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Frequency assignments in IEEE 802.11 WLANs with efficient spectrum sharing

Eduard Garcia Villegas*,†, Rafael Vidal Ferré and Josep Paradells

Wireless Networks Group, Entel Department, Technical University of Catalonia (UPC), Avda. del Canal Olímpic, 15, 08860 Castelldefels, Spain

Summary

As the number of WLAN users grows, the need to perform efficient radio resource management strategies becomes essential due to the fact that most popular technologies, those based on IEEE 802.11 standards, use unlicensed frequency bands. A good channel assignment improves the network performance, producing benefits that are perceived by the users and also by the network administrators. In this paper, we present a new frequency management scheme for IEEE 802.11 WLANs in the 2.4 GHz ISM band that minimizes interference to increase the throughput available to client stations by adapting a weighted DSATUR algorithm for graph coloring. The algorithm takes both co-channel and adjacent channel interference into account, and makes use of all available channels instead of the traditional non-overlapping three. In this way, collisions as well as transmission errors are minimized, thus improving the network capacity and the user experience. Different architectures are discussed for the implementation of our approach, including the possibility to incorporate client stations into the management system. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: WLAN; IEE 802.11; radio resource management

1. Introduction

The increasing demand for wireless communication brings the need to use new technologies. There are currently two main approaches to enhancing wireless capacity. The most common approach is to improve the radio interface. Technologies such as adaptive modulation coding, MIMO or orthogonal frequency division multiplexing (OFDM) are recent improvements that are able to increase the bitrate, but the ceiling on spectral efficiency will make further improvements difficult if not impossible. The only approach that can offer continuous improvement is the channel reuse according to a cellular pattern. Using smaller cells increases capacity, but it also makes radio resource management a more complex challenge.

In most of the literature, radio resource management in WLAN 802.11 networks is studied as part of the design of multicellular infrastructure-based WLANs. A good design is achieved if two basic requirements are met: full coverage of the required area and a capacity suitable for supporting the offered traffic is provided without service degradation as the number of users increases. Although there is an endless list of parameters to consider, the requirements

*Correspondence to: Eduard Garcia Villegas, Wireless Networks Group, Entel Department, Technical University of Catalonia (UPC), Avda. del Canal Olímpic, 15, 08860 Castelldefels, Spain.
†E-mail: eduardg@entel.upc.edu

mentioned above can be met using an exhaustive selection of access point (AP) locations and the proper set of channels and power levels. Many authors have contributed to solving this problem by developing different algorithms [1]. Rodrigues [2] and Hills [3] pioneered the application of these techniques to IEEE 802.11 WLANs. Since then, most of the work has been based on a thorough knowledge of the scenario: traffic demand in the different areas to cover, orography and obstacles, etc. An offline calculation is then made to evaluate certain parameters and configure the APs before they are deployed. In a more realistic scenario, the possible interfering sources are unpredictable, and the number of APs, client nodes, and the traffic demand vary randomly. Thus, the initial settings should be adapted dynamically to fit the new environment. Therefore, the frequency assignment problem (FAP) requires a new mechanism capable of evolving according to new conditions and supporting the various WLANs in a given area. Planning is an effective solution for the deployment of a sole multicellular network. In the real world, however, network administrators know neither when nor where a new interfering node is going to appear. Moreover, they cannot manage all devices involved, since they may belong to different networks and thus to different owners. Centralized management systems are therefore losing ground due to their poor scalability and lack of robustness and dynamism. Future wireless networks (4G) are expected to have an *ad hoc*, dynamic structure and ubiquitous nodes that must have the individual ability to self-configure and promote collective awareness. Controlling such a network implies coping with uncertainty. For this reason, a new approach to the control and coordination of future networks will be needed. Centralized control will be replaced with highly decentralized control. One widely accepted approach is to develop self-organizing systems based on the interaction of smart but simple nodes that provide network-wide coordination.

Nevertheless, there is no need to imagine uncertain future scenarios; solving distributed resource management in IEEE WLANs is a challenging field of research not only because it is a close 4G testbed, it is also relevant to current applications. In densely populated areas, enterprise WLANs, public hotspots, wireless domestic users, etc., coexist and share the same frequency spectrum. Described in Reference [4] as a chaotic network, this scenario is characterized by unplanned and unmanaged deployment. The aforementioned study also states that, in most cases, the density of nodes (many interfering sources and a limited number of non-overlapping frequency channels) is such that administrators cannot ensure innocuous coexistence. It is clear that as the number of neighboring nodes increases, the undesired effect of interference becomes more problematic and affects network performance. Usually, two types of interference are distinguished: co-channel interference, caused by undesired transmissions on the same frequency channel, and adjacent channel interference, caused by transmissions on adjacent or partially overlapping channels.

The nodes of a WLAN share the medium in a similar manner to the nodes of an Ethernet segment. A carrier sense multiple access with collision avoidance (CSMA/CA) scheme is used for medium access control. The nodes sense the air interface before transmitting a frame; if it is busy, they wait until it is released. Physical and virtual carrier sense functions are used to determine the state of the medium. Virtual carrier sense is referred to as the Network Allocation Vector (NAV). The NAV maintains a prediction of future traffic on the medium based on the duration information announced in some frames. Basically, the physical layer provides a busy/idle medium recognition based on the detection of any energy above a given threshold P_{th}; the physical layer can also report a busy medium by detecting an 802.11 signal (above or below P_{th}). This makes the study of interferences in IEEE 802.11 WLANs quite different from what is done in other radio networks due to the particular influence of co-channel interference: in a cell suffering only co-channel interference, even if there is no traffic on it, the nodes may defer their transmissions if they detect other nodes using the channel from an interfering cell; these nodes are called *exposed terminals*.

The presence of adjacent channel interference reduces the effective Signal-to-Interference and Noise Ratio (SINR). Therefore, the number of reception errors increases affecting the packet error rate (PER) and, consequently, the throughput.

In this paper, we present a new frequency assignment algorithm intended to minimize both co-channel and adjacent channel interference, and thus increasing the capacity of the network. The algorithm uses the available spectrum (including partially overlapping channels) to optimize a cost function which is based on capacity estimations. These capacity estimations are obtained by adding the effect of interference to existing well-known models. The resulting implementation requires low computational efforts so it is

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suitable for running in embedded devices that can be used to build a distributed management.

The remainder of this paper is organized as follows. In Section 2, we analyze the effects of interference and argue that the use of all available channels is justified. In Section 3, we use this analysis to derive a throughput upper bound in a multicellular WLAN that takes the effect of interference into account. In Section 4, we present our frequency assignment algorithm, which is based on the capacity estimation presented in Section 3. Section 5 shows that this algorithm can be deployed and run either in a centralized or distributed way, and that it can be enhanced by promoting cooperation with client devices. A more in-depth study on these issues can be found in Reference [5]. An evaluation is presented in Section 6, and concluding remarks are given in Section 7.

2. Understanding Interference in IEEE 802.11 WLANs

IEEE 802.11 a/b/g networks operate in the 5 GHz (.11a) and 2.4 GHz (.11b/g) unlicensed ISM frequency bands. Communications in these bands need to implement spread spectrum techniques and limit their transmitted power in order to minimize the impact of interference with other devices. The IEEE 802.11 standard defines various spreading techniques, but the devices that can be found today on the market are based on the direct-sequence spread spectrum (DSSS) and OFDM. These standards specify the use of Barker codes (1 and 2 Mbps) and complementary code keying (CCK) in 5.5 and 11 Mbps for the chip sequence in DSSS systems. As a rule of thumb, the null-to-null bandwidth in DSSS is 2X the chip rate. Since all DSSS modulations use a chip rate of 11 Mcps, the null-to-null bandwidth of the spread signal is 22 MHz.

