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# PERFORMANCE EVALUATION OF AUTOMATIC CHANNEL ASSIGNMENT MECHANISM FOR IEEE 802.11 BASED ON GRAPH COLOURING

Janne Riihijärvi, Marina Petrova, Petri Mähönen, and Jovander de Almeida Barbosa
RWTH Aachen University, Department of Wireless Networks
Kackertstrasse 9, D-52072 Aachen, Germany

## ABSTRACT

We present the design and implementation of graph colouring -based channel assignment mechanism for infrastructure mode IEEE 802.11 networks. Several enhancements to earlier designs as well as results from a thorough performance evaluation in a WLAN testbed are given. The performance of the colouring scheme is compared with random and "fixed default" channel assignments, as these are the ones commercially available access points most often use. It is shown that the colouring approach leads to improved utilization of wireless resources, and considerably enhances the performance of the networks.

## I. INTRODUCTION

In recent years the popularity of Wireless LAN (WLAN) hotspots has increased dramatically. Today numerous public places such as airports, cafeterias, and even complete city centres are equipped with numerous access points (APs) to offer almost ubiquitous wireless connectivity. At the same time the increased density of WLAN access points has started to highlight the negative effects or shortcomings of the original IEEE 802.11 standards. Most importantly, no standard frequency allocation method exists for WLAN access points. This has lead to the situation where large majority of APs is using default channel settings, leading to highly inefficient use of the already crowded spectrum in the ISM bands. This situation is especially critical in the 2.4 GHz band, due to the small number of non-overlapping WLAN channels available, and coexistence problems with several other wireless technologies.

In earlier work [1, 2] we have proposed the use of *graph colouring algorithms* in collaborative manner amongst the access points to efficiently allocate channels in hotspot networks. In this paper we extend this work by presenting enhancements for the basic scheme that have proven to be useful in dense networks, where partially overlapping channels must be used by adjacent access points. We also present a prototype implementation of our scheme on Linux platform, and demonstrate the effectiveness of the colouring approach in real wireless network testbed. This work thus extends the previous algorithm, presents the real implementation details, and outlines the performance evaluation results. Naturally, several other authors have tackled the frequency allocation problems in WLAN context [3, 4, 5, 6]. However, we believe the colouring approach adopted is very suitable one compared to others due to its simplicity and very acceptable computational overhead achieved by efficient use of heuristics. Finally, we would like to note that graph colouring has been used in frequency allocation previously, but then confined to *off-line* use (see, for example, [7, 8, 9, 10]).

The rest of the paper is organized as follows. In section II we present a concise overview of the graph colouring method used in [1]. We continue in section III by presenting enhancements to this scheme for dense networks, which were included to the prototype implementation described in section IV. We then present results from a performance evaluation of the system in section V before concluding the paper in section VI.

## II. OVERVIEW OF THE COLOURING METHOD

In this section we shall introduce the frequency allocation problem for WLANs in terms of graph-theoretic colouring problem, and briefly discuss the DSATUR colouring algorithm we chose for our implementation. A comprehensive introduction to graph theory is given in, for example, [11].

From the basic graph theory a simple graph $G = (V, E)$ is defined with a set of vertices $V$ and set of edges $E$ connecting the vertices in a way that loops and multiple edges between vertices are not allowed. A *vertex colouring* for the graph $G$ is a map $c : V(G) \to F$, where $F$ is a set of *colours*, usually some small subset of positive integers. The colouring is *admissible*, if $c(V_i) \neq c(V_j)$ for all *adjacent* $V_i$ and $V_j$. An admissible colouring minimising the size of the colour set used, $|c(V)|$, is referred as an *optimal* colouring. The number of colours used by the optimal colouring is called the *chromatic index* $\chi(G)$ of the graph.

Having the colouring problem explained above we can now map it to our frequency allocation problem. If we want to optimally assign frequencies to a set of access points $\{V_i\}$, we could form an *interference graph* $G = (V, E)$ as follows. The vertex set $V$ is mapped to the set of access points $\{V_i\}$. Furthermore the set of edges $E$ consists of those pairs $\{V_k, V_l\}$ of vertices, that correspond to access points $V_k$ and $V_l$ that would interfere with each others' transmission should they be assigned the same channel. Finally, the set of "colours", $F$, corresponds the collection of channels available to the access points. It is now easy to see that the channel allocation problem is simply finding an admissible colouring of $G$ with the colour set $F$. An illustration of such an interference graph and corresponding admissible colouring is given in figure 1.

