A topology control based self-organisation in wireless mesh networks

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Abstract: An algorithm for self-organisation that assigns the channels intelligently in Multi-Radio Wireless Mesh Networks (MR-WMN) is important for the proper operation of MR-WMN. The aim of the self-organisation algorithm is to reduce the overall interference and increase the aggregate capacity of the network. In this paper, we have first proposed a generic self-organisation algorithm that addresses these two challenges. The basic approach is that of a distributed, light-weight, co-operative multiagent system that guarantees scalability. Second, we have evaluated the performance of the proposed self-organisation algorithm for two sets of initialisation schemes. The initialisation process results in a topology control of MR-WMN by way of spatial distribution of connectivity between the mesh nodes. The results have been obtained for realistic scenarios of MR-WMN node densities and topologies. We have shown further the need to develop non-transmit power control based algorithms to achieve a further increase in system capacity.

Keywords: multi-radio routers; self-organisation; mesh networks; scalability; stability; 802.11 WLANs; performance evaluation; topology control; algorithms; interference cost.

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1. Introduction

The main purpose of the multi-radio wireless mesh networks (MR-WMN) is to operate as a back haul network that links access networks to the wired IP backbone. MR-WMN is essentially constituted of multi-radio nodes called wireless routers that transport the data wirelessly amongst each other by multi-hop communications. This way the traffic is routed to and from the wired Internet entry points termed *mesh portal nodes*. Research (BelAir Networks 2006) has shown that due to the co-channel interference the throughput of the link between each hop progressively decreases in a single radio mesh network. In contrast, multi-radio routers for which channels are assigned smartly result in a decrease of the interference between the channels of two adjacent routers. The aim of the self-organisation process is thus to make the throughput of the links less susceptible to the channel interference as much as possible.

The two main issues associated with the self-organisation of wireless mesh networks (WMN) are that the algorithm should be scalable and stable. Scalability is important because WMN 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 algorithm 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, our contributions are two fold: First, we propose and discuss our method for autonomous self-organisation in mesh networks. Our method can operate on any radio technology that is used in the mesh networks. The basic approach of our algorithm is that 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. Second, our work involves also the study of the impact on the self-organisation algorithm performance by the way in which the mesh nodes are selected at initialisation (start-up) for channel assignment. The initialisation process results in a *topology control* of MR-WMN by way of spatial distribution of connectivity between the mesh nodes. In this regard, we present and discuss key Java based stochastic simulation results that reflect the impact of the initialisation process on our self-organisation algorithm. These results we have obtained for different MR-WMN node densities and typical topologies.

We have shown through simulations that there is a need for non-transmit power control based topology control algorithms to effectively increase the number of shortest paths to the portal nodes and distribute them evenly with respect to the portal nodes. This way a further increase in system capacity can be realised.

This paper is organised as follows: In Section 2, we present our 802.11 radio based wireless mesh network infrastructure. Section 3 reviews some of the important work in the literature for the self-organisation of multi-radio mesh networks. Section 4 presents and explains stepwise our algorithms for self-organisation. It also tabulates the measurement techniques and operational parameters that could be adopted from 802.11a/b/g/k. Section 5 explains the process for initialisation of channel self-organisation in the MR-WMN along with the simulation results that show the impact of initialisation process on the self-organisation algorithm performance. In section 6, results are presented to show the need for developing topological algorithms that create and evenly distribute the shortest paths to the portal nodes so as to further increase the system capacity. Conclusions that can be drawn are given in section 7.

2. Network Topology Overview

An underlying 802.11 mesh infrastructure, as shown in Fig. 1, is proposed to facilitate broadband wireless connectivity to the heterogeneous access networks such as GSM, WiMax, CDMA. The wireless connections in Fig. 1 are shown by means of the dashed lines and the solid lines indicate wired connectivity. Nodes in a WMN are generally static but the clients may be mobile or static.

Recent work on 802.11 Mesh Networks, such as by Raniwala and Chiueh (2005), is predicated on a network whose prime purpose is to route traffic to and from nodes connected to the wired network in which case there is assumed to be no traffic between end-user nodes. The root node in the mesh networking terminology is known as the *mesh portal* as shown in Fig. 1. Each of the mesh nodes i.e. mesh routers which also has access point functionality is termed as the *mesh access point* (MAP). The MAPs in Fig. 1 essentially multi-hop the traffic bi-directionally between the access networks and the wired Internet.

3. Self-Organisation - Architectures and Algorithms

3.1 Techniques used for Self-Organisation

The channel assignment algorithms that we have reviewed can be broadly classified to use the following approaches that could be carried out in a centralised or distributed mode:

*Static Assignment (*Kyasanur and N.H. Vaidya, 2005): In this approach a channel is assigned to an interface either permanently or over long periods of time. This approach is further sub-divided into two subclasses – (a) Common channel approach and (b) Varying channel approach. In a common channel approach the interfaces of all the nodes are assigned to a common set of channels, as such this approach ensures connectivity between the nodes at the cost of decreased throughput. In a varying channel approach the interfaces of different nodes are assigned to different group of channels. Although this approach will increase the network capacity it may not ensure connectivity and hence network partitions may arise.