The IEEE 802.11a/g standards specify an OFDM physical layer that splits an information signal across 52 separate subcarriers. Four of the subcarriers are pilot subcarriers that are used as a reference to disregard frequency or phase shifts. The remaining 48 subcarriers provide separate wireless 'pathways' for sending the information in a parallel fashion. The resulting subcarrier frequency spacing is 0.3125 MHz (20 MHz/64) and the total bandwidth is 20 MHz, although only 16.6 MHz are actually occupied.

In these bands (2.4 and 5 GHz), the available channels are defined with 5 MHz separation between consecutive carriers. This brings the need to use, at least five channels of separation to guarantee that two simultaneous transmissions will not interfere with each other. Consequently, whereas in the 5 GHz band there are up to 19 (12 in USA) non-overlapping channels, in the 2.4 GHz band only 3 out of 13 (11 in USA) are non-overlapping (traditionally, channels 1, 6, and 11).

Bearing in mind the aforementioned scenarios, where the density of nodes can be very high, just three channels are not enough to guarantee the innocuous coexistence of several WLANs. Previous empirical studies have stated that a separation of four channels can be used without reducing performance [6], so channels 1, 5, 9, and 13 (where available) could be considered. The idea of using all available channels appeared for the first time in Reference [7]; later, in Reference [8] authors provided new details about the effect of interference from overlapping channels. A simple experiment can be carried out to illustrate these statements: the scenario consists of two totally overlapping WLAN cells, each composed of one 11b AP and one client station. One of the clients, used as the interference source, is pushed to saturation (i.e., there is a frame ready to be sent in the transmission buffer at all times). The other is used to test the UDP and TCP capacity of its cell for different channel settings: while one of the cells remains in channel 1, the other moves from 1 to 6. The throughput measurements are shown in Figure 1. Observe that under co-channel interference the performance is better than that obtained with 1 channel separation, which shows a minimum. With co-channel interference (channel distance = 0), both transmitters are able to share the medium due to the CSMA/CA access scheme. However, with channel distance >0, transmissions from the other station are RF filtered and the received signal may drop below the carrier sense threshold so the

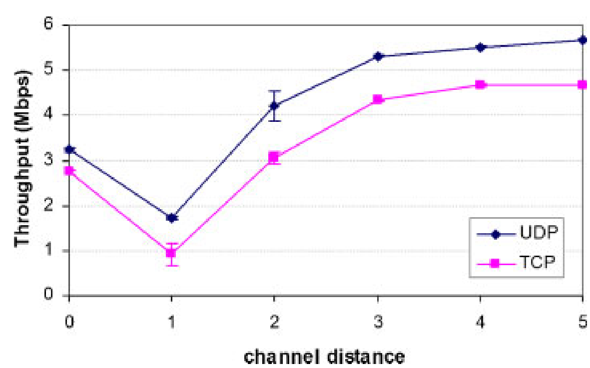

Figure 1. Throughput with interference from various channels (conf. intervals for 95 per cent).

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transmitters will not be able to avoid the possible collision. In this case, simultaneous frames sent on overlapping channels are treated as noise, and the desired packet is received with errors; hence the throughput degradation. As we increase the channel distance, the RF filter discriminates interfering signals to the point where the interference is completely removed (channel distance >4). In consequence, we can conclude that it is sometimes preferable to use partially overlapping channels and sometimes not. This section will help in the understanding of these issues.

2.1. Measuring Adjacent Channel Interference

Logically, as the distance (in frequency) between two simultaneous transmissions increases, the effects of interference become less harmful. As explained above, in order to avoid interference, transmissions should be separated by at least five channels (>22 MHz).

However, the IEEE 802.11 standard defines a transmit spectrum mask that limits the energy of the transmitted signal that invades adjacent channels: at around f_c, the signal is unmodified; at frequencies beyond $f_c \pm 11$ MHz, the transmitted spectral products shall be less than -30 dBr, and -50 dBr for frequencies $f_c \pm 22$ MHz. In OFDM, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 18 MHz, -20 dBr at 11 MHz frequency offset, -28 dBr at 20 MHz frequency offset and (40 dBr at 30 MHz frequency offset and above (see Figure 2). Consequently, a band-pass filter must be applied before transmitting to the medium. Moreover, a similar filter is applied in reception to isolate the desired signal from other sources. This way, the energy received from transmissions on adjacent channels is substantially reduced. In Figure 3, a MATLAB simulation

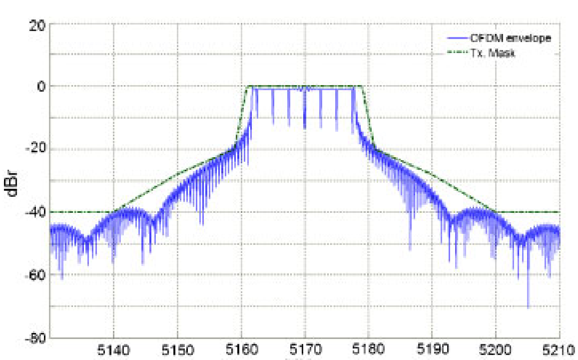

Figure 2. Spectral density of an 802.11 OFDM signal.

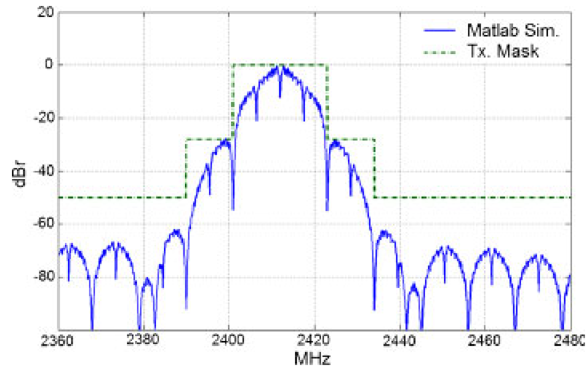

Figure 3. Spectral density of an 802.11 DSSS filtered signal.

illustrates the effect of applying the spectrum mask to a DSSS signal using a 4th-order elliptic filter with 22 MHz of bandwidth and a stop band 50 dB down.

In order to quantify the interference caused by transmissions on partially overlapped channels, we compute the power spectral density (PSD) of the filtered signal. Assume a receiver tuned to f_c, and a transmitter that is c channels apart sends a signal represented by $Pw(f)$ in the frequency domain. Also, assume that the two devices use an identical filter for transmission and reception; if the filter's frequency response is represented by $F_{f_c}(f)$, where f is the frequency in MHz, the overlapping energy of the interfering signal is computed as

$$P_{\text{int}} = \int_{-\infty}^{+\infty} Pw(f) \cdot F_{f_c}(f - 5c) \cdot F_{f_c}(f) df \qquad (1)$$

For our purposes, the integral can be done only in the region of interest, that is $f_c \pm 22$ MHz. Thus, we quantify the interference caused by 802.11 transmissions, according to the attenuation of the filter for a specific channel, normalized by the amount of energy the receiver would get if tuned to that channel. In other words, if we call P_0 the power that the receiver gets when both the receiver and the transmitter are on channel 1, and P_c is the new power obtained after moving the sender c channels away, then the normalized loss factor is P_c/P_0. Table I shows the values in dB, obtained by means of MATLAB simulations.

Table I. Adjacent channel attenuation.

c (ch. sep.)	0	1	2	3	4	5
DSSS	0	0.37	1.79	8.03	23.47	53.21
OFDM	0	0.55	2.46	6.60	34.97	51.87

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For example, if a DSSS receiver is tuned to channel 1, it receives all transmissions in channel 1 ($c = 0$) without attenuation, but interfering transmissions on channel 4 are reduced by more than 8 dB ($c = 3$).

