF, environnement résidentiel, gestion du spectre radio, réseaux locaux sans fils

1. INTRODUCTION

Wireless Internet access in residential environments is now widely used, with for example, more than 10 million residential gateways deployed in France. However, the global throughput of WiFi communication depends strongly on the interference level. Interference is due to other WiFi equipment present in the home environment, but can also be generated by various radio devices such as microwave ovens, Bluetooth equipment, or remote control devices [1]-[2]. The jamming level depends on the frequency channels used, on the relative distances between the devices, and also on the power levels of the signals. There are 13 channels with 5 MHz spacing in the 2.45 GHz ISM frequency band in Europe. Only 3 non-overlapping channels can be re-used for WiFi, for example 1-6-11 or 1-7-13. This does not guarantee that it is possible to find an optimal solution to the frequency assignment problem in a multi-storey residential building, i.e. a solution providing a sufficiently low interference level that does not degrade WiFi performances. Previous studies [8] have proved that it is of interest to use partially overlapping channels to improve the WiFi capacity. However in the case of the home network with a high density of Access Points (APs) and a particular propagation path loss due to the presence of various building materials, this approach needs to be analyzed.

The aim of this work is to study, by simulation, the 802.11a/bg capacity limits for a typical deployment case and according to various frequency assignment strategies, based on an accurate propagation modeling. This paper

focuses on interference resulting from WiFi devices in adjacent cells disregarding the other effects. As it was not possible to have in practice a measurement site with the possibility to configure all the WiFi access points (AP), the use of MAC level simulation was required.

The first section of the paper presents the context and the basis used for the study: the propagation path loss measurement and modeling for the home environment, the software tools and the parameters used for simulation. The next section discusses the frequency planning, its impact on interference level, and on capacity.

2. CONTEXT OF STUDY

2.1 Description of the simulated environment

The typical environment defined for simulation is a set of 2 residential buildings of 5 floors and comprising approximately 25 apartments per floor. The average surface area of the apartments is 70 m^2 . These measurements are in accordance with investigations which have been made regarding the characteristics of typical home environment surface areas in some urban areas

One AP is placed in each apartment. The placement rule consists in placing one AP per apartment, generally in the living room or in a medium sized room. Fig.1 depicts a 3D view of this environment. Fig.2 displays the AP locations. The main building materials are plasterboard and concrete.