*Dynamic Assignment (*Kyasanur and N.H. Vaidya, 2005): This approach offers the advantage of using different channels per radio interface so as to result in a high throughput. However, the drawback of this approach are (i) that a node that is communicating with another node needs a coordination mechanism to inform the other node of when to switch the channel and to what frequency to switch to (ii) this feature has to be carefully designed to avoid instability that would happen when a network never converges and endlessly circles between different channel assignments.

*Hybrid Assignment (*Kyasanur and N.H. Vaidya, 2005): This approach combines the strategies of static and dynamic assignment - static assignment is done for some interfaces and a dynamic assignment for other interfaces. A further classification is formed based on if the interfaces that adopt a static assignment use a common channel or a varying channel approach. An advantage of hybrid assignment is that they combine the flexibility of dynamic assignment along with simplified coordination algorithms that can be provisioned by static assignment.

Centralised channel allocation: Allocation is done in a centralised manner by a single entity. The positive aspect of this approach is that it can sometimes offer an optimal solution. While the drawbacks are that it does not scale well, it is not robust enough and increases communication overheads as the nodes need to communicate with a central node. Consequently, solutions using this approach have very limited scope of use.

Distributed channel allocation: In this approach the nodes that create links are involved in a channel assignment process. This approach results in scalability but individual implementations can suffer from poor performance and significant communication overhead.

Load aware channel allocation: This approach takes into consideration the load of a particular link and assigns the channels with less interference to links with higher loads. In general, the load on all the links is different and as such this approach is useful.

Measurement based channel allocation: Channels are allocated based on empirical measurements (usually signal to noise plus interference ratio.) carried out by involved nodes. Scanning methodology involves switching to RFMon (RF monitoring) mode supported by all 802.11 wireless interfaces. The same mode is used by Wi-Fi diagnostic software NetStambler and Kismet.

Use of transmit power control (TPC): Further reduction in interference is possible if the transmission power is reduced on links that do not requite high data rates. However introduction of this feature can increase complexity of the scheme. In addition, a maximum transmit power in frequencies used by 802.11 based transceivers is established by regulatory bodies that prescribe different maximum transmit power in different countries. These differences are outside of the scope of this review but have to be taken in account when designing systems that are going to be used in more then one regulatory domain.

Use of partially overlapping channels: The research done by Mishra, Rozner, Banerjee, and Arbaugh (2005) demonstrates that better performance can be achieved by using partially-overlapping channels instead of using just orthogonal channels.

3.2 Related Works

We have carried out an extensive literature review in the area of wireless mesh networks (WMN) that uses distributed algorithms for self-organisation with a focus on the attributes of scalability and stability. These algorithms do not require changes at the 802.11 MAC layer. We discuss below some of the key aspects of the literature that we have reviewed.

The channel assignment problem was initially addressed in the work of Kaufmann, Baccelli, Chaintreau, Papagiannaki, and Diot (2005) and more recently by Leith and

Clifford (2006) and Mishra, Shrivastava, Agarwal, Banerjee and Ganguly (2006). These references consider the problem of interference in an 802.11 based infrastructure networks when collocated networks are owned by different entities and there is no wireless connectivity present between them. Since this research does not consider WMN it is not directly related to our work. However, it is still important because it proposes a fully distributed self-organisation algorithms for the collocated networks and the use of partially overlapping channels for traffic transfer as in Mishra, Shrivastava, Agarwal, Banerjee and Ganguly (2006) The algorithm proposed by Kaufman is based on a Gibbs's sampler and does not require an explicit coordination among network devices such as access points (APs). *Gibbs sampling is an algorithm that uses the joint probability distribution of two or more random variables to generate a sequence of samples.*

Kaufmann, Baccelli, Chaintreau, Papagiannaki, and Diot (2005) assume that the impact of non-cooperative APs and end user devices will be mitigated through policies outside the scope of their proposal. On the other hand work of Ko, Misra, Padhye, and Rubenstein (2006) targets the channel assignment problem in WMN. Ko, Misra, Padhye, and Rubenstein (2006) have adopted a theoretical work and created a self-stabilizing distributed protocol for channel assignment. The main limitation of their proposal, as well as those in (Raniwala and Chiueh, 2005 and 2004) is the use of one 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 parts or the whole network unusable to obtain a satisfactory throughput. In addition, the method of Ko, Misra, Padhye, and Rubenstein (2006) assumes that the interference is symmetric and is based up to a range of three hops. The method results in improvements of data throughput of only 20% compared to random channel assignment. 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. Raniwala and Chiueh (2005) extend their proposal with the use of a virtual control network instead of a dedicated interface-channel on each router. The virtual control in Raniwala and Chiueh (2005) means that a certain fraction of bandwidth is reserved on each channel for channel assignment purposes rather than reserving one exclusive channel.