Knowing that the power of a signal received at a distance of d can be computed as $P_{rx}[\mathrm{dB}] = G(c) + P_{tx} - k \cdot 10 \log_{10}(d)$ [9], where P_{tx} is the transmitted power, k is a factor that depends on the environment ($k = 2$ for open space), and $G(c)$ is a factor that captures the effect of various gain/loss elements (including tx/rx filters and antennas); if we isolate d:

$$d(c) = 10^{\frac{G(c)+P_{tx}-P_{rx}}{10k}} \tag{2}$$

We obtain d_{th} when $P_{rx} = P_{th}$, that is d_{th}, which is also known as the carrier sense range—the minimum distance between two nodes required to prevent the carrier sense mechanism from reporting a channel as occupied when the other station is transmitting. Note that $d(c)$ decreases with c, which means that the minimum distance required to avoid interference between two transmitters (due to CSMA/CA) is reduced by increasing the channel distance ($d_{th}(0) > d_{th}(1) > \cdots > d_{th}(c)$). Again, it may be preferable to use partially overlapped channels rather than a channel that is already in use. Hence, the best channel assignment for a scenario like the one depicted in Figure 4 (with $\max(d_{xy}) < d_{th}(0)$) will be that using channels 1, 5, 9, and 13. In this case, the use of partially overlapped channels avoids the exposed node problem [10].

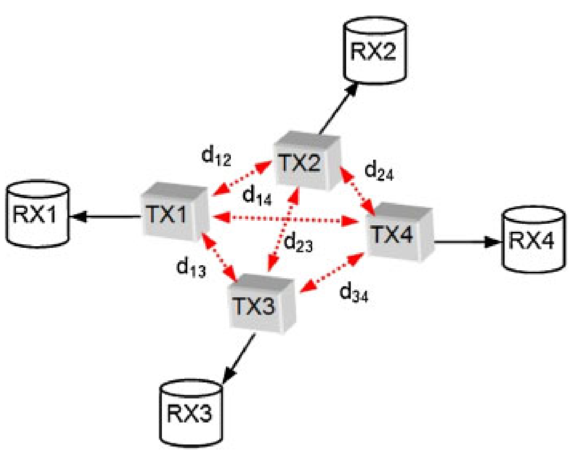

Figure 4. Scenario with four Tx/Rx pairs. All TXs are within each other's carrier sense range. RXs are only within range of their corresponding TX.

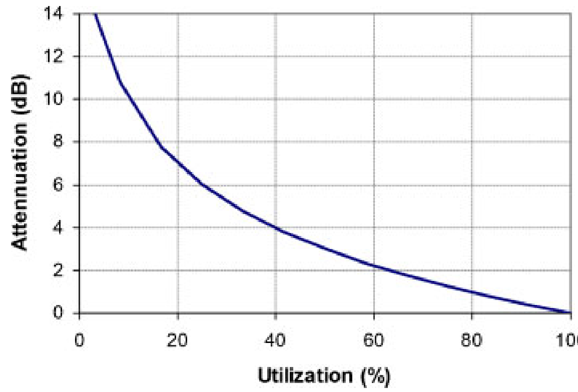

Figure 5. Average attenuation equivalent to a given utilization.

2.2. Effects of Utilization on Interference Measurements

The previous subsection showed how to evaluate the interference caused by transmissions in overlapping channels. Note that the spectrum densities studied correspond to activity periods, that is a snapshot taken when the transmitter is actually transmitting. It is therefore logical to draw the conclusion that a node that injects only a few frames per second is a source of interference that we can disregard in the presence of another node that is transmitting at the highest possible rate, even though the first station's frames are received with much more energy than the latter's. Therefore, the next step is to include the effect of utilization as a new parameter in order to consistently quantify interference from adjacent channels. Here, utilization is understood as the portion of time the node is actually transmitting into the air.

To do so, the mean power received from a source in saturation state is taken as a reference (considered 100 per cent utilization[‡]). Each utilization degree is measured with a spectrum analyzer, which covers 44 MHz around the center frequency f_c 10 times per second, taking samples every 100 kHz. Figure 5 shows the resulting average (normalized) attenuation equivalent to a given degree of utilization. This equivalent attenuation is computed as the difference between the mean power received from a saturated station and the mean power measured with lower utilizations.

The values provided by the spectrum analyzer are directly proportional to the decay of the utilization.

[‡]Note that the utilization taken as reference does not actually correspond to a busy time of 100% due to backoff intervals and inter-frame spaces.

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Thus, the attenuation in dB corresponds to the equation $10 \cdot \log_{10}(u)$, where u represents the utilization ($0 < u \leq 1$). That is, a utilization of 50 per cent means that the source is transmitting half of the time, and hence the averaged measured power is halved (i.e., the equivalent attenuation is 3 dB).

Let us conclude our characterization of interference in partially overlapping channels with a complete example: if a receiver is tuned to channel 1, an interfering source continuously transmitting frames in channel 1 ($c = 0$) will not be filtered. But, if the transmitter moves to channel 4 ($c = 3$) and reduces its utilization to 50 per cent, the interference it produces is reduced on average by 8 (filter) + 3 (utilization) = 11 dB.

Although the utilization model's accuracy was validated with practical measurements with a spectrum analyzer, it is not applicable when the PER is computed from SINR values. The effects of utilization will depend not only on the ratio of active-to-idle periods, but also on the frame size distribution and the process describing inter-frame times in the interfering source. First of all, whenever the filtered signal is above P_{th}, the physical carrier sense mechanism will defer transmission for all of the interfering station's frames, so in this case, the interference does not affect the PER and therefore there is no sense in applying the attenuation due to the utilization factor. Otherwise, the interference can be added to the SINR before deriving PER.

The resulting PER can be approximated by $\text{PER}_u = u \cdot \text{PER}_1$, where PER_u is the PER obtained with an adjacent interferer's utilization of u and PER_1, the PER when the interferer's utilization is in saturation ($u = 1$). This PER variation can be translated to an equivalent $\log 10(1/u)$ increase in the SINR, which is corroborated by empirical measurements and simulations [11]. Returning to the example used above, if a receiver is tuned to channel 1, an interfering source continuously transmitting frames in channel 1 ($c = 0$) will not be filtered. However, if the transmitter moves to channel 4 ($c = 3$) and reduces its utilization to 50 per cent, the interference it produces, with regard to PER computation, is on average attenuated 8 (filter) + 0.3 (utilization) = 8.3 dB.

3. Evaluating the Design of a Multicell WLAN

In order to evaluate the quality of a design prior to its deployment, we need tools capable of predicting WLAN performance. Simulators are often used, but they are expensive and the way they model interference in multicell environments is not accurate due to simplifications in the physical layer: co-channel and adjacent channel interference emulation does not behave as observed in real testbeds [12]. One alternative is to use analytical models, which also make significant assumptions. However, they are faster in providing a reliable approximation of a network's performance and the results are precise enough to allow the objective evaluation of various WLAN designs. In this section, after showing how partially overlapping channels affect neighboring stations, we present a model that assesses the saturation throughput of a WLAN, that is it estimates the network capacity, including the effect of interference, as shown in Section 2. This estimation will also be included in the metric used to compare different frequency channel allocations.