The size of the colour set is obviously technology dependent. For example, the $F$ has thirteen elements for IEEE 802.11b from which only three channels are non-overlapping. For the IEEE 802.11a and IEEE 802.11g the set of available channels is considerably larger.

There are number of colouring algorithms that can be applied to optimally assign frequencies. In [1] we showed that the simple "degree of saturation" (DSATUR) heuristic of Brelaz [12] gives very satisfactory colourings for problems of this

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Figure 1: Example interference graph.

type. Degree of saturation is defined as the number of colours used in the neighbourhood of a vertex. At the beginning of the algorithm the degrees of saturation of all vertices are set to zero. An uncoloured vertex with the highest degree of saturation is chosen. In case there are more than one vertex with the same degree of saturation, the one with the highest number of uncoloured neighbours is selected. The selected vertex is further on coloured in a greedy manner using the smallest colour admissible. The process continues with updating the degrees of saturation of the uncoloured vertices. Based on the update, a new vertex with the highest degree of saturation will be chosen for colouring and so on. The algorithm runs until all the vertices are coloured. The details of the algorithm can be found from [12] and [1, 2].

Even though *exact* graph colouring typically requires exponentially increasing computation time with the increasing graph size, the DSATUR heuristic operates in strictly polynomial time. Interference graph consisting of thousands of nodes can be coloured in less than a second in hardware routinely used in today's WLAN APs.

## III. Enhancements for Dense Networks

The application of the colouring algorithm as described in the previous section is straightforward if the interference graph is three-colourable. We can simply assign the three colours to any three non-overlapping channels available in IEEE 802.11b (the frequency spectrum used by the different 802.11b and 802.11g channels is shown in figure 2; clearly only three non-overlapping channels can be used at a time). If more colours were required, we would have to establish a more complicated mapping between the integer colour assigned by DSATUR, and the channel chosen by the AP. A key parameter to be used in this decision is the effect traffic flows on (partially) overlapping channels have on each other. This effect can easily be quantified in a simple experiment with two node pairs generating traffic at rate high enough to saturate the channel, and by varying the "separation" of channels used by the node pairs. Results from such an experiment are shown in figure 3.

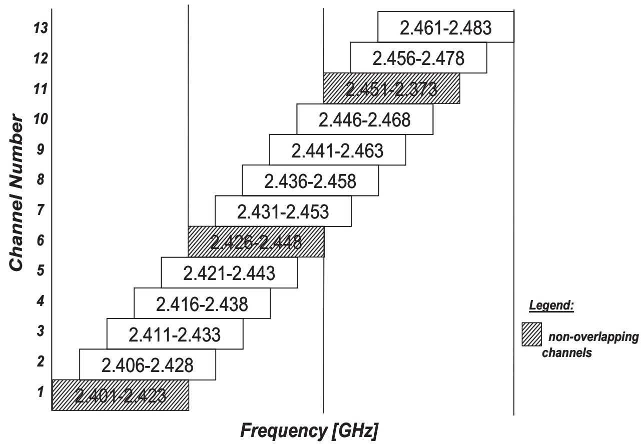


Figure 2: The spectrum use of different IEEE 802.11 channels in the 2.4 GHz ISM band.

From the figure it is clear that instead of using channel distances less than four, assignment of APs to same channel is actually preferable. The reason for this is simple. If the same channel is used the IEEE 802.11 MAC layer performs fairly well in achieving good utilization of the channel. In the case of channel distances being in the range of 1–3, the co-channel interference leads to a high proportion of corrupt frames, which must be resent. The MAC protocol has no chance of correcting the situation, since it no longer receives the frames from interfering nodes.