Subramanian, Gupta and Das (2005) proposes use of non-orthogonal channels. Their interference model is theoretically based on a conflict graph and similar to our work, the interference data is acquired through the measurement of link pair interference. Subramanian, Gupta and Das (2005) uses integer linear programming to obtain bound of optimal solution and evaluate the proposed algorithm. The main drawback of the proposal in Subramanian, Gupta and Das (2005) as well as the one by Ramachandran, Belding., Almeroth, and Buddhikot (2006) is the scalability since a centralised algorithm is used. However, both proposals motivate further investigation since they indicate a 40% performance gains in comparison to static assignment.

Table I: A comparative study between our and other key proposals.

Literature Attributes	***Raniwala (2005)***	***Ko (2006)***	***Subramanian (2005)***	***Our work***
Type of algorithm	Distributed/ Centralised	Distributed	Centralised & Distributed	Autonomous distribution
Parameter	Interference + Load	Interference	Interference	Interference + Load
Dedicated Channel for assignment	NO	YES	NO	NO

Non-orthogonal channels used	NO	NO	YES	YES
Transmit Power Control	NO	NO	NO	Under development
Scalability	Addressed	Addressed	Partially Addressed	Addressed
Stability	Not addressed	YES	NO	YES

4. Proposed Self Organising Algorithm

Before we explain our proposed algorithm for MR-WMN the notations and assumptions used in the remainder of this paper are stated below:

- Available channels: 1,. . . ,*K*.
- A node is a set of radio interfaces where each interface is associated with a particular channel. The node has blocks of interfaces that belong to different radio types. We assume for simplicity that each interface has its own, independent MAC layer.
- A link is a pair of interfaces where each interface is assigned the same channel.
- Notation: nodes are denoted by *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….
- 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 $V_a = \bigcup_{n\ S} S_n$
- $^{t}_{x}$ is the channel used by "x" to communicate at time *t* where "x" may be either an interface or a link.
- *f(·, ·)* is an interference cost function that is defined between two interfaces or two links. It estimates the cost of interference to one interface caused by transmission from the other interface
- 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.
- The abbreviation SNIR means "signal to noise plus interference ratio".

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

4.1 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 an 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. 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*. 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.

(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.

Essentially, the cluster formation process involves that the seed node (interface) broadcasts a "Hello" packet say at a 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. This process is repeated for all the remaining interfaces of the seed node. The following algorithm represented in an illocutionary language summarizes 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 $b$       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 section 4.2 below.

4.2 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. For this the joining node (interface) broadcasts a "Hello" packet say at a 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 summarizes 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")) > $\kappa$ {
set          j;
break; } else {set          arg $\max_x${SNIR (receive accept hello[$id_a$, $id_x$] on channel k")};}}
in time [t –1, t];
set b       arg $\max_x$ { SNIR receive "accept hello[$id_a$, $id_x$] on channel k")};
transmit "request link[$id_a$, $id_b$,      ]" at time $t$;
if receive "accept link[$id_a$, $id_b$,      ]" by time t+s then
transmit "inform info[$info_a$]" with a[i] on channel      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.

4.3 Method for adjusting the channels.

1. Proactive logic

Proactive active logic in our algorithm attempts to adjust the settings on the network to improve performance when sections of the network are temporarily stable. Our proactive logic is a development of the ideas in Ko, Misra, Padhye, and Rubenstein (2006).

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 say at a 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 of neighbouring nodes the interference cost function may not be symmetrical. If the sum of non-symmetrical interference cost function for a frequency f_1 is below a threshold range then the frequency f_1 is assigned to the node interface for which the proactive logic was applied.

Selflock in the algorithm is to prevent node *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 summarizes the proactive logic process.

```
choose node a at time $t - 2$; set $V_a = \bigcup_{n\ S} S_n$;
    $x$  $V_a$ transmit “propose organise[$a, x, p$]”;
unless  $x$  $V_a$ receive “overrule organise[$a, x, q$]” in [t – 2, t – 1] where q > p do
{  $x$  $V_a$ transmit “propose lock[$a, x, t, t+1$]”;
if  $x$  $V_a$ receive “accept lock[$a, x, t, t+1$]” in [t- 1, t] then {
unless  $x$  $V_a$ receive “reject lock[$a, x, t, t+1$]” do {improve a;}}}
where: improve a = {choose link α  $a$ on channel  $^t$;
set B  $\sum_S f(\ |\ ) + \sum_S f(\ |\ )$;
if (feasible) re-route α’s traffic;
for  = 1,……K  $^t$ do {
if $\sum_S f(\ |\ ) + \sum_S f(\ |\ )$ < B x ε then {
```

```
t 1          ; selflock node a in [t + 1, t + k]; break;};};
x   V_a transmit “α’s interference test signals”;
apply load balancing algorithm (not discussed herein) to S_a ;}
```

2. Reactive logic

Reactive reasoning is concerned about dealing with unexpected changes in the agent’s environment. The aim of our reactive module is simply to restore communication to a workable level that may be substantially sub-optimal. This is not discussed herein.