For our evaluation, we performed a mathematical analysis based on Bianchi's model [13]. This model is used to compute the saturation throughput of an IEEE 802.11 WLAN for a single isolated cell that is free of transmission errors and hidden terminals; the number of competing stations is known and it is assumed that they always have frames to send. In Reference [14], the effect of errors is added to the model, given an average PER for a given cell; the PER can be derived from the SINR.[§] Adapting this model to a system based on multiple WLAN cells is not trivial, but we can apply several simplifications without deviating from the expected values. Two types of interference are considered: adjacent channel interference (caused by transmissions on overlapping channels) and co-channel interference (caused by nodes using the same channel).

3.1. Effect of Packet Errors in Saturation Throughput

Bianchi's original model allows an accurate evaluation of the saturation throughput of IEEE 802.11 distributed coordination function (DCF) networks under the assumption of ideal channel conditions and considering unlimited retransmissions, by employing a Markov chain. It concludes with the following expression for saturation throughput:

$$S_t = \frac{P_{\text{tr}} P_{\text{S}} E_{\text{p}}}{E_S} \tag{3}$$

[§]We use the term SINR when the interference is known; otherwise (or when there is no interference) we use SNR.

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where S_t is the saturation throughput defined as the fraction of time the channel is used to successfully transmit payload bits; E_s the average length of a renewal interval, defined as the time between two consecutive transmissions or the time between two consecutive backoff decrements; E_p the average payload length; P_{tr} the probability that at least one user station transmits in a randomly chosen slot time and P_s the probability of a successful transmission. The detailed derivation of the above parameters can be found in Reference [13].

Several papers have built on this basic model. The work in Reference [14] extends Bianchi's analysis to include finite retransmission attempts; References [15,16] adapt the model to backoff mechanism variants. In References [17,18,19], the effect of error probability is introduced in the model. Finally, Reference [20] includes the hidden terminal problem. In addition to the throughput analysis, some of the aforementioned papers also provide a companion derivation of the average transmission delay performance.

For our evaluation, we depart from Chatzimisios' expression for saturation throughput in the presence of transmission errors [17]. Chatzimisios *et al*. redefine the E_s value of Equation (3), define P_{er} as the probability that a frame is received in error, and include the PER in the P_s expression:

$$E_s = (1 - P_{tr}) \cdot \sigma + P_{tr} \cdot P_s \cdot T_s + P_{tr} \cdot P_c \cdot T_c + P_{tr} \cdot P_{er} \cdot T_{er} \tag{4}$$

$$P_{er} = \frac{n \cdot \tau \cdot (1-\tau)^{n-1}}{1-(1-\tau)^n} \cdot \mathrm{PER} \tag{5}$$

$$P_s = \frac{n \cdot \tau \cdot (1-\tau)^{n-1}}{1-(1-\tau)^n} \cdot (1 - \mathrm{PER}) \tag{6}$$

where n is the number of contending stations; σ the duration of an empty slot; T_s, T_c, and T_{er} are the average time intervals that the medium is sensed busy due to a successful transmission, a collision or a transmission error, respectively; and τ is the probability that a station transmits a frame in a randomly chosen slot time [13].

As explained in Section 2, we know that adjacent channel interference reduces the SINR and, hence, reception errors appear. The PER for each node's transmission will depend on the SINR sensed by the corresponding AP upon reception of the node's frames. Based on the SINR values and the modulation used by the station for its transmissions, we can derive the bit error ratio (BER) for a given client, which can be obtained theoretically using the formulas given in References [9,21,22]. However, to achieve more realistic results, empirical curves can be used. Usually, these BER *versus* SNR curves are included in the transceiver datasheet. For our algorithm, we use the data provided with Intersil Prism HFA3863 [23]. The following approximation is used to compute the PER, in which the BER and the average length of the packet (L bits) are known

$$\mathrm{PER}_L = 1 - (1 - \mathrm{BER})^L \tag{7}$$

We have omitted the effect of losing an ACK frame since its probability is negligible due to its small size and the fact that it is usually transmitted at the slowest (i.e., most reliable) bitrate.

3.2. Effect of Co-Channel Interference

Due to the *CSMA/CA* mechanism, co-channel interference results in undesired effects, such as the hidden node and exposed node problems (*cf.* Reference [10]). Bianchi's model was again revised to incorporate co-channel interference, but the authors of Reference [24] only considered two interfering cells. Our approach is based on the fact that WLAN throughput in the presence of co-channel interference can be modeled assuming long-term fairness among the nodes sharing the same channel. That is, in the long term, all stations have the same probability of gaining access to the common channel. Although this assumption ignores observable phenomena that arise in various topologies (e.g. see [25]), we have found that the error introduced with individual flow calculations is not critical for the estimation of the global capacity. In infrastructure mode, given a set of nodes N, the algorithm computes the available throughput for every node $i \in N$, S_i as

$$S_i = s(i, \mathbf{C}_i) \cdot Sth(\mathbf{C}_i); \quad s(x, Y) = \begin{cases} \frac{1}{|Y|}; & 1 - \sum^{j \in Y \neq x} u_j \leq \frac{1}{|Y|} \\ 1 - \sum^{j \in Y \neq x}; & \text{otherwise} \end{cases} \tag{8}$$

where $\mathbf{C}_i \subset N$ is the subset of the elements of N that compete with i for the channel. This subset $\mathbf{C}_i$ depends

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not only on the nodes associated with i's AP, but also on the co-channel stations from other cells that are within carrier sense range of i. Thus, we include the influence of exposed nodes. The hidden node problem is minimized by using *RTS/CTS*. We found that the number of competing stations for i can be well approximated using the larger of the following two values: the number of nodes in i's cell and the maximum interference clique to which i belongs. Plotting stations and their interference as an undirected graph, a clique is a subset of nodes such that every pair of nodes are interferers. This method for modeling co-channel interference (henceforth *CL* model) involves the resolution of the clique problem, which is *NP-complete*. However, this is not an issue since a tree search function can be easily added to the code, which solves the clique problem without hindering the operation of the algorithm. If only the stations in range are taken into account (*CR*), the resulting approximation is good for lower densities. Figure 6 shows the differences between *CL* and *CR*. The function $Sth(\mathbf{C}_i)$ computes the saturation throughput for the set $\mathbf{C}_i$, according to Equation (3) and the revisions of Reference [17]. Finally, The multiplier $s(i, \mathbf{C}_i)$ is used to reflect the effective share available to i. If the utilization of the remaining contenders is greater than $|\mathbf{C}_i|^{-1}$, long-term fairness will ensure a share $s(j, \mathbf{C}_i) = |\mathbf{C}_i|^{-1}\, \forall j \in \mathbf{C}_i$. Otherwise, the excess bandwidth not used by the members of $\mathbf{C}_i$ is available to i. Figure 6 illustrates this: following both models (CL and CR), node j will ideally receive 1/2 of the maximum throughput (ignoring collisions, errors and other effects to simplify the example), since there is only one competing station i. However, i competes with four (CL) nodes, so at most it will receive just 1/4 of the share. Therefore, in practice, j is competing with just 1/4 of a node, thus obtaining 3/4 of the maximum throughput. Recall that u_j represents the node j's utilization (as defined in Section 2.2); in saturation, $u_j = S_j/Sth(C_j)$. In this case, the values $S_j\, \forall j \in \mathbf{C}_i$ are required to obtain S_i. That is, in order to obtain S_i, we need to know the value of S_i in advance. To avoid this incongruity and minimize the error we introduce, we follow a simple heuristic: S_i is computed starting with the node with the greatest number of competitors (highest degree), and so on.

