Performance Evaluation of a Self-Organising Scheme for Multi-Radio Wireless Mesh Networks

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Abstract

Multi-Radio Wireless Mesh Networks (MR-WMN) can substantially increase the aggregate capacity of the Wireless Mesh Networks (WMN) if the channels are assigned to the nodes in an intelligent way so that the overall interference is limited. We propose a generic self-organisation algorithm that addresses the two key challenges of scalability and stability in a WMN. The basic approach is that of a distributed, light-weight, co-operative multiagent system that guarantees scalability. The usefulness of our algorithm is exhibited by the performance evaluation results that are presented for different MR-WMN node densities and typical topologies. In addition, our work complements the Task Group 802.11s Extended Service Set (ESS) Mesh networking project work that is in progress.

1. Introduction

Wireless Mesh Networks (WMNs) have emerged as a feasible way of providing the last mile connectivity between the access networks and the Internet. The growing impetus of WMNs prompted IEEE in 2004 to initiate an ESS Mesh Networking task group - 802.11s.

Initially, the research in the area of mesh networks based on 802.11a,b/g standards focused on a single radio (single channel) WMN. However, in a single radio network the throughput of the link between each hop progressively decreases due to the co-channel interference between the adjacent hops as well as interference from the neighbouring links [1]. These limitations have lead to the introduction of multiple radio interfaces on each node to form a multi-radio Wireless Mesh Networks (MR-WMN). The key benefits offered by MR-WMN are:

(i) Cost effectiveness in providing the last-mile connectivity to the Internet.
(ii) Increased scale of deployment and Reliability.
(iii) Creates disjoint collision domains due to which an overall increase in network capacity is realised.

The 802.11 standards provide a limited number of non-overlapping channels however the interference caused by the reuse of these channels from neighbouring links represents the key factor that limits the performance. Through an extensive study we have identified scope for improvement in the key areas of scalability and stability for the channel assignment process. Scalability is important because WMNs will be deployed over large metropolitan areas and hence the self-organisation process should occur within a reasonable time. By stability we mean that the process should be robust enough to sustain the assignment of channels over a period of time rather than trigger a frequent assignment of channels.

In this paper, we propose a self-organising algorithm in a multi-radio WMN that is based on the approach of a distributed, light-weight, co-operative multi-agent system that guarantees scalability. We have validated both the scalability and stability aspects of our algorithm by means of analysis and provided key simulation results that show the impact of node density and MR-WMN typical topologies on the algorithm performance. Our self-organisation mechanism operates over MR-WMN so that the interference between the channels of routers in its interference range is reduced. Each hop in a MR-WMN has a throughput that is dependent mainly on

This work is supported by a grant from Alcatel-Lucent and the Australian Research Council.

the radio type, the distance between the transmitter and receiver, the modulation schema, and interference.

The paper is organised as follows: In Section 2, we review some of the important work related to the channel assignment in wireless networks. Section 3 presents and explains our algorithm for channel self organisation. It also presents validation by means of analysis. The simulation results obtained for algorithm performance are presented and discussed in Section 4. The paper concludes in Section 5.

2. Related work

The proposals in literature that are discussed herein can be classified for use in either: (i) cellular systems and infrastructure mode 802.11 networks (BSS) or (ii) MR-WMN. Although the problems addressed by the first group are somewhat different, important parallels justify the coverage of related methods in this review. The use of channel assignment approach in cellular systems for WLANs has been exhaustively reviewed in [2]. A conclusion of particular interest is that as a cell size becomes smaller distributed scheme becomes more attractive because of high centralisation overhead. The review of this work also reveals the main differences between cellular and 802.11 based networks viz. (i) the usage of an unlicensed spectrum in 802.11 that is public (ii) base stations in cellular networks are at fixed distances whereas 802.11 APs are in most cases at random distances from each other.

In most of the reviewed papers the graph colouring theory is used as a base for the theoretical modelling of channel assignment. References [3,4] use weighted graph colouring with the weight calculation based on a number of clients that are affected by the interference affecting an AP on a particular channel. Reference [5] uses waited graph colouring in form of interference graph. In this model each vertex represents a WLAN and edges represent interference between corresponding WLANs. Although models based on graph colouring theory have proven their usefulness in modelling interference in infrastructure based WLANs, we agree with the conclusion of [6] that graph colouring models do not adequately capture all the constraints of a multi radio WMN.