4.4 Triggering criterion for the method to adjust channels.

The triggering criteria is established based on the following explanation: By using equations in Sayandeep (2006) and Analyses of Measurements and Simulations in Multi-hop Ad-hoc Environment (2001) a formula is derived for the theoretical value of the received SNIR expected by the node (interface) based on the topology (i.e. distances, obstructions/free space) of the set of interfering links in the carrier sensing range. We then use the value of the expected SNIR to evaluate the expected bit error rate (BER) and expected frame error rate (FER). The expected value of FER is then used to determine the expected value of the airtime link metric, which is a radio-aware routing metric that has been proposed in the draft of IEEE 802.11s amendment (Bahr, 2006). The airtime cost c_a is given by equation below (Bahr, 2006):

$$c_a \quad \left[O_{ca} \quad O_p \quad \frac{B_t}{r}\right] \frac{1}{1 \quad {}_{fr}} \tag{1}$$

where; O_{ca} = Channel access overhead. This depends on the type of 802.11 transmission technology used i.e. 802.11b/g/a, O_p = MAC protocol overhead; This depends on the type of 802.11 transmission technology used, B_t = Number of bits in a test frame; r = Transmission bit rate (Mb/s); ε_{fr} = frame error rate, based on the current conditions of the radio channel.

If the airtime link metric c_a calculated by a node on the basis of the actual measured parameters is greater than the expected c_a by some pre-assigned margin then the node (interface) will decide to trigger the proactive logic as explained above. This will essentially occur when the measured FER is greater than the expected FER. The typical range of c_a will be the values of c_a for which an acceptable link quality of service is obtained.

But before it triggers the proactive logic the node (interface) will broadcast to all the other nodes in its interference range about its intent to initiate the process of proactive logic and the level of priority that it wants to use for this process. If no other node contends the priority level then the node that wants to trigger the proactive logic will go ahead and do so.

4.5 Self-Organisation Algorithm: Adoption of measurement techniques and parameters from 802.11a/b/g/h/k.

Our algorithm relies to an extent on the mechanisms to obtain the operational parameters defined as a part of 802.11 suite of standards- 802.11a/b/g/h/k. Below we tabulate the specific parameters and techniques from each of the stated 802.11 standards Walke, Mangold and Berlemann (2006) that our algorithm can make use of.

Table 2: Measurement techniques adopted from 802.11

Report Request	**Std.**	**Info.**	**Algorithm**
Active Scanning	802.11a/b,g	BSSID, Channel	Neighbour discovery
Passive Scanning	802.11a/b.g	BSSID, Channel	Neighbour discovery
Basic report	802.11h	Path loss	Link Initialisation algorithm
"Quiet" request	802.11h	-	Interference cost measurement
Noise Histogram report request	802.11k	Noise level for the particular channel	Channel selection
Beacon report request	802.11k	BSSID, Channel.	Neighbour discovery (speeds up)
Frame report request	802.11k	Summary of the traffic between two stations	Link Initialisation
Hidden Station report request	802.11k	List of possible hidden station as well as indication of traffic generated by them.	Interference cost measurements
Medium Sensing Time Histogram report request	802.11k	Represent busy and idle time as probability densities.	Channel selection
STA Statistics Request	802.11k	General status/health of the station	Link Initialisation, Interference cost measurement
Location Configuration Information report request	802.11k	Physical location of the station	Link Initialisation

From the channel measurement aspect scanning is important and thus we elaborate on it. Scanning can be of two types- (a) Passive and (b) Active scanning. The main differences between these are: (i) in the passive mode a station does not generate request messages i.e. probe frames. Whereas active mode provides accelerated information through these messages. (ii) probe response frames need to be acknowledged by the actively scanning station to ensure the integrity of the data delivery (iii) passive scanning has lower power consumption and is thus useful for battery operated devices (iv) passive scanning does not produce additional traffic and therefore scales well.

However, passive scanning can be too slow for some requirements. Decreasing the beacon interval has the effect of lowering the scanning delay but increasing the bandwidth used by a beacon.

5. Performance Evaluation

5.1 Simulation model and attributes

In this section, we first present the details of the Java simulation framework developed by our team to test the performance and behaviour of the algorithms. 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 transmit 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 interfaces, which is not symmetrical.

- Interference factor between partially overlapping channels as provided in Mishra, Rozner, Banerjee, and Arbaugh (2005).