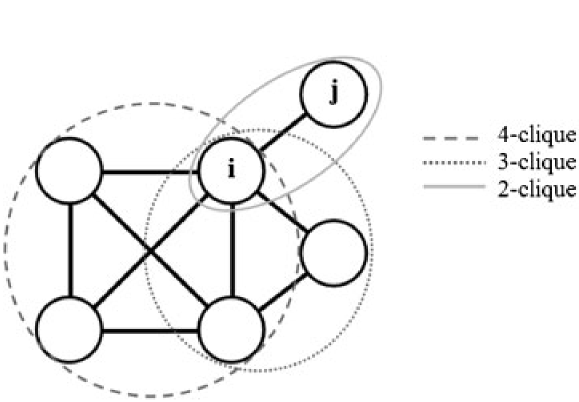

Figure 6. Interference graph and competing stations for node i: 4 (*CL*); 6 (*CR*).

This co-channel model has been evaluated through extensive NS-2 simulations [26]. Note that wireless communication in NS-2 uses different and independent channel objects for different cells; as a result, cross-channel noise and interference are not simulated. To correct this, our simulation consisted of *ad hoc* nodes using only one channel object. Four fixed stations playing the role of APs were located so that their coverage ranges were partially overlapping. The rest of the nodes were placed randomly throughout the area and were configured to send data to the closest AP. All these 802.11b nodes were driven to saturation by setting up a constant bitrate (CBR) UDP source so that there is always a 1500 byte datagram ready for transmission in each node's queue. So as to isolate the effect of co-channel interference, no transmission errors were introduced. Figure 7 compares the results of the simulations for both models (CL and CR). The figure shows that the error introduced with individual calculations is compensated in the overall estimation; hence, our approach does not deviate significantly from the expected values. Also note that these approximations are only valid for infrastructure mode. *Ad hoc* schemes usually require that nodes cooperate to forward each other's packets through the network. This means that the throughput

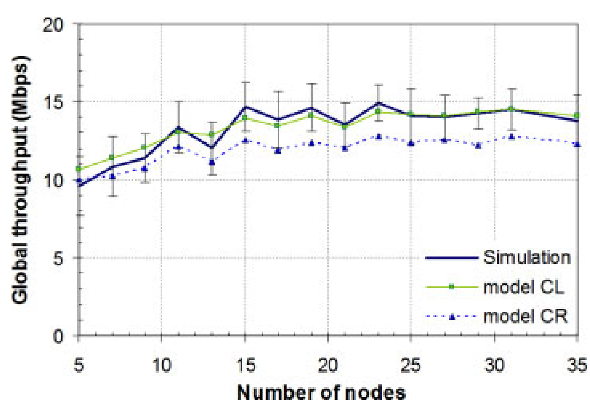

Figure 7. Evaluation through simulation of throughput models with co-channel interference. *CL* obtained by solving maximum clique; *CR* obtained by counting co-channel nodes in range.

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available for each node's applications is limited not only by the raw channel capacity but also by the forwarding load imposed by distant nodes [27].

4. Frequency Assignments in IEEE 802.11 WLANs

4.1. Related Work

The algorithms for the FAP can be classified according to their objective. When the purpose is to find a feasible solution that fits certain restrictions, we use the feasible frequency assignment problem (F-FAP) or maximum service FAP (Max-FAP) variants. This is the method most widely used in 802.11 networks; assignments that satisfy the five-channel separation for adjacent cells are found [2,28,29]. Optimizing the number of channels (MO-FAP: minimum order FAP) or the area of the frequency spectrum used (MS-FAP: minimum span FAP) does not make sense since the entire ISM band is freely available. For these reasons, we argue that the most appropriate approach for the WLAN 802.11 DCF is the one that minimizes interference between cells, thereby improving the performance of each cell. This strategy has been used in Reference [30], but this scheme is able to avoid interference by changing the AP placement. Moreover, the model used captures very roughly the interference and does not take into account the evident effect of utilization. The FAP formulation which aims to minimize interference, is known as minimum interference FAP (MI-FAP) and is usually modeled using interference graphs $G=(V, E)$. The interference graph G consists of a set of vertices V, representing the WLAN cells in a region, interconnected by a set of edges E. The existence of an edge between two vertices indicates that the two cells are overlapping. There are various methods for solving these graphs [31], many of which are designed to find optimal solutions. However, they all involve a large computational effort. The graph coloring heuristic methods stand out due to their simplicity and low computational overhead. Graph coloring tries to assign 'colors' to the vertices of a graph so that neighboring vertices (i.e., those connected by an edge) have different 'colors.' The DSATUR algorithm [32], which was also used in Reference [29], provides a fast, simple heuristic. It establishes the order in which vertices are colored and the colors assigned. At each iteration, the vertex with the highest saturation degree (i.e., having the largest number of colored neighbors) is selected to be colored. If two or more vertices have the same saturation degree, the one with the highest ordinary degree (i.e., having the largest number of neighbors) is selected; if the draw persists, then a random selection is performed. Since the assignment may be computed on several different devices, all of which must obtain the same result, all nondeterministic steps must be replaced; for example in Reference [29] ties are broken using the physical addresses. The color assigned to the selected vertex is the lowest channel not being used on any of the vertex's neighbors. The steps are summarized as follows:

1. Arrange the vertices by decreasing order of degrees.
2. Color a vertex of maximal degree with color 1.
3. Choose a vertex with a maximal saturation degree. If there is an equality, choose any vertex of maximal ordinary degree in the uncolored subgraph.
4. Color the chosen vertex with the least possible (lowest numbered) color.
5. If all the vertices are colored, stop. Otherwise, return to 3.

When there is a high density of nodes and edges (e.g., when the graph contains a clique of 4, as in Figure 6) and we have just three colors, this algorithm is not useful since it tries to solve a problem that has no feasible solution. That is to say, like F-FAP, it is limited by the use of just three colors (i.e., three non-interfering channels) in 802.11b/g networks. To overcome this limitation, authors in References [33,34] allow the use of 'forbidden' colors by evaluating a certain cost. In Reference [35], for example, the cost is limited to the number of clients in conflict (i.e., affected by interference from neighboring cells), but the degree of the interference is not evaluated.

4.2. Proposed Algorithm

The three main requirements for our channel allocation algorithm are fast adaptation to changes and a low degree of complexity, thus allowing the algorithm to be run in low-featured devices (e.g., the AP itself). Therefore, our algorithm must work in a timely manner at a low computational cost. Moreover, the algorithm must be able to maximize the network capacity making use of all the available channels. For these reasons we adapted the DSATUR with costs to fit the particularities of IEEE WLANs. This algorithm does not always provide the optimal solution,

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but it is fast and requires few resources. However, as mentioned above, if we use overlapping channels in interfering cells, performance degradation occurs. We therefore made some modifications to the algorithm in order to reflect the effects of interference. In our approach, the cost is based on the capacity estimations presented in Section 3.