We focus in the remainder of this section on the performance, complexity, scalability and stability of WMN related proposals. The work in [7] specifically targets the channel assignment problem on WMN. Authors have adopted their theoretical work in [7] and created a self-stabilizing distributed protocol and an algorithm for channel assignment. Reference [7] assumes that the interference is symmetric and is based on an interference range of three hops. This results in improvements of only 20% compared to random channel assignment. In reality, most of the times interference will be asymmetric because neighbouring node interface may transmit on the same channel at different powers. In contrast, our proposal does not assume symmetric interference and does not require a dedicated channel for frequency co-ordination, which is a significant advantage. The other main limitation of proposal in [7] is the use of a common channel on each node for the management of channel assignment. We have avoided this approach because it can be wasteful of bandwidth and imposes severe limitations on network capacity especially when nodes have only two interfaces. Furthermore, a strong source of interference on the frequency that is used for the coordination of channels can render the throughput of parts or the whole network unsatisfactory.

3. Proposed algorithm

Before we explain our proposed algorithm for channel assignment the notations and assumptions used in the remainder of this section are stated below:

- Available channels: *1, . . ,K.*
- A node is a set of radio interfaces where each interface is associated with a particular channel, together with a controller that assigns the channel to each interface. The node has blocks of interfaces that belong to different radio types. In its current state all existing wireless standards need bridging (relaying on layer 2) or routing (relaying on layer 3) functionality to connect with other wired or wireless networks. We assume that each node provides such functionality.
- A link is a pair of interfaces where each interface is assigned the same channel. The idea is that two interfaces communicate through a shared link. That is, if an interface is part of a link its state will be “listening and transmitting”, otherwise its state will be “listening only”.
- Notation: nodes are denoted by Latin letters: *a, b, c,...* the interfaces for node a are denoted by: *a[i]* for $i = 1, . . .$, and links are denoted by Greek letters: α, β, γ...The interfaces communicate using an illocutionary communication language that is defined informally (for the time being) with illocutions being encapsulated in quotation marks: “•”.
- For any node n, S_n is the set of nodes in node n’s interference range. Likewise, for any link α, S_α is the set of links that contain nodes n’s interference range. Given a node “a”, define $V_a = \bigcup_{n \in S_\alpha} S_n$
- Γ_x^t is channel used by x to communicate at time t where x may be either an interface or a link.
- $f(\bullet, \bullet)$ is an interference cost function that is defined between two interfaces. It estimates the cost of

interference to one interface caused by transmission from the other interface. This function relies on estimates of the interference level and the level of load (i.e.: traffic volume).

• An interface is either 'locked' or 'unlocked'. A locked interface is either locked because it has committed to lock itself for a period of time on request from another interface, or it is 'self-locked' because it has recently instigated one of the self-organisation procedures explained in this section. A locked interface is only locked for a 'very short' period during the operation of each of those procedures. This is simply to ensure that no more than one alteration is made during any one period— this is necessary to ensure the stability of the procedures. We also say that a node is locked meaning that all the interfaces at that node are locked.

• SNIR means "signal to noise plus interference ratio".

The proposed algorithm is explained below in different steps that correspond to the different states of the system.

A) Initialising the system.

This procedure initialises a network from system start-up. It begins by building a spanning tree from a root interface (mesh portal) that spans a designated area of the mesh network. Such a tree may also be used if the network operator requires a systematic method to communicate with all nodes such as updating the nodes' algorithms — this use of spanning trees is not discussed further here. The algorithm has three steps:

1. Construct a spanning tree with the property that any node in the area is within the interference range of a node on the tree. The spanning tree's nodes are called *seed nodes*. The construction of a good spanning tree requires reference to topological information that may be obtained by a low cost GPS chipset — we do not discuss this here. Operational parameters such as transmit power, obtained from the nodes within the interference range of each seed node are stored in a table at the seed node. This information we term as "infoa".

2. Each seed node in turn then builds a cluster of nodes around itself. The seed node builds its cluster one node at a time. Each seed node is strategically chosen so that the clusters formed around the seed nodes cover most of the area in the wireless mesh region. The cluster formation process involves that the seed node broadcasts a "Hello" packet at frequency f_1 to all the nodes in its interference range. All these nodes respond to the seed node with an accept Hello packet. The seed node then assesses the SNIR value of the transmission between itself and each of the responding nodes. It will then assign the frequency f_1 to the responding node (interface) for which a maximum value of SNIR was obtained. The following algorithm represented in an illocutionary language summarises this process (Notes: id_a is a MAC identifier.)

for j=1,……,.K do {
transmit "inform hello[id_a]" with a[j] on channel j;
set b $\leftarrow$ arg max$_x$ {SNIR(receive "accept hello[id_a, id_x] on channel j")};
transmit "inform channel [id_a, id_b, j]"; };

3. In the event that the above procedure fails to establish links with all nodes (due perhaps to unforeseen external events) we assume that those unconnected nodes will invoke the procedure described in part B below.