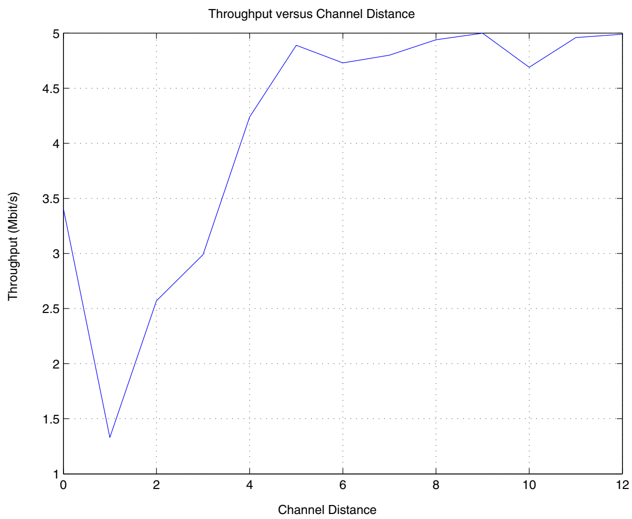


Figure 3: Effect of channel separation on achievable bitrate in 802.11b channels.

It is straightforward to integrate algorithm into the basic colouring scheme to enforce this channel separation constraint. We simply establish an array of look-up tables mapping the

Table 1: Mapping from DSATUR output $c$ to the channel number depending on the number of colours required.

| | Chromatic index $\chi(G)$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $c$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 3 | | | 11 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 4 | | | | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| 5 | | | | | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | | | | | | 5 | 5 | 5 | 5 | 5 |
| 7 | | | | | | | 9 | 9 | 9 | 9 |
| 8 | | | | | | | | 13 | 13 | 13 |
| 9 | | | | | | | | | 1 | 1 |
| 10 | | | | | | | | | | 5 |

DSATUR output to the channel number, indexed by the chromatic index of the interference graph. Such a construction is shown in table 1. Naturally, any permutation of the numbers in a given column would do as well. This remaining freedom could be used to take into account, for example, noise levels and other propagation details in channel assignment. Nevertheless, in the prototype implementation we decided to adopt the straightforward approach given in the table.

## IV. Implementation Architecture

Next we elaborate on the implementation of the frequency allocation mechanism. Our frequency allocation program tool is of a client-server type and comprises of two parts: one running in the server side (Linux machine connected to the APs via Ethernet) and the other running in the clients and/or APs. During the implementation process we took care to build a flexible software architecture in order to be able to add and remove APs easily. In the testing phase, as access points, we used regular laptops with NETGEAR MA401 PCMCIA IEEE 802.11b cards with Prism 2 chipset, running HostAP [13]. HostAP is a Linux driver that supports so called HostAP mode in which the WLAN card acts as an ordinary AP. The implementation is lightweight enough that it is straightforward to port to actual AP devices, especially into Linux based ones.

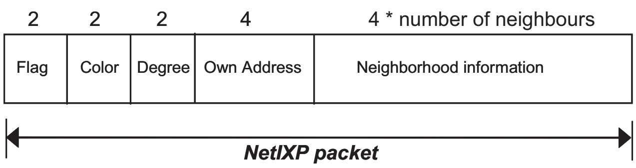


Figure 4: NetIx packet.

The actual DSATUR algorithm calculating the frequency allocation is running on the server side. It means that the processing of the collected data from all the APs and the construction of the interference graph is done in a centralized fashion. In order to be able to provide the neighbourhood information to the server we designed a protocol for exchanging information called Network Information Exchange (NetIx). The packet structure of the protocol is shown in figure 4. The protocol requires 10 bytes for the header information and rest of the UDP packet for the payload where the IP addresses of the neighbouring APs can be transmitted. The NetIx defines the following header fields:

- **Flag** is a two-byte field used to identify the packet type. We have defined six different packets showed on the message flow diagram in figure 5 .
- **Colour** is a two-byte field that carries the new colour calculated by the DSATUR algorithm.
- **Degree** carries the information about the number of neigbours that a certain AP have.
- **Own address** field shows the IP address of the AP sending the packet.