The saturation degree maintains its definition from the original DSATUR: number of colored neighbors. The concept of ordinary degree is modified: the new ordinary degree evaluates the interference of a node seen from its neighbors, including its utilization, as explained in Section 2. In the simplest case study, let us assume that each vertex of the graph corresponds to an AP, that is, V represents the set of APs; an edge between two vertices denotes that the two APs are within reach of each other. To compute an interference-based cost, we then use a matrix $\mathbf{C}$ whose elements $c[i][j]\,\forall\, i, j \in V$ represent an average of the signal level received in AP j from the cell of AP i; $c[i][j] = 0$ means that in graph $G = (V, E)$, the edge $(i, j) \notin E$; $c[i][i] = 0\,\forall\, i\ V$. The sum of the elements of the ith row of $\mathbf{C}$ gives the total interference caused by node i and is used in our algorithm as the ordinary degree. The interference level received by a node could also be used likewise, obtaining similar results. Also note that all uncontrolled APs in the graph (not participating in the process) must be considered as colored nodes from the beginning. The idea is as follows:

Input*: (G, C, F)*
Output*: an assignment f*

while !(f(v) ≠ 0 ∀ v ∈ V) do
  select v with f(v) = 0 and maximum saturation degree
    if there is a tie, select v with maximum new ordinary degree
  f(v) = bestChannel(v, G)
  update saturation degree of nodes in V

First of all, the nodes are arranged by decreasing order of degree; the degree of a node is decided by two criteria: (1) saturation degree and (2) new ordinary degree. Then, all APs in V are colored in order. We define $f(v)$ as the channel assigned to the AP v. The function *bestChannel* assigns a channel to v such that the capacity of the colored cells is maximized. This way, we do not define any 'blocked colors' and so there is always a feasible solution, in contrast to other versions of DSATUR. Capacity estimations are based on a simplification of Equation (8). Function *bestChannel* can be written as

$$bestChannel(v, G) = \arg\max_{f \in F} \sum_{i \in V : f(i) \neq 0} S_i \qquad (9)$$

where F is the set of available channels and S_i is obtained from Equation (8), but only taking APs and their cross-interference into account in this case. Here, the values u_j are known in advance, so the specific heuristic explained in Section 3.2 need not be applied. Note that the sum of S_i does not actually represent network capacity unless all nodes are driven to saturation.

It turns out that the choice of the first channel assigned has considerable impact on the quality of the assignment. Since no generally good rule could be identified as to which channel should be assigned first, the algorithm is actually run $|F|$ times, each time starting with a different channel, and finally the best assignment is chosen.

4.3. Client-Driven Enhancement

Two distant APs (out of decodable range of each other) can belong to interfering cells if there is a client station within transmission range of both APs. In an AP-only approach, the graph will not reflect the actual interference. However, it should be recalled that the original cost function (8) also includes interference as seen by clients. The forthcoming IEEE 802.11k amendment will allow APs to request from their clients a list of in-range APs and other radio measurements that better describe the actual interference. Moreover, the optimization metric will be more accurate once we include the information provided by the clients. The next section presents more details on this issue.

5. Implementation Issues and Architecture

As mentioned above, the channel allocation mechanism is implemented in two ways: centralized and distributed. Although the main issues are covered in Reference [5], this section offers some details on the implementation of the mechanism presented in this paper, including issues related to the participation of terminals.

Due to the great diversity of WLAN networks that may coexist in a given area, it may be difficult to coordinate all nodes in order to obtain optimal frequency assignments [4]. This makes centralized

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management solutions difficult to implement (*cf.* Reference [36]). A distributed system of some sort would therefore be appropriate, but this would require additional intelligence for the participating devices. This requirement is supported by current technology trends, which are expected to keep producing devices with improved features, that is, new APs will have faster CPUs, greater storage/memory capacity, etc. Nevertheless, it must be remembered that current off-the-shelf APs still have limited features. Therefore, we took several steps to reduce the complexity of our algorithms so that the computational cost would be affordable enough for execution in commercial APs. For example, although capacity estimations are accurate enough for our needs, some errors are introduced due to the assumptions made in the model. Consequently, there is no need to fully implement the complexity introduced by Bianchi's formulation in the function *Sth()*. In fact, *Sth()* returns tabulated values from a matrix whose coordinates represent the average PER and the number of contenders. As a result, the computational cost is reduced without further affecting accuracy. This makes the algorithm run faster, which allows several executions for a given scenario, introducing and evaluating small variations in the solution set. Thus, the algorithm is able to produce better assignments. These variations are deterministic in a distributed implementation and random in a centralized architecture, as with simulated annealing optimizations.

In contrast, centralized management systems rely on a central entity capable of running complicated processes without hindering the normal operation of the managed devices. Centralized solutions simplify many issues that are still immature in the distributed solutions (e.g., security, communication among members, etc.). For the sake of brevity, since centralized management mechanisms are well known and do not involve extra complexity, the next subsection will focus on the implementation of the distributed mechanism. We then discuss various client-driven techniques that are valid for both centralized and distributed management.

5.1. Distributed Architecture

In order to run the simplified algorithm presented in Section 4.1, an interference graph must be built in all APs. To do so, all APs must send information, including their own utilization and the signal power they receive from neighboring cells (without any filter), to all other members. In a centralized architecture, the required signaling is limited to the reports sent from the APs to a central unit (as shown in Figure 8c). If the central unit detects that a channel switch could improve the capacity of the network by a preset threshold, it sends the new channel assignment to each AP. The problem of adding signaling capacity to a group of elements that cooperate to better utilize a shared resource was studied in Reference [5]. Garcia *et al.* argued that, although most WLAN networks are infrastructure based (use of APs), from an inter-network point of view, their behavior could be compared to that of *ad hoc* networks. Following this idea, our scenario consists of a varying number of APs that can appear and disappear unpredictably in a region. Although its immediate application is limited by the boundaries of a single administrative domain, cooperation among independent domains ruled by different owners is also desirable when they share resources, as with the unlicensed ISM frequency bands used in 802.11 WLANs. In these cases, cooperation allows better resource utilization than greedy behavior by the competing domains. However, inter-domain cooperative resource management is difficult to establish due to the potential for malpractice and other security issues.

In Reference [37], the simplest solution is implemented: all APs are connected to a common wired broadcast domain, but if the infrastructure is expensive to use or there is no common infrastructure at all, this solution is not suitable. The possible lack of a common wired distribution system makes us 'think wireless,' so we propose using APs with more than one wireless interface: one is devoted to keep working as an AP, and the others can be used to join a wireless mesh network for inter-AP communication (see Figure 8a). In addition to signaling, inter-AP communication could also be used to build a wireless backbone, as proposed in Reference [38], which would allow the additional cost introduced by the extra interface to be redeemed. Moreover, the lack of wires makes it easier to rapidly satisfy communication needs in temporary locations such as emergency sites, sporting events, etc.

To allow new custom software to be developed and tested in commercial APs, these devices should incorporate an open-source development environment. The main problems found during implementation were due to differences between driver developers, which are often inevitable due to differences between manufacturers in the way the physical layer is accessed. For example, signal levels provided by different firmwares are usually represented in different scales with non-standard units. This makes interference

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calculation difficult and causes erroneous results. In addition, not all models can perform frequency scans when acting as an AP or even report any type of signal measurement. See Reference [5] for a comprehensive study on the implementation of a distributed management framework for frequency assignments and other resource management strategies.

5.2. Client-Driven

Next-generation networks are distributing core functionalities toward the boundaries of the operator, to the point that 4G anticipates that even client devices will participate [39]. Like the authors of Reference [40], we argue that terminals may hold the key to improving resource management. In our case, interaction with client devices is justified by the need to build a complete interference graph. Ideally, client devices should send information, including the interference received from both neighboring clients and APs within range, to the management system (as depicted in Figure 8b and d). Recall that IEEE 802.11k-enabled devices will be able to send these interference reports to their APs. With this information, we can use the original formulation instead of the simplified version used previously. Reference [41] proposed an alternative to 802.11k, which is currently under development: UMTS-Wi-Fi hybrid terminals could use the UMTS interface to exchange signaling with a central unit in order to assist in various key management functions.