B) Process for adding a new node.

The objective of this process is for a new node that is introduced to the mesh topology to join the mesh. The description is from the point of view of node *a* that wishes to join its interface *a*[*i*] to the mesh. The aim of the joining process is for a node to establish connectivity with a node in its interference range. For this the joining node broadcasts a "Hello" packet at frequency f_1. The "Hello" packet is essentially a Registration packet. Whichever nodes can provide connectivity to the joining node they respond back with an "accept Hello" packet. The joining node then selects the node with which it wants to establish connectivity on the basis of the maximum SNIR transmission value between itself and the responding node. The following algorithm represented in an illocutionary language summarises this process.

for j =1,….,K do {
transmit "inform hello[id_a]" with a[i] on channel j
if (SNIR (receive "accept hello[id_a, id_x] on channel j") > κ {
set Γ $\leftarrow$ j;
break; } else {set Γ $\leftarrow$ arg max$_x${SNIR (receive accept hello[id_a, id_x] on channel k")};}}
in time [t –1, t];
set b $\leftarrow$ arg max$_x$ { SNIR receive "accept hello[id_a, id_x] on channel k")};
transmit "request link[id_a, id_b, Γ]" at time t;
if receive "accept link[id_a, id_b, Γ]" by time t+s then
transmit "inform info[$info_a$]" with a[i] on channel Γ and stop; else start again;

Notes: constant *s* is set to be sufficient to permit node *b* to be released from a locked state in the event that it is locked. The constant *κ* represents an acceptable level of SNIR that the node will accept without further consideration. id_a is a MAC identifier.

C) Self- Organisation: Proactive Logic

Our solution is based on the distinction in multiagent systems between proactive and reactive reasoning. Proactive reasoning is concerned with planning to reach some goal. Reactive reasoning is concerned with dealing with unexpected changes in the agent's environment. So in the context of self-organising networks we distinguish between:

• a reactive logic that deals with problems as they occur. The aim of our reactive module is simply to restore communication to a workable level that may be substantially sub-optimal.
• a proactive logic that, when sections of the network are temporarily stable, attempts to adjust the settings on the network to improve performance.

The reactive logic provides an "immediate fix" to serious problems. The proactive logic, that involves deliberation and co-operation of nearby nodes, is a much slower process. The following methods are independent of the operation of the load balancing algorithm.

Method for adjusting the channels - Proactive logic

Informally the proactive logic uses the following procedure:

• Elect a node *a* that will manage the process
• Choose a link *α* from *a* to another node — precisely a trigger criterion permits node *a* to attempt to improve the performance of one of its links with a certain priority level.

• Measure the interference
• Change the channel setting if appropriate

The process for proactive logic involves that the node broadcast a "Hello" packet at frequency f_1 and it then determines the sum of the interference cost function between its link and each of the other links (one-by-one) with respect to each other. Note: Due to non-symmetrical nature of transmission caused by different transmission powers the interference cost function may not be symmetrical. If the sum of non-symmetrical interference cost function for a frequency f_l is below a threshold range then the frequency f_l is assigned to the node interface for which the proactive logic was applied. Our proactive logic is a development of the ideas in [7,8].

Selflock in the algorithm is to prevent *a* from having to activate the method too frequently. The constant $\varepsilon < 1$ requires that the improvement be 'significant' both for node *a* and for the set of nodes S_a. The stability of this procedure follows from the fact that it produces a net improvement of the interference cost within S_a. If a change of channel is effected then there will be no resulting change in interference outside S_a. The above method reduces the net observed inference cost in the region V_a. The following algorithm represented in an illocutionary language summarises the proactive logic process.