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:

- Simple grid - the routers were positioned from each other in a uniform grid with their in between distances randomly varying by 5%. An example of simple grid is the cellular network.
- Random grid – the same as previous grid but with 50% of random variation.
- Completely random grid – in this topology the arrangement of the routers was generated completely randomly. An example of completely random topology is the ad hoc network.

5.2 Sequential Initialisation Process

The initialisation process that we had used in 4.1, for our self-organisation algorithm to obtain its performance evaluation involved the construction of a spanning tree. The spanning tree was constructed from a root interface (mesh portal) that spans a designated area of the mesh network. The spanning tree's nodes are called *seed nodes.* The seed node in turn then builds a cluster of connected nodes around itself. Each seed node was sequentially selected along the spanning tree to cover most of the area in the wireless mesh region.

5.2.1 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.

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. In these studies the mean of interference cost (IC) reduction across all topologies and network (node) densities obtained is 36.7.

A) Impact of network (node) density on the performance

It can be seen from Fig. 3. 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.

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 (IC) reduction. Furthermore, the impact of node density on the algorithm is relatively consistent for all topologies at the same router densities. From Fig. 3 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.

B) Impact of typical topologies on the interference cost

Figure 4 shows the variation in the interference cost reduction as a function of network topology across different node densities.

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. 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.

C) 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 3: 98% bounds of absolute interference cost
(**Table 3a:** 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 3b:** 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 3a & 3b, 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 its invocation.

D) Performance Comparison across the Network

In this study, we obtained interference cost (IC) in different regions of the MR-WMN for the same set of links before and after the self-organisation algorithm is invoked. Comparison of the results obtained is shown in Fig. 5 where the Interference cost is on the X-axis.

From Fig. 5 we can see that there were no nodes (square symbol points) that caused more interference after the self-organisation than it had caused before (diamond symbol points) the self-organisation was invoked.

5.3 Improved Initialisation Process- Random Initialisation

The use of sequential algorithm in creating a spanning tree will result in a higher number of links between adjacent nodes. As a result of this a higher level of channel interference may exist amongst the node clusters due to the low spatial diversity of the links between the neighbouring nodes. Furthermore, an important factor that is not catered for by the sequential algorithm is the provision of a higher number of links between the mesh portal nodes and the neighbouring nodes. This is especially important because the mesh portal nodes carry the overall aggregate traffic of the WMN to the wired Internet as well as these nodes are limited in number.

Our conclusion from prior experiments with sequential initialisation algorithm (section 5.2) is that an initialisation algorithm that uses a mechanism for a distributed connectivity within mesh topology should be studied. The objective is to create a simple but improved distributed initialisation algorithm. This is done by introducing control mechanisms for spatial diversification between the links and more connectivity between the mesh portal nodes and the rest of the WMN. Each of the nodes in the WMN performs the random initialisation process simultaneously and autonomously. In this regard, our revised initialisation algorithm operates along the following steps:

- We designate the node, which wants to establish connectivity with the neighbouring nodes as the link creator (LC) node.
- Instead of sequentially connecting to the neighbouring nodes each LC node in the WMN creates a pool of neighbouring nodes interfaces. It then selects randomly one of the neighbouring node's interfaces.
- The selected interface of the neighbouring node is then connected to the LC node. As this process occurs autonomously and simultaneously it is quite possible that a selected interface will block the creation of a link as explained in the blocking process later on in this section.
- The initialisation process is then continued iteratively until all the nodes in the WMN are connected.

A) Blocking Process in Random Initialisation

We consider the *blocking* process to be of two types- Neighbouring nodes blocking and node self-blocking. The operation of neighbouring nodes blocking facilitates simultaneous creation of links in spatially diversified parts of the WMN. The possibility of spatial diversification is further increased by a LC node blocking a set of neighbouring nodes until the link is established.

Whereas, node self-blocking results in a relatively higher probability for a node connectivity closer to the mesh portal node than further away from it (or in any other part of the network if desired). This probabilistic control over node connectivity is introduced by means of a node self-blocking parameter. For example, a lower self-blocking parameter provides a higher probability for a node to establish connectivity with its neighbours. The main advantages of combining probabilistic node connectivity with the above improved algorithm are:

- Due to the overall link spatial diversification the degree of interference between links will be decreased.
- A higher degree of connectivity will be established closer to the wired Internet, which will facilitate to carry the high volume of aggregate traffic.
- The number of links created will be lesser than with the sequential algorithm.

5.3.1 Results and Discussion

Table 4 distinctly shows an improvement in absolute interference cost (IC) reduction across the wireless mesh region for different node densities- This improvement is obtained by using the proposed random initialisation algorithm in comparison to the sequential algorithm, which translates to an improvement in the overall capacity.

Table 4: Absolute IC difference before self-organisation between sequential (SEQ) and random (RND) initialisation.

Initialisation	Density 35	70	100
SEQ	4713.753	21668.55	44102.47
RND	4035.834	19476.50	39593.98
DIFF %	14.38172	10.11626	10.22276

A) Performance bounds

We have calculated the 98% confidence bounds per link for absolute interference values across all topologies and different network densities for our random initialisation algorithm before and after self-organisation is invoked. This is shown in Fig 6.