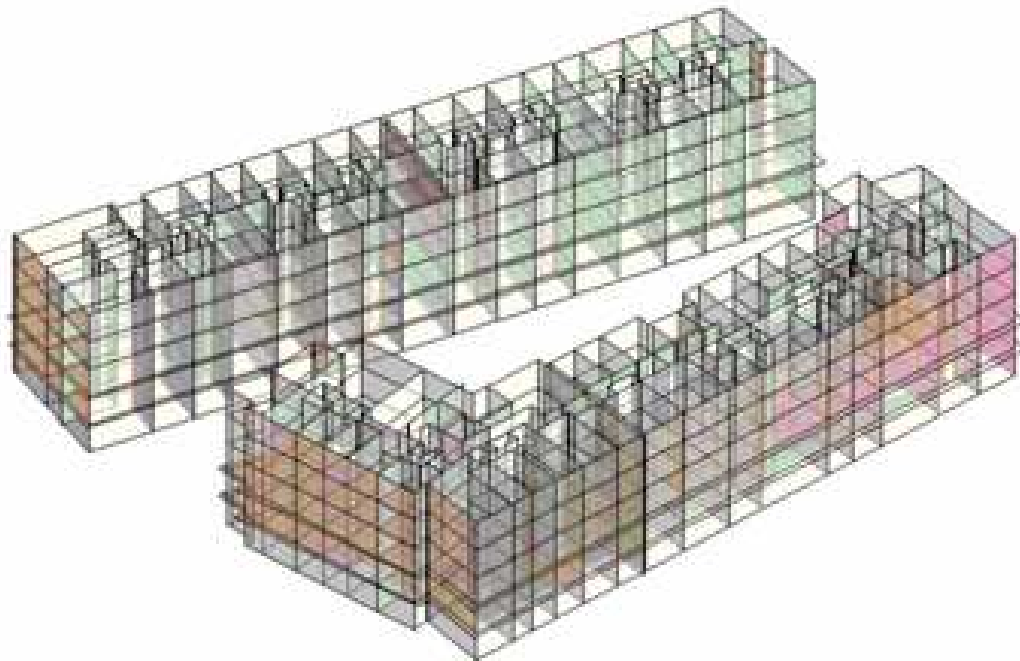


Fig.1. 3D view of the simulated environment



Fig.2. AP locations

2.2 Path loss modeling in home environment

A simplified ray tracing model is used for indoor radio coverage and interference level predictions [3]. To reduce the computing time, only the transmissions through materials are considered. Such a model provides also a quite acceptable accuracy. The model parameters have been tuned using extensive measurement campaigns performed in 8 residential buildings in the 2.45 and 5 GHz frequency bands. The average surface area of the measured apartments was 80 m². A least square linear regression algorithm [4] was used for tuning the model parameters from the radio measurements.

The transmitters consisted in WiFi access points with standard omni-directional dipole antennas (CISCO AIR-ANT 4941 and CISCO AIR-ANT5135D-R). The EIRP was fixed at 17 dBm around 2.45 GHz and at 20 dBm around 5 GHz. The APs were placed at five heights above the floor level: 0.25 m, 0.5 m, 0.75 m, 1.25 m and 1.75 m. The receiver was a laptop with a PCMCIA WiFi Card (CISCO 802.11ab/g), 1 m above the floor level. The data acquisition was performed using the measurement tools developed by France Télécom R&D [4-9].

The average propagation path loss (fast fading removed) depends on the transmitting AP antenna height (h_{AP}), on distances and on the building materials. The measurements show that the path loss decreases and then tends to stabilize for h_{AP} above 1.25 m. The presence of furniture (tables, chairs, cupboards) explains this fact: low obstacles have less impact when the AP antenna height h_{AP} is above 1.25 m, but high obstacles like cupboards can not be avoided by waves. The following notations are used to define the model.

Notations:

PL [dB]:	average propagation path loss
h_{AP} [m]:	AP antenna height above the floor level
dist [m]:	distance between transmission and reception
LOS:	direct line of sight radio link
NLOS:	non line of sight radio link
M_1 :	inner load-bearing wall (concrete)
M_2 :	dividing wall (plasterboard)
M_3 :	dividing wall with windows
M_4 :	wooden door
M_5 :	flagstone
N_i :	number of transmissions through the material M_i along the direct path
σ_{mod} :	standard deviation of the model error
σ_{mes} :	standard deviation of the measured path losses
N:	number of measurement points

The path loss model parameters used for the simulations are given below (1)-(2)-(3)-(4)-(5). The path loss model for LOS around 2.45 GHz is given by (1),

$$PL = 60.75 + 17 \log(dist) - 0.3 \min(1.25, h_{AP}) \quad (1)$$

with $\sigma_{mod} = 8.5$ dB, $\sigma_{mes} = 9.3$ dB and $N = 1009$

The path loss model for NLOS around 2.45 GHz is given by (2),

$$PL = 65.90 + 17.1 \log(dist) + 1.8 N_2 + 4.2 N_1 + 2. N_3 + 0.7 N_4 + 6.7 N_5 - 1.7 \min(1.25, h_{AP}) \quad (2)$$

with $\sigma_{mod} = 7.5$ dB, $\sigma_{mes} = 9.3$ dB and $N = 3945$

The path loss model for LOS around 5 GHz is given by (3),

$$PL = 65.6 + 15.2 * \log(dist) - 2.2 \min(1.25, h_{AP}) \quad (3)$$

with $\sigma_{mod} = 8.5$ dB, $\sigma_{mes} = 9.2$ dB and $N = 1033m$

The path loss model for NLOS around 5 GHz is given by (4),

$$PL = 70.3 + 17.3 \log(dist) + 2.2 N_2 + 4.6 N_1 + 2.2 N_3 + 0.4 N_4 + 10.6 N_5 - 2.6 \min(1.25, h_{AP}) \quad (4)$$

with $\sigma_{mod} = 8.3$ dB, $\sigma_{mes} = 10.0$ dB and $N = 3806$

2.3 Interference modeling

The performances of the frequency plans studied in this paper are evaluated from the cumulative distribution functions (*CDF*) of the signal to noise plus interference ratio (*SINR*). Interference is treated as if it is a Gaussian noise source and adds its effects to the Gaussian thermal noise [5]. This is a common approximation that tends to be true in the case of multiple interferences.