The process of new frequency allocation can be in general triggered by a new client (AP) coming into the network or by any client if the interference level is such that it produces serious impairment in the wireless communication. For our testing and measurements we implemented only the first option. When the server gets a *request for new frequency* message from a client (flag=0), it broadcasts a *request for network information* message back. At this point the access point will start to exchange neighbourhood information among each other, in an ad hoc mode, by sending three broadcast packets with the flag=2 via the wireless interface (e.g., all APs switch to channel 12). It should be shortly mentioned that in our experiment the entire communication between the clients and the server is done through the Ethernet. The exchange of neighbourhood information is a one hop communication. When the process is finished, each client sends a neighbourhood report to the server via a message with the flag set to three. After these packets are acknowledged the neighbourhood information is fed to the DSATUR which constructs the new interference graph and calculates the frequency allocation. The colouring algorithm unicasts the assigned frequency for each AP. The cycle is finished as long as each client acknowledges the receipt of the new frequency.

The transmission of the NetIx protocol messages is done over the UDP/IP packets. In order to increase the reliability of the UDP we added an ACK policy for the unicast packets so that each successfully received packet is acknowledged. Missing ACK will initiate a packet retransmission.

## V. Performance Evaluation

To evaluate the performance of the colouring-based channel allocation we set up a controlled testbed consisting of a collection

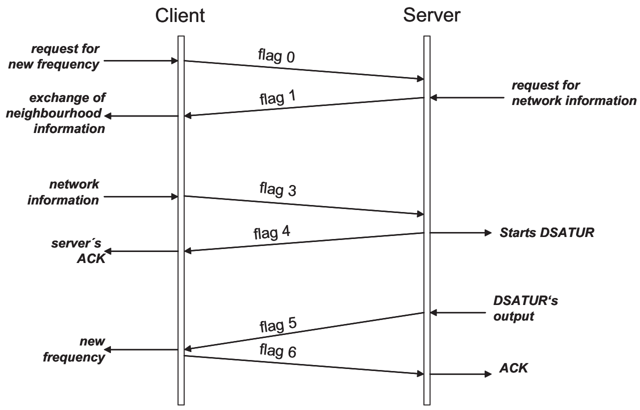


Figure 5: Client-server information exchange.


Figure 6: Example of the scenarios used in the measurements.

of laptops. Half of the laptops we running in the master-mode of the driver, acting as access points, and the rest operated as clients. Experiments were repeated using different numbers of access points to estimated the dependency of the performance obtained from the network density. One of the clients was randomly chosen to run `iperf`, using UDP traffic at various offered bitrates to probe the capacity available through the access point. Other client-AP pairs were transmitting data at high enough rate to saturate the respective channels.

Three channel assignment schemes were used in the measurements: fixed, random, and colouring-based. The fixed allocation corresponds to the situation where all access points are utilizing the same channel. This is actually the case with the majority of present-day access points. In the random case the channels for the access points were randomly drawn from the uniform distribution. This channel selection mechanism can be enabled in some commercially available APs. Finally, the colouring-based approach utilized the prototype software described in the previous section. Fairly dense topologies were used in all experiments, as can be seen from the example shown in figure 6.

The results for the fixed scheme are shown in figure 7. As can be expected the bitrate achieved degrades severely already when two or three access points share the same channel. Random channel assignment achieves already considerably improved performance, as can be seen in figure 8. However, from the differences of the two curves depicted, and from the error bars it is obvious that the performance is highly varying. By far the most stable performance is obtained by the colouring method, the results for which are shown in figure 9. The scaling of the average bitrate achieved as a function of offered bitrate is almost linear, and the channel is very stable as shown by the small error bars. If we superimpose the *worst-case* performance of different schemes as observed in the experiments, as shown in figure 10, the superiority of the colouring method becomes clearer still.

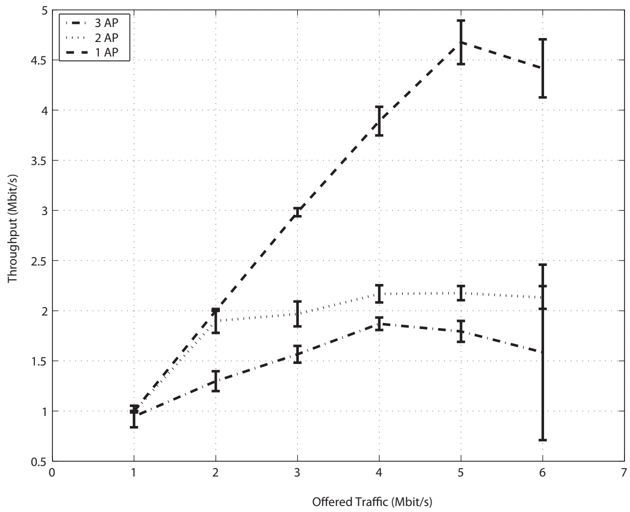


Figure 7: Achieved bitrate when default channels are used by the APs.