choose node a at time t – 2; set $V_a = \bigcup_{n \in S_\alpha} S_n$ *;*

$\forall x \in V_a$ *transmit "propose organise[a, x, p]";*
unless $\exists x \in V_a$ *receive "overrule organise[a, x, q]" in [t – 2, t – 1] where q > p do {*$\forall x \in V_a$ *transmit "propose lock[a, x, t, t+1]";*
if $\forall x \in V_a$ *receive "accept lock[a, x, t, t+1]" in [t- 1, t] then {unless* $\exists x \in V_a$ *receive "reject lock[a, x, t, t+1]" do {improve a;}}}*
where: improve a = {choose link $\alpha \in a$ *on channel* Γ_α^t*;*
set B $\leftarrow \sum_{\beta \in S_\alpha} f(\alpha \mid \beta) + \sum_{\beta \in S_\alpha} f(\beta \mid \alpha)$*;*
if (feasible) re-route α's traffic;
for $\Gamma_\alpha = 1, \ldots\ldots K$ $\Gamma_\alpha \neq \Gamma_\alpha^t$ *do {*
if $\sum_{\beta \in S_\alpha} f(\alpha \mid \beta) + \sum_{\beta \in S_\alpha} f(\beta \mid \alpha) < B \times \varepsilon$
then {$\Gamma_\alpha^{t+1} \leftarrow \Gamma_\alpha$*; selflock node a in [t + 1, t + k]; break;};};*
$\forall x \in V_a$ *transmit "α's interference test signals";*
apply load balancing algorithm to S_a *;}*

4. Performance Evaluation

4.1 Simulation model and attributes

In this section, we present the details of the Java simulation framework developed by our team to test the performance and behaviour of the algorithms.

Each link was initially generated with a randomly assigned channel. By recursively using this approach all the routers (mesh nodes) were connected to the network. When one or more routers were left without any connectivity to the rest of the network (often in completely random topology) the simulation is repeated until the topology with all routers connected is obtained. Four values of interference cost were calculated for such a network and in the rest of the paper are labelled with the following abbreviations: **ICB** - Interference Caused by the link Before self organisation algorithm is triggered. **IAB** - Interference At the link Before self organisation algorithm is triggered. **ICA** - Interference Caused by the link After self organisation algorithm has been triggered. **IAA** - Interference At the link after the self-organisation algorithm has been triggered. ICB and IAB are used as reference values to calculate the decrease in interference cost after the self-organisation algorithm was applied. Below, we state the key attributes of the simulation model:

- The self-organising channel assignment process was limited to a single channel change per link.
- All radio interfaces were static, deployed with omni-directional antennas, based on 802.11g standard, and transmits power for each interface was generated randomly with a 50% variation.
- Calculation of interference cost was based on the following parameters:
  - Distance between interfaces.
  - Signal strength of transmitting interface (consequently it is not symmetrical).
  - Interference factor between partially overlapping channels as provided in [8].
- All networks generated occupied an equal size area of 750 X 500 meters. Three different densities of routers per sq. unit of area were deployed in each topology: 35, 70 and 100.
- Three different topologies were generated:
  - The simple grid - the routers were positioned from each other in a uniform grid with their in between distances randomly varying 5%. An example of simple grid is the cellular network.
  - The random grid – the same as previous only with 50% of random variation.
  - The completely random – in this topology the arrangement of the routers was generated completely randomly. An example of completely random topology is the ad hoc network.
- The number of interfaces per router was generated randomly to be between 3 and 5.
- Each simulation for a topology with specific random grid variation and router density was repeated 12 times and a mean and confidence interval was calculated (108 simulations in total).
- We generated 5252, 5292 and 5064 links for simple grid, random grid and completely random topology respectively. This high number of simulated links enabled us to obtain statistically valid confidence interval of 98%.

4.2 Results and Discussion

The interference cost reduction for a link discussed herein is measured as the difference between absolute interference (AI) values obtained before the channel assignment process and after the channel assignment process. For example, if $AI_{before}= 5$ and $AI_{after}=4$ the absolute difference is $AD=1$ which is 20% decrease in the absolute interference. Consequently, the performance is always expressed as a percentage of the decrease. The mean of IC reduction across all topologies and network densities is 36.7.

Our simulation studies consider realistic scenarios of different node densities and topologies in a typical wireless mesh network hence are more reflective of evaluating the true performance of the algorithm.

4.2.1 Impact of network density on the performance It can be seen from Fig. 1. that as the density of network increases (i.e. an increase in the number of routers located within the same area) the IC reduction relatively decreases. This trend is shown across all the topologies.

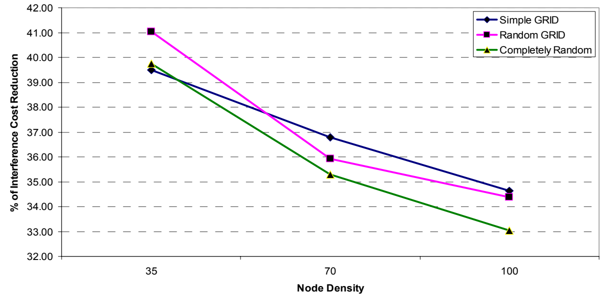

Figure 1: Interference cost reduction as a function of network density

We attribute this result to the limited number of non-overlapping channels available in IEEE 802.11b/g standard that in tight proximities of the nodes (i.e. increase in node densities) shows more effects of a higher absolute interference and thus a relatively lower interference cost reduction. Furthermore, the impact of node density on the algorithm is relatively consistent for all topologies at the same router densities. From Fig. 1 it can also be observed that the range of the interference reduction across the topologies at router densities of 35 routers and 100 routers is 1.55 and 1.58, respectively.