Client-network cooperation is also required to smooth AP channel switching. We noticed that a sudden channel change can be traumatic for active clients. After the AP performs a channel change, active clients do not receive layer 2 ACKs, so they use up their maximum number of trials and activate the RTS/CTS mechanism, assuming there is a hidden node problem. If no answer is received, the clients start an active scan until the AP is reached. The transmissions are then resumed without repeating the association and authentication process. The total duration of connectivity loss is between 200 and 450 ms, depending on the card manufacturer and the traffic load on the different channels. IEEE 802.11h [42] amendment establishes new mechanisms that an AP can use to announce a channel switch to all of its clients before it is actually performed. This synchronization will prevent harmful connectivity losses.

6. Experiments and Results

First of all, in order to evaluate the goodness of the algorithm, a C program was made to generate random graphs. By solving a large number of these graphs, we verified that if a feasible solution is obtained with original DSATUR (i.e., up to three channels are needed to avoid interferences), it will also be obtained using our modification with exactly the same cost. When DSATUR cannot provide a feasible solution (e.g., the graph is not three-colorable), using all possible channels always has a better cost. As argued in Section 2 and shown in following paragraphs, this translates into improved capacity. In addition, the assignments provided by the proposed algorithm are

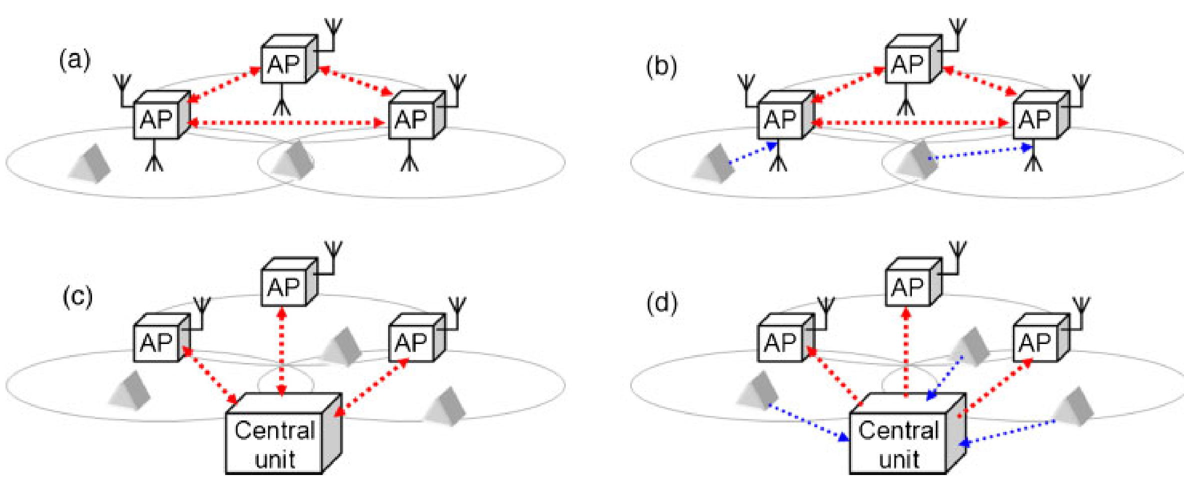

Figure 8. Possible architectures for distributed (a, b) and centralized (c, d) management. Enhanced management is achieved with client-originated information, which is sent to the client's AP (b) after association process or directly to a central unit (d) regardless the association status (via UMTS).

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compared with the optimal solution (obtained using a branch-and-cut method) in order to measure its effectiveness and efficiency. Paper [4] use statistics gathered in different US cities to provide useful hints for building WLAN interference graphs. Those statistics present extreme values, for example, graphs with more than 8000 nodes, and nodes with a degree higher than 80 (i.e., an AP with more than 80 neighbors). However, the graphs are not connected, and even though the maximum connected component can have a size of hundreds of APs, the average connected graph has 10–16 APs. Moreover, more than half of the nodes have only two neighbors or less, which gives a low density, defined as $D = 2 \cdot |E| / (|V| \cdot (|V| - 1))$. Therefore, to represent real-life dense scenarios, we built random connected graphs with $10 \leq |V| \leq 30$ and $3/(|V| - 1) \leq D \leq 8/(|V| - 1)$, so that the APs have 3–8 neighbors on average. The results showed that our algorithm obtains the optimal solution in near 40 per cent of the tests (see Figure 9); in the 90 per cent of the tests the error is below 10 per cent.[¶] On the other hand, our algorithm is able to provide a solution set in 1–3 s running on a commercial AP (CPU MIPS 400 MHz, RAM 64 MB) while the optimal set takes from 1–2 min for small graphs, to more than 10 h for graphs with 20 or more nodes, when the branch-and-cut algorithm runs on a server station (2xCPU Intel Xeon DC 2.4 GHz, RAM 2 GB).

The improvements obtained using a channel assignment strategy aimed at increasing the available capacity per station had been previously proved in Reference [37] by means of practical measurements and implementing an early version of our mechanism: in a small testbed with four APs we obtained from 10 to 16 per cent of increased capacity. Here, we present a more complete study where the benefits of our approach are evaluated through a vast number of independent simulations, providing small confidence intervals, which are therefore not shown in the figures. The simulator implements all the details specified in IEEE 802.11 standard, including the effect of interference in a multicellular environment. The simulator was validated, and the details of its implementation were presented in Reference [43]. The simulated scenario consisted of a $250 \times 250\,m^2$ area where 20 APs and a varying number of randomly placed client

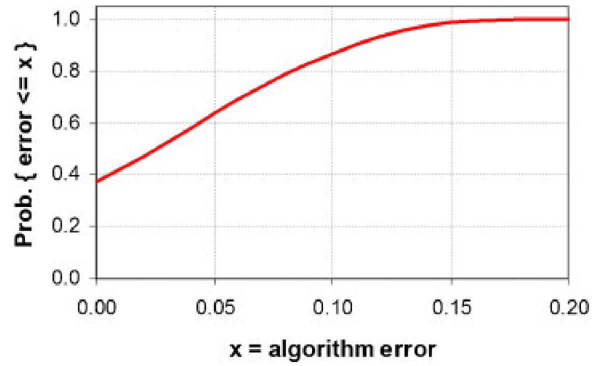

Figure 9. Cumulative distribution of the error committed with the proposed algorithm, compared against the optimal solution.

stations (STAs). Using a semi-open urban propagation model [9], with all stations (APs and STAs) transmitting 15 dBm with omni-directional antennas, the transmission range varies from 25 to 30 m due to the randomness introduced by the propagation model. Thirteen channels were available, only three of which were non-overlapping. The load offered by each station was also random.

In the first set of simulations, we set the ratio of saturated stations (always have 1500 byte frames in the transmission queue) to 10 per cent. In this case, all four solutions tested (random allocations, the proposed algorithm, three- and four-coloring) were able to carry the offered traffic. However, the harmful effects of interference became more noticeable as the number of active users increased (see Figure 10). The proposed solution minimized both adjacent channel interference (thus improving PER) and co-channel interference (reducing collision probability). With random allocations, the PER was very high, but on the other hand, collision probability was better than with three- or four-coloring because the number of cells using the same channel was low. If all stations try to obtain the maximum possible throughput (100 per cent saturation), a frequency management strategy aimed at reducing interference increased carried traffic by about 18 per cent, as shown in Figure 11; that is, a higher cost means a higher capacity (*cf.* Section 3). Note that even a random allocation improved the network performance obtained with the traditional three-coloring.

With low loads, the presence of radio resource management was not noticeable; hence, network performance was the same for all channel allocation strategies. As the network load increased, the need for good radio resource management became critical. In these scenarios, the performance of our proposal

[¶]If a is the capacity estimation obtained with the optimal set and b the metric obtained with our algorithm, the error is $(a - b)/a$. An error of 0 means that the algorithm provided the optimal solution.