The *SINR* level depends on the desired signal level but also on the frequency offset between the desired and the interfering WiFi signals. This effect is modeled with coefficients noted $K(\Delta f_i)$ [dB], where the frequency offset is Δf_i MHz. These coefficients express the fact that a jammer shifted from Δf_i MHz to the desired signal and received with a power P_{int} [dBm] after the antenna connector, produces the same degradation as a co-channel WiFi signal received with a power $P_{int} - K(\Delta f_i)$ [dBm]. These coefficients K are typical of the equipment considered. Medium range equipment is considered for this study. The coefficients K have been deduced from the cut-off level differences of a WiFi link jammed by another WiFi link [5]-[6]. The thermal noise level N_o level is fixed at -93 dBm, from the value returned by the WiFi card used. *SINR* is given by (5),

$$SINR[dB] = C[dBm] - 10 \log(N_0[mW] + \sum_{i=1..n} 10^{\frac{K(\Delta f_i)}{10}} I_i[mW]) \quad (5)$$

where C is the power level of the desired signal, and $I_i=1..n$ are the power levels of the n interfering signals.

Fig.3 depicts which area is typically covered by one AP (70 m²) with a sensitivity threshold equal to -75 dBm and which area is potentially jammed by one AP (400 m²). Interference on the other floors is also high, the interfered surface being then 350 m². This explains why it is so difficult to optimize the channel choices and to find how to re-use channels. The simulated environment comprises 125 APs. As there are 13 available channels for each AP, there are 13¹²⁵ possible frequency plans. The optimization problem cannot be solved in a simple way with a reasonable computing time. The problem is solved by the implementation of specific algorithms and heuristics to make it possible to find an approached optimal solution with a computing time of a few seconds. This solution is not the best solution, which is seldom calculable, but a very close second. An automatic frequency assignment software module is used to find the frequency plans. This software is based on previous work concerning mobile networks. This study considers wireless links, for which the traffic is mainly on the downlink and which is usually the case in home environment. The same algorithm that is defined for mobile network [7] has been adapted for WiFi.

Table I recaps the parameters selected for simulation presented in section 3.

TABLE I
SIMULATION PARAMETERS

	802.11b/g	802.11a
EIRP [dBm]	17 dBm	20 dBm
AP antenna (CISCO)	AIR-ANT 4941	AIR-ANT5135D-R
Sensitivity threshold	-75 dBm	- 75 dBm
Design margin	11 dB	11 dB

3. FREQUENCY PLANNING ANALYSIS

3.1 Case of the 2.45GHz ISM frequency band

Only 3 channels are non-overlapping in the 2.45 GHz ISM frequency band, for example the 1-6-11 channels. This explains why frequency plans using these 3 channels are often recommended. Some studies show that it is also possible to consider 4 channel frequency plans, depending on the equipment used, while other studies [8] recommend to use overlapping equipment 4 channels. Simulations have been performed according to these various planning strategies. The frequency planning is optimized using the tools and path loss models presented in section 2. The evaluation of the frequency plan (FP) performances is based on the CDFs of the signal to interference plus noise ratio. All computed values are restricted to the coverage area, defined by the sensitivity threshold and the design margin.

Two $SINR$ CDFs are given as references. The first one corresponds to the case of all the APs sharing the same channel. The associated frequency plan is noted FP(1). This is the worst case of interference. The second one corresponds to the situation where only one AP is activated at any time. There is no interference and only thermal noise N_0 . This is the best case.