In Fig. 6 the solid lines and the dashed lines indicate the results obtained before the invocation of self-organisation and after self-organisation, respectively. It can be seen that after self-organisation the interference cost (IC) per link decreases. Also, it can be seen that the 98% confidence interval per link interference cost is small and tight. The increase in capacity that results due to a decrease in the interference cost by using random initialisation before self-organisation is shown in Fig 7.

B) 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. Results in Fig. 8 were obtained when random initialisation algorithm was used.

Comparison of the results obtained is shown in Fig. 8 where the Interference cost is on the X-axis. From Fig. 8 we can see that there were no nodes that caused more interference after the self-organisation (square symbol points) than it had caused before the self-organisation (diamond symbol points) was invoked.

6. Non-TPC based Topological Control

In sections 5.2 and 5.3, we had introduced the concept of topological control – sequential and random initialisation based schemes. As part of our further study we have identified the need to improve on the concept of topological control. This could be possible by means of suitable algorithms to increase the number of shortest paths between the client nodes and the portal nodes. Client nodes herein refer to the multi-radio routers with an *exclusive* wireless connectivity. By means of stochastic simulations we conclusively show in this section that the distribution of shortest paths from the client to the portal nodes is very uneven, which motivates the need for the above stated algorithms. Such a topological control coupled with an algorithm that evenly distributes the client nodes amongst the available portal nodes would result in a noticeable increase of the overall WMN capacity. We base this anticipated outcome on the simplistic preliminary premise that the client nodes generate the traffic load evenly.

A much more advanced study will be undertaken that considers more realistic traffic generation by the client nodes to determine the level of increase in capacity. It will be logical to carry out this advanced study only after suitable algorithms for the preliminary simplistic premise have been created. The preliminary algorithms will then be iteratively refined for the advanced study.

We have used a Java based framework to carry out the simulations for the results shown and discussed in this section. The key attributes of the simulation were:

Number of interfaces per router was randomly selected from 3 to 5.

Default signal strength was 100 mW (20 dBm) – Signal strength for each interface was randomly generated with +/- 25% variation.

Network size had an area of 750 m X 500 m.

The simulations were carried for realistic node densities and topologies as specified in table 4:

Table 4: Node densities considered for different topologies

Node Densities	**Topologies**
35	Grid +-5% variation, Grid +-50% variation, Random topology
70	Grid +-50% variation Grid +-5% variation Random topology
100	Grid +-50% variation Grid +-5% variation Random topology

In all, we have carried out a total of 900 simulations that includes 100 simulations per each of the node density and topology combination. The large number of simulation runs has helped us to generate 98% confidence intervals for the obtained results.

6.1 Distribution of client nodes per portal node(s)

We have conducted a simulation study to determine the variation in the number of client nodes distributed per portal node for node densities of 35, 70 and 100. From the graph of Fig. 9, we can see the percentage variation in the number of client nodes that are associated with the portal nodes. It can be concluded from the Fig. 9 that there is a need for a suitable algorithm to evenly distribute the client nodes per portal node as was explained earlier in section 6.

In Fig 10 we have shown the percentage variation in the distribution of client nodes for 3 different topologies for 100 node density with a confidence interval of 98%. It can be seen from the Fig. 10 that for the different network topologies the variation in the distribution of the client nodes is more or less same per portal node.

We can see from Fig. 10 and table 5 that there is a *maximum difference* in the mean client distribution across different topologies of approx. 14%. However, as the density of the network increases this difference reduces- so for 100 nodes density is less than half of the 35 node density i.e. approx. 6%. These results indicate that the node density influences the client node distribution significantly more than the topology of the network. The results tabulated in Table 5 are shown in Fig. 11.

Table 5: Percentage difference in mean client distribution across different topologies for different node densities.

Densities	%age mean difference
100	6.536575
70	11.53844
35	13.87283

6.2 Path length problem

This part of study investigates the path length as a function of different topologies and densities. In this regard table 6 gives a cumulative distribution of the number of hops for mean number of links across all network topologies and densities.

Table 6: Number of links for different hop counts (path lengths).

Hops	**Mean number of links**	**StDev**	**Minimum**	**Median**	**Max**
1	12.138	3.294	4.000	12.000	19.000
2	22.192	9.477	4.000	23.000	46.000
3	18.908	10.212	1.000	19.000	42.000
4	8.043	5.219	0.000	7.000	24.000
5	2.3811	2.7968	0.000	1.000	18.000
6	0.5378	1.1465	0.000	0.000	10.000
7	0.1078	0.4431	0.000	0.000	5.000
8	0.02222	0.16187	0.000	0.000	2.000

The variation in the hop count (path length) for a node density of 100 across all the topologies is shown in Fig 12. It can be seen that the hop count is more or less the same across all the three topologies.