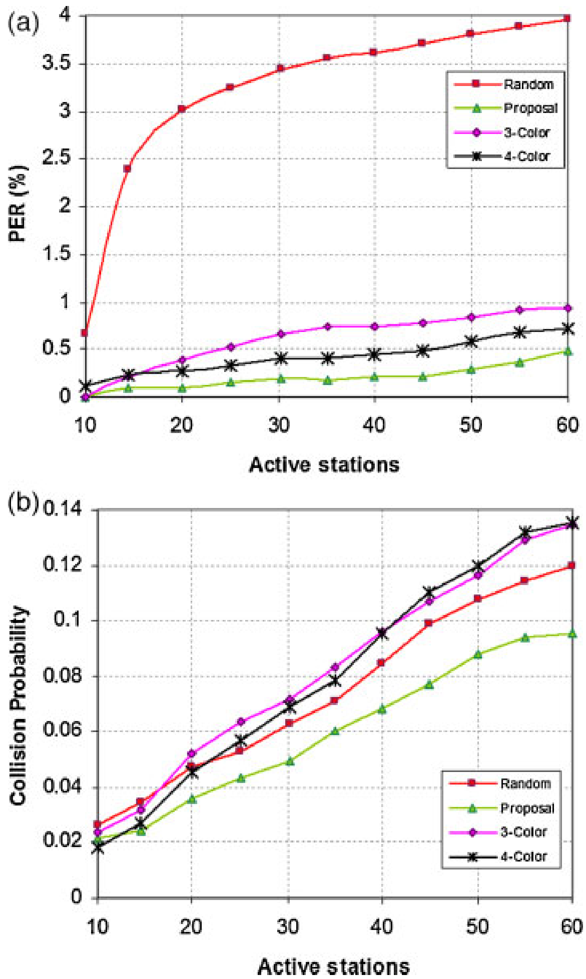

Figure 10. Average PER (a) and collision probability (b) per STA with 10 per cent saturation.

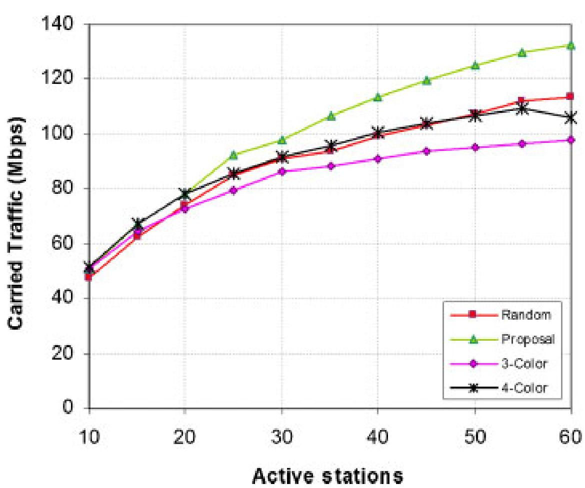

Figure 11. Carried traffic with 100 per cent saturated.

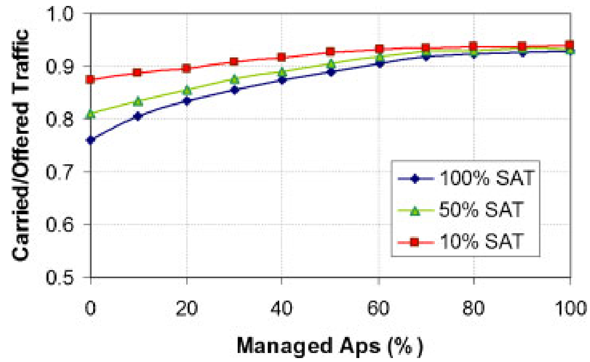

Figure 12. Carried/offered traffic with varying number of managed APs and saturation levels.

stood out. Although our channel assignment mechanism supports the coordination of APs from different domains (*cf.* Reference [5]), in the real world, the presence of interfering cells from outside of the managed set of APs is inevitable. From the managed network's point of view, these sources are treated as a fixed-channel node in the interference graph. Logically, performance improves as the number of managed APs increases, but as shown in Figure 12, under low load conditions, controlling 40–50 per cent of the APs is enough to optimize network performance. With higher loads, at least 70 per cent of the APs should participate in frequency management.

Finally, client-driven enhancements were verified in the last set of simulations. Figure 13 shows the carried traffic with different number of saturated stations (10, 50 and 100 per cent), using both the basic (AP-based) and client-driven algorithms. These improvements, which reached a maximum of 6 per cent, were most visible when the network load was high.

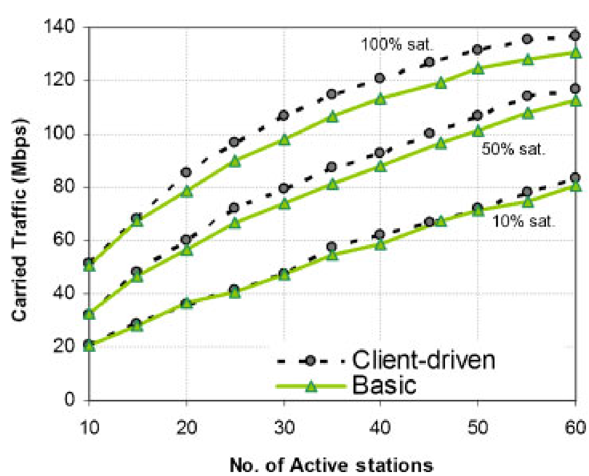

Figure 13. Client-driven enhancements on carried throughput.

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7. Conclusions

In this paper, we have introduced a new mechanism that solves the FAP in IEEE 802.11 WLANs. We used all available channels, rather than just the traditional non-overlapping three, in order to effectively reduce both co-channel and adjacent channel interference.

We justified the use of the entire available spectrum, including partially overlapping channels, by studying the effects of adjacent channel interference. We also derived a model that estimates the capacity of a multicellular WLAN. Based on this estimation, we built a cost function that can accurately evaluate different channel assignments. We demonstrated that optimizing our cost function effectively reduces both types of interference, which logically increases the capacity of the whole network. This improvement becomes more noticeable as the load is intensified.

The benefits of good frequency management can be further amplified by integrating the role of client devices into the system thanks to the valuable information they can provide to build a complete interference graph. Both approaches—basic (AP-based) and client-driven enhancement—can be implemented following either centralized or distributed paradigms. In fact, all possible architectures have been implemented as proof of concept prior to large-scale deployment.

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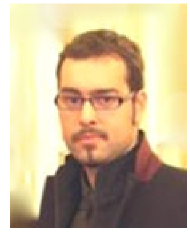
Authors' Biographies



Eduard Garcia Villegas received his M.Sc. degree on telecommunication engineering from the Technical University of Catalonia in 2003. In 2004, he was granted a research fellowship by the Generalitat de Catalunya. At present, he is an Assistant Professor at the same university and a member of the Wireless Networks Group (WNG). He is currently working toward his Ph.D. He has worked in several public funded research projects. His research interests include Radio Resource Management in WLANs, wireless security and wireless mesh networks.

Rafael Vidal Ferré received his M.Sc. degree from the Technical University of Catalonia in 1997. He is an Assistant Professor at the same university and a member of the Wireless Networks Group (WNG). He is currently working toward his Ph.D. He has worked in several public funded research projects. His research interests include Mobility Management and Self-Configuration in wireless networks.

Josep Paradells is a Professor at the Technical University of Catalonia. He is the head of the Wireless Networks Group (WNG). His expertise areas are network convergence and ambient intelligence, combining theoretical studies with real implementations. He has been participating in national and European public funded research projects and collaborating with main Spanish telecommunications companies. He has published his research results in conferences and journals.

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