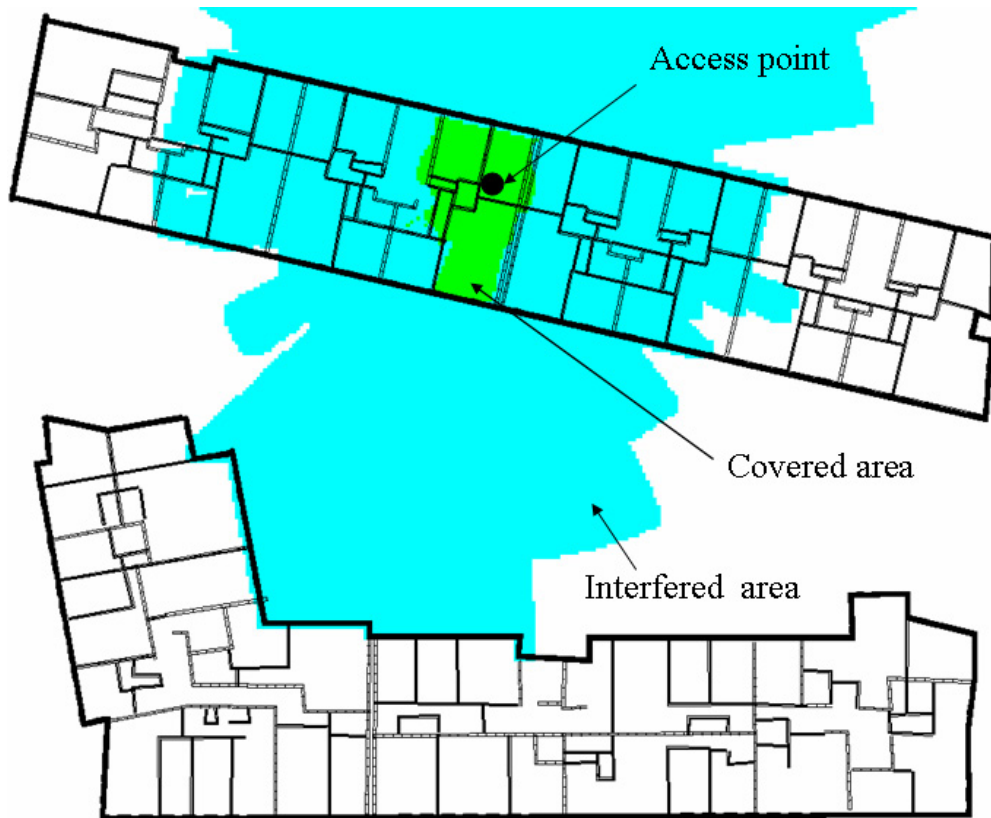


Fig.3 Covered and interfered area with an 802.11b/g AP

Frequency plans using only 1-6-11 (FP(3)), or 1-5-9-13 (FP(4)) channels or all the 13 available channels (FP(13)) are computed. Fig. 4 compares the corresponding $SINR$ distributions for the 2nd floor. FP(1) clearly demonstrates the presence of strong interferences, with a total noise rise around 28 dB compared to the reference case with only thermal noise. Fig.4 proves that FP(3), FP(4) and FP(13) does not make it possible to reach optimal performances. However, the noise rise is less pronounced with FP(13). The total noise level rises up to 12 dB compared to the ideal situation. This leads to a large reduction of the performances.

The other floors present similar results, except the first and the last floor, for which the interference level is reduced by a few dB. The $SINR$ distribution is also analyzed when the only active APs are on the second floor (Fig. 5). For this case, FP(13) provides quite good performances, with a noise level increase below 5 dB. Inter-floor interference is a strong limitation for WLAN systems in the 2.45 GHz frequency band. FP(3) or FP(4) are not recommended for multi-storey residential buildings. Interference between floors may be reduced using more directive AP antenna and advanced antenna processing.

To complete these results, random FPs have been also considered, as in practice APs of different users may be arbitrarily configured. Monte Carlo simulations were performed, based on 5000 random choices of the AP channel. The median $SINR$ distribution (Fig.6) shows that a random FP performs as well as FP(3) with a 50% probability. This highlights the poor performances of FP(3).