4.2.2 Impact of typical topologies on the interference cost. Figure 2 shows the variation in the interference cost reduction as function of network topology and it can be deduced that the impact of the topologies on the performance of the algorithm (i.e. in terms of interference cost reduction) is insignificant.

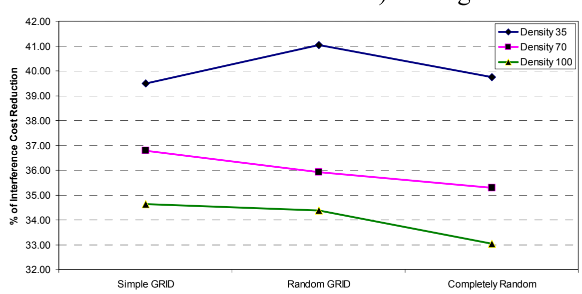

Figure 2: Interference Cost Reduction

The mean of IC reduction calculated from the data obtained shows that the topology with the smallest average IC reduction is the completely random with a mean of 36.02 and topology with the most IC reduction is the random grid with a mean of 37.12 The difference in performance between best and worst case is just 1.1 which confirms that the performance of the algorithm is almost completely independent of the type of topology.

4.2.3 Performance bounds. In addition to previously discussed results for the algorithm, we have calculated the 98% confidence bounds per link for absolute interference values across all topologies and different network densities.

Table 1: 98% bounds of absolute interference cost (Table 1a: Before Self-Organisation)

Topo -logy	Simple Grid		Random Grid		Completely Random	
Dens.	Min	Max	Min	Max	Min	Max
35	5.04	5.5	5.47	5.50	5.87	6.41
70	11.44	12.0	11.70	12.27	12.56	13.22
100	16.0	16.6	16.1	16.7	17.87	18.64

(Table 1b: After Self-Organisation)

Topo -logy	Simple Grid		Random Grid		Completely Random	
Dens.	Min	Max	Min	Max	Min	Max
35	3.04	3.34	3.22	3.53	3.53	3.87
70	7.24	7.58	7.50	7.86	8.13	8.55
100	10.47	10.83	10.58	10.95	11.98	12.46

On comparison of the respective interference values of Tables 1a & 1b, we can see that the 98% confidence interval per link interference cost is smaller and tighter after self-organisation is invoked in contrast to before the invocation.

4.2.4 Performance Comparison across the Network In this study, we obtained Interference cost in different regions of the MR-WMN for the same set of links before and after the self-organisation algorithm is invoked.

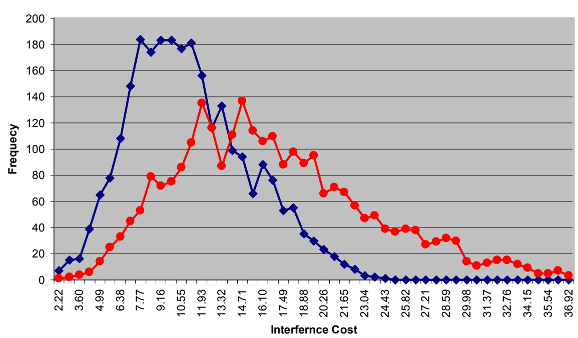

Figure 3: Comparison of IC across the network before (red) and after (blue) self-org.

Comparison of the results obtained is shown in Fig 3 where the Interference cost is on the X-axis. From Fig 3 we can see that there were no nodes (blue dots) that caused more interference after the self-organisation than it had caused before (red dots) the self-organization was invoked.

5. Conclusions

In this paper, we have proposed a self-organization algorithm that addresses the two major challenges of scalability and stability. Scalability is ensured by progressively assigning the channels to nodes in clusters during the wireless mesh network system start up phase. The stability is offered by means of the proactive and reactive logic of the algorithm. These attributes were validated through analysis. Key performance evaluation results obtained from extensive simulations showed the effectiveness of the algorithm for different node densities, topologies and across different parts of the multi-radio mesh network.

6. References

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