The frequency distribution of the hop count (path length) across all the 3 topologies and 100 node density with a 98% confidence interval is shown in Fig 13. The previous result of invariance with topologies is reconfirmed.

In addition we have obtained the frequency of links normalised with respect to the node densities for different hop counts across different topologies. This is shown in Fig. 14. From the results presented in this subsection, we intend to create and evaluate the algorithms for path length reduction that will preserve the interference cost and result in an increase of network system capacity.

7. Conclusions

We have proposed an intelligent multiagent system based self-organising algorithm for multi-radio wireless mesh networks (MR-WMN) that can operate on any radio technology. The algorithm ensures scalability by progressively assigning the channels to nodes in clusters during the WMN 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. We have studied the impact of two sets of initialisation processes proposed on the performance evaluation of our algorithm. This study was conducted for different node densities, topologies and across different parts of the multi-radio mesh network. The impact was shown in terms of channel interference because the initialisation process results in a *topology control* of MR-WMN by way of spatial distribution of connectivity between the mesh nodes. It was also discussed that there is a need for creating topological algorithms to increase the number of shortest paths to the portal nodes and for their even distribution. This would help to improve the system capacity.

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FIGURES

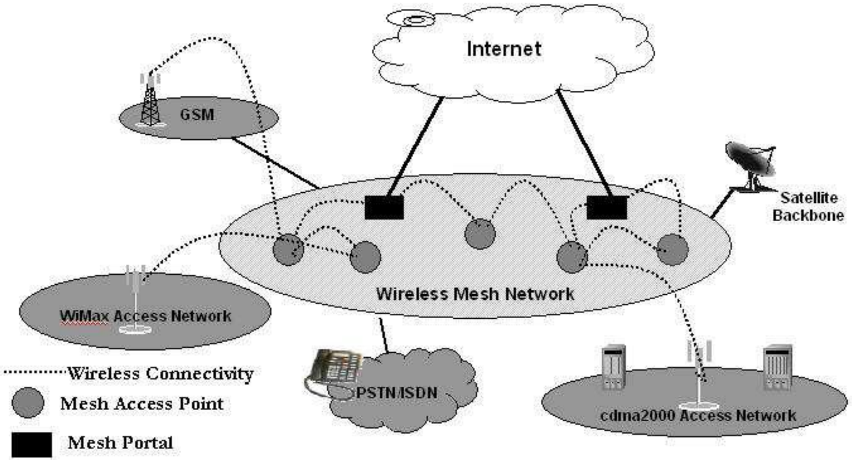

Figure 1: Wireless mesh network infrastructure.

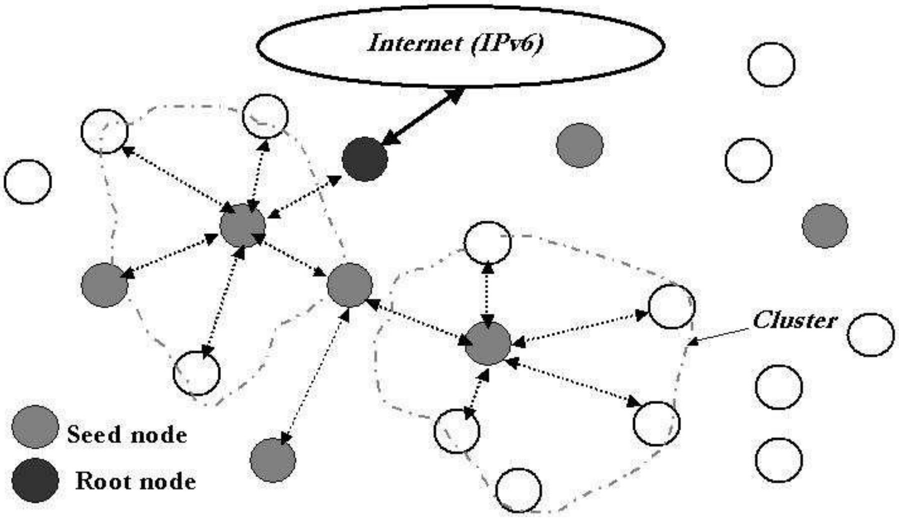

Figure 2: Cluster formation.