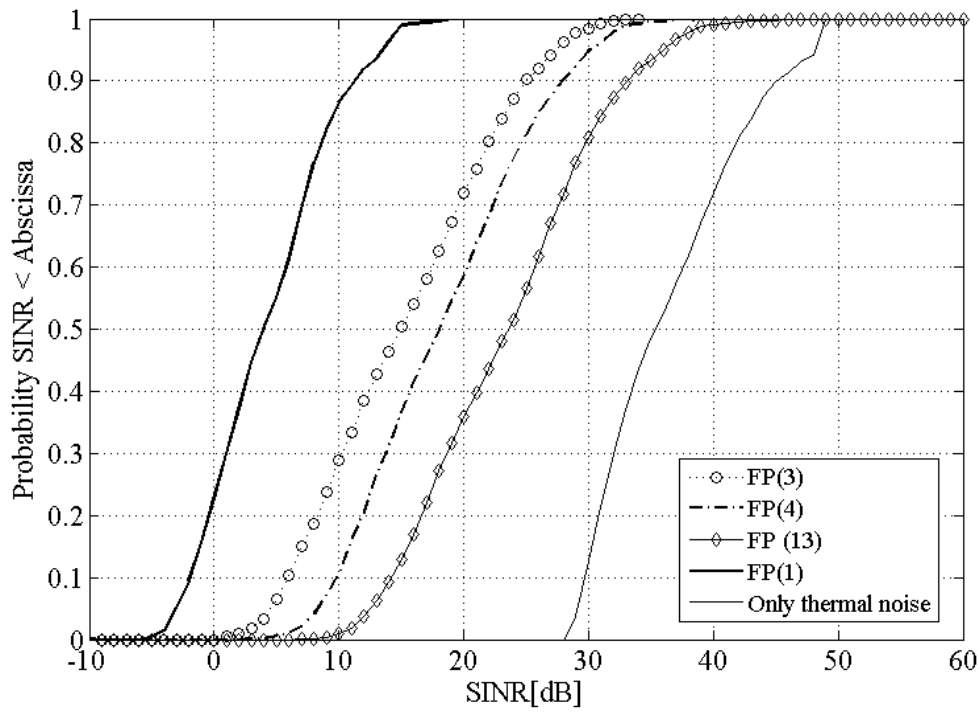


Fig.4 SINR distribution for various FPs

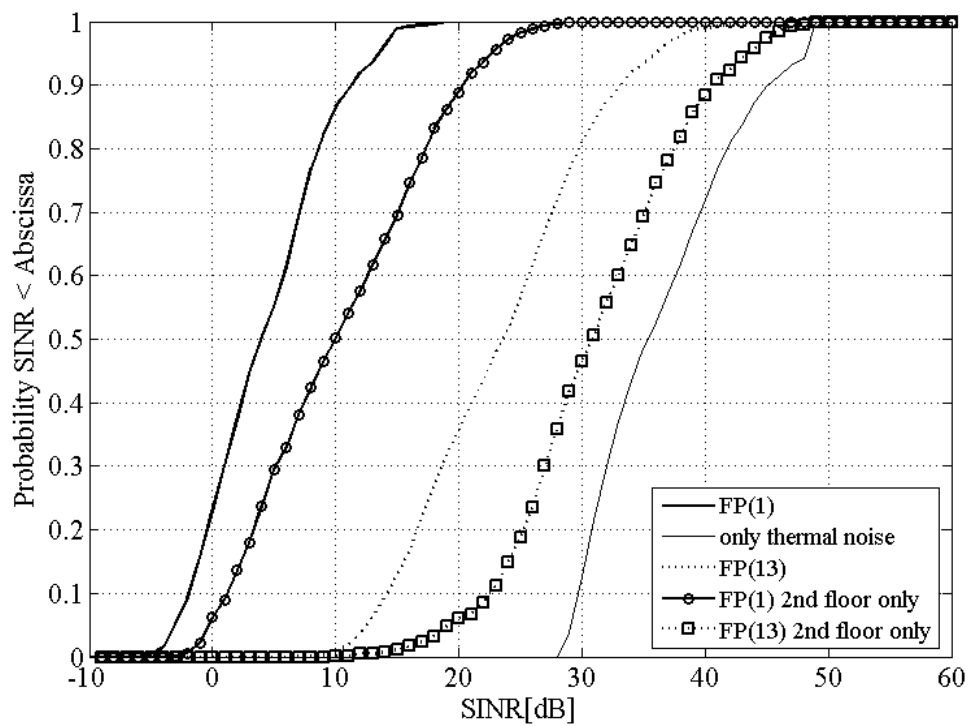


Fig. 5 SINR distribution for various FPs, when only the APs of the 2nd floor are activated