## VI. Conclusions

We have described enhancements and a prototype implementation of a graph-colouring based channel assignment scheme for IEEE 802.11 networks. Using measurements conducted in a real wireless testbed, we showed that the colouring scheme performs very well in practise compared to common mechanisms utilized in most commercially available access points.

## Acknowledgments

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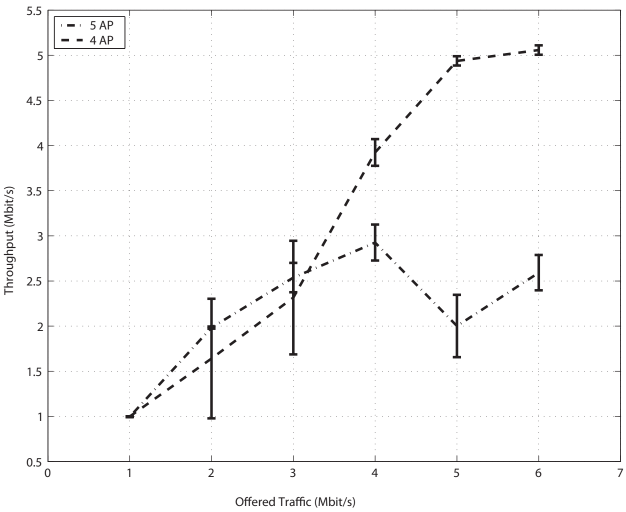


Figure 8: Performance of the random channel assignment.

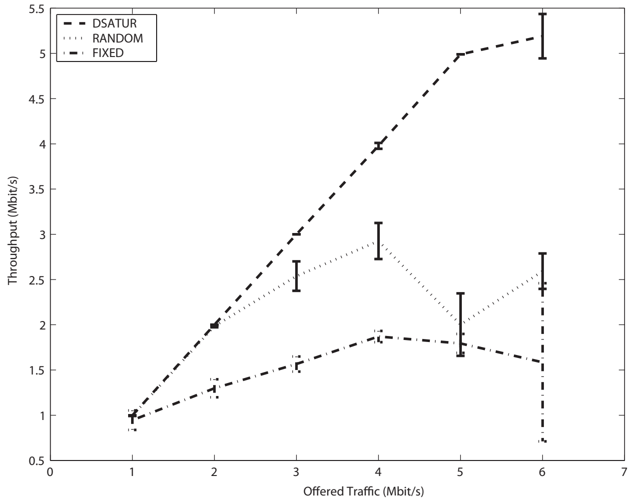


Figure 10: Worst-case performance of the channel assignment techniques studied in the measurements.

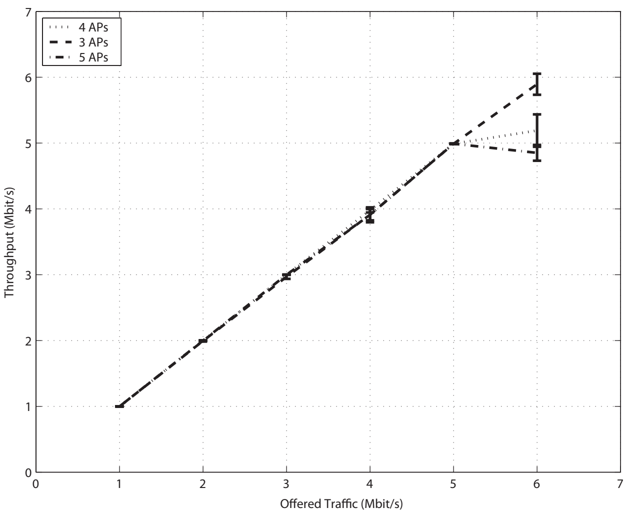


Figure 9: Achieved bitrate when the colouring method is applied.

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