3.2 Case of the 5 GHz frequency band

The lower and the upper part of the 5 GHz frequency band are authorized in Europe. Some protection mechanisms like power control (TPC) and dynamic frequency selection (DFS) have to be used to facilitate the coexistence with other devices like radars. Without TPC, the EIRP is limited to 20 dBm. 8 quasi non-overlapping channels are available in the lower part of the 5 GHz band and 11 quasi non-overlapping channels in the upper part of the band. The WiFi capacity is consequently higher than in the 2.45 GHz ISM frequency band. Jamming by devices other than WiFi is rare.

The 5 GHz propagation path loss is a little higher than in the 2.45 GHz frequency band (1)-(2)-(3)-(4). The measurements show an average 4.5 dB path loss difference between the two frequency bands. This can be compensated in part by increasing the EIRP by 3 dB. It is also important to notice that the inter-floor path loss is greater around 5 GHz than around 2.45 GHz. Inter-floor interference is then reduced. This is due to propagation and material effects but also to the antenna used which have a lower aperture in elevation at 5 GHz than around 2.45 GHz (40° instead of 70°)

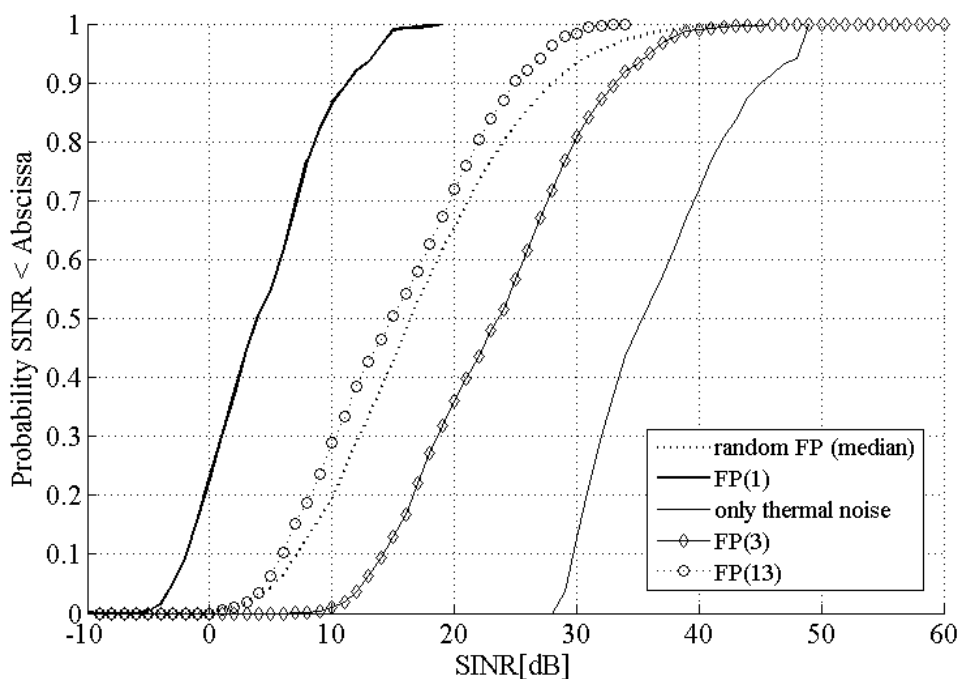


Fig. 6 SINR distribution for random FP

Frequency plans using from 3 to 8 channels are compared (Fig. 7). The solution with 8 channels FP(8) approaches the optimal situation. The noise rise is at least 12 dB for 802.11b/g. For 802.11a, the noise rise can be reduced to 3.3 dB with FP(8). Moreover, a FP using more than 5 frequencies outperforms all the 802.11b/g FPs. The use of 802.11a is strongly recommended to benefit from non interfered radio links. The major drawback is the use of DFS which prevents the user from choosing the channel of its AP. A centralized frequency management including DFS would be the best solution.

3.3 Capacity analysis

The results presented in sections 2.2 and 2.3 concern a network where all the APs are activated and used simultaneously. These results may be considered as a worst case that provides the 802.11a/bg limits. The load of the network is not considered. MAC simulations have been also carried out and they are discussed in this section to refine the analysis. An 802.11 MAC simulator developed by our lab has been used for MAC level simulation. The MAC simulator principle is similar to more popular simulators like ns-2, ns-3 or OPNET with two major exceptions. The path loss between the radio devices is computed using models (1)-(2)-(3)-(4). Fast fading and shadowing are also taken into account to have more realistic propagation effects, by adding a random variable to the average path loss.

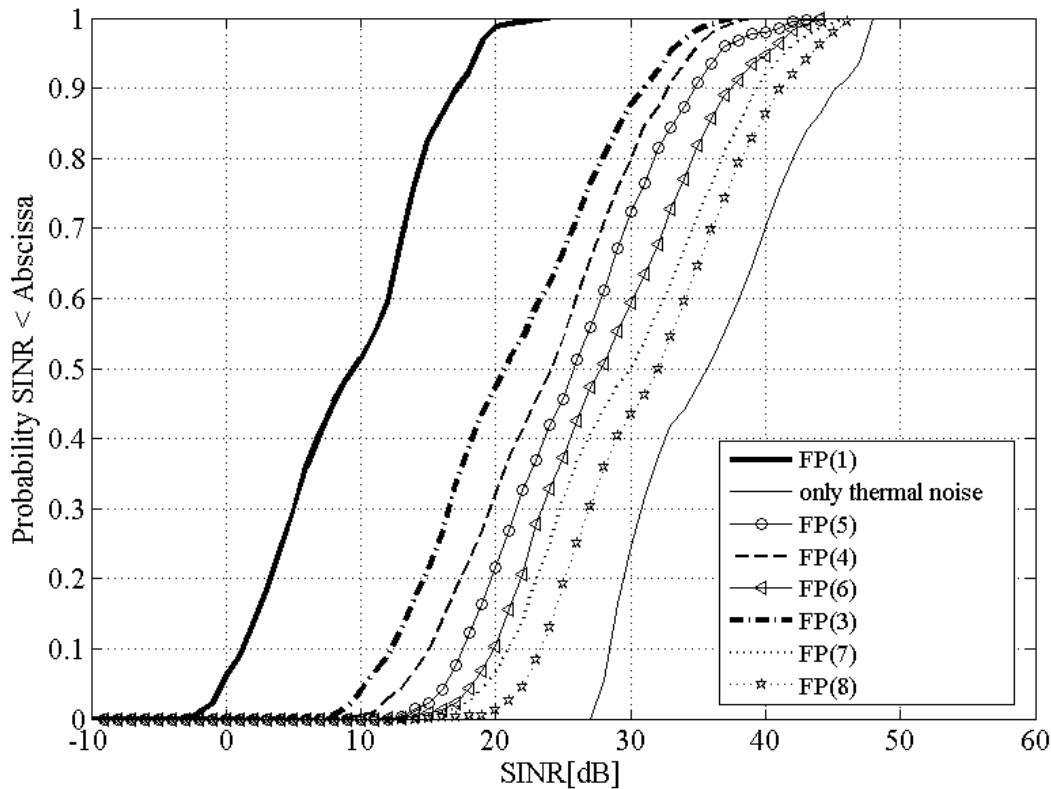


Fig.7 Comparison of frequency plans for 802.11a

The other main difference concerns the interference modeling. Our simulator implements the model (5). $SINR$ aggregates all WiFi interference and $SINR$ is considered as time variant over the frame duration. The maximum $SINR$ value is then compared to the required sensitivity levels of the 802.11 receiving devices. It is then decided if the received frames are to be accepted or rejected and retransmitted.

Three scenarios have been simulated. The first is the reference scenario, with no interference. This scenario does not have any reality, since there is no optimal FP for the studied case, but it is useful to have reference throughput values only limited by the thermal noise and the propagation path loss.

The second scenario is the worst case: all the APs share the same channel. The third scenario uses FP(13).

The simulated traffic is a UDP video traffic (1350 bytes packets) on the down-link. 125 clients were randomly placed, one in each apartment. Fig.8 presents the average throughput per client versus the offered load. It is obvious that FP(1) leads to very low performances. The throughput is shared among the 125 clients and hardly reaches 500 kbits/s. Without any interference, the average throughput reaches 14 Mbits/s, but only 7 Mbits/s for real time services. Similar results could be obtained for 802.11a with optimized channels. The maximum 802.11b/g throughput with FP(13) is 4 Mbits/s and only 2 Mbits/s for a real time service. The noise rise of 12 dB due to interference, results in a throughput decrease of 10 Mbits/s. A bad 802.11b/g channel assignment leads to very low performances, but an optimized one is not sufficient to suppress limitations due to interference. The conclusion is that 802.11b/g is not recommended for a generalized deployment in a multi-storey building for video services or other high throughput services.

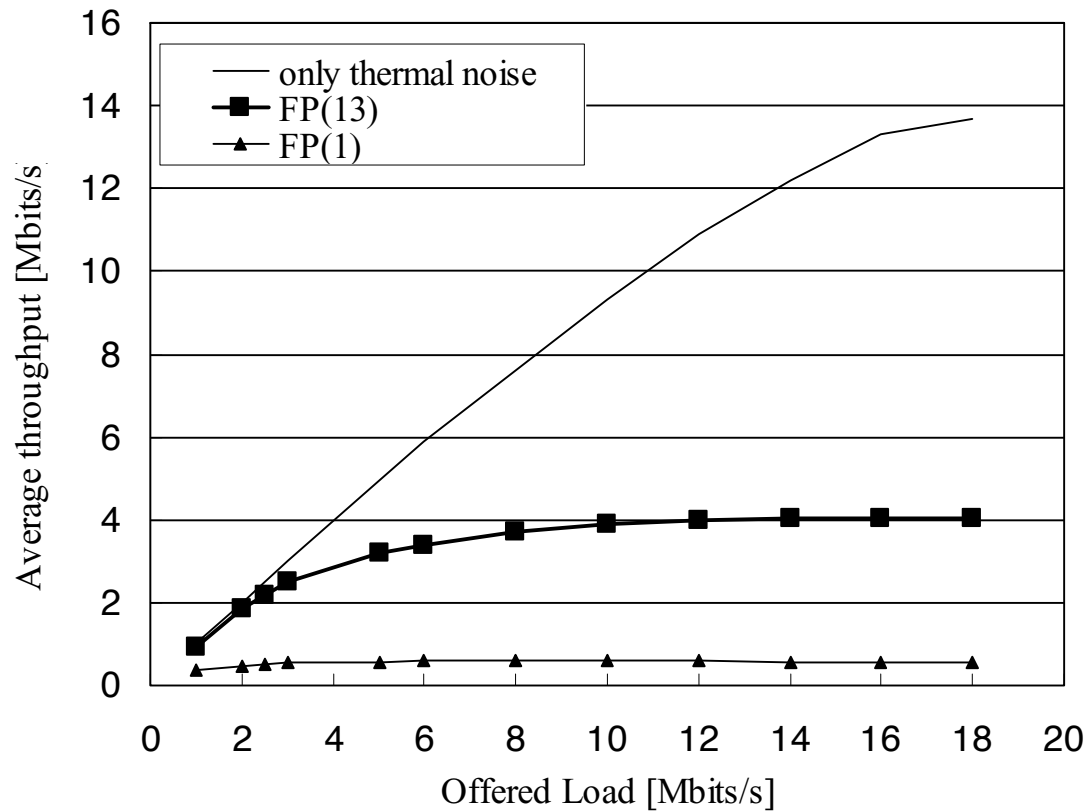


Fig. 8 Average throughput versus the offered load per AP

4. CONCLUSIONS

This paper reveals what the limits of 802.11b/g are in case of a deployment generalized in a multi-storey residential building. The capacity may be improved significantly with 802.11a thanks to a higher available bandwidth. Advanced antenna processing like beam forming would be also a promising solution to study for reducing the interfering signal level, particularly if it is associated to a MIMO physical layer like 802.11n. Power control would be another technique to analyze in future work.

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