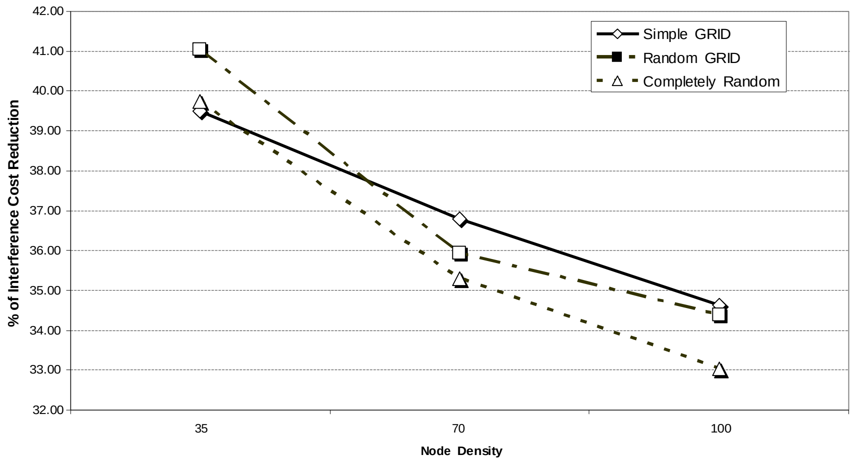

Figure 3: Interference cost reduction as a function of node density.

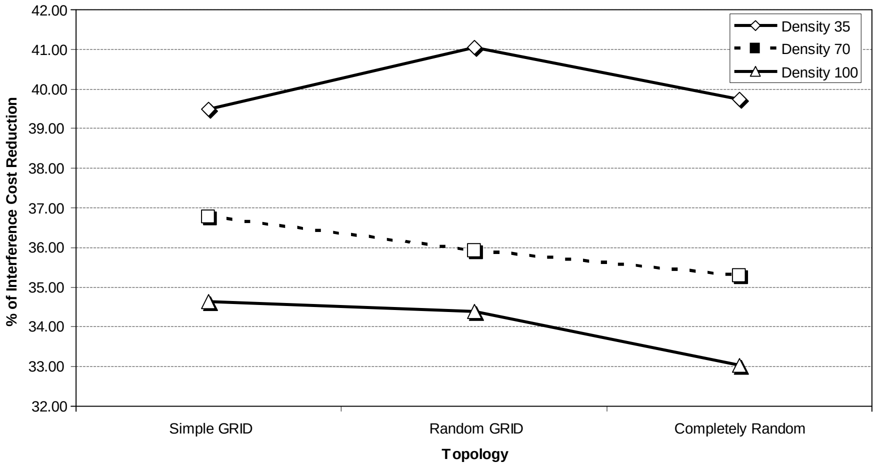

Figure 4: Interference cost reduction as a function of topologies.

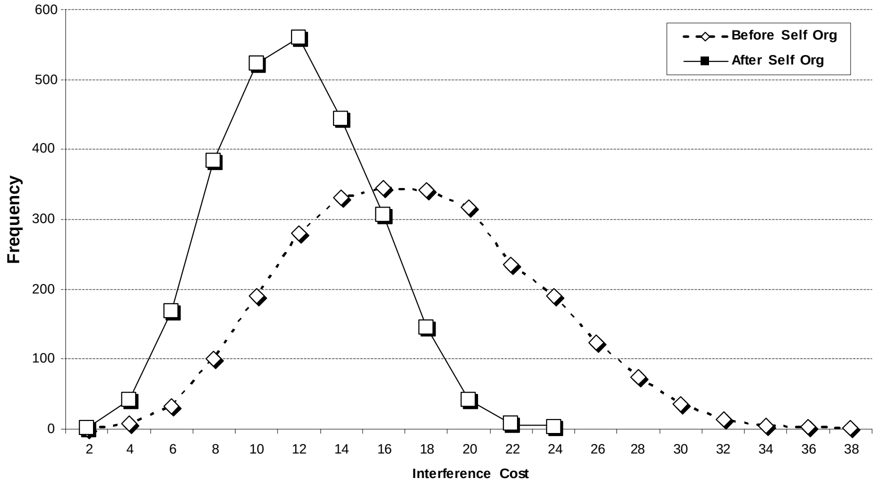

Figure 5: Comparison of IC across the network before (diamond symbol points) and after (square symbol points) self- organisation.

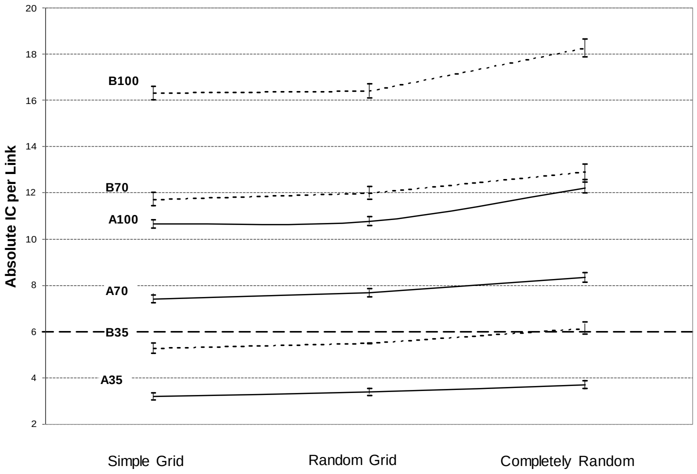

Figure 6: 98% bounds of absolute interference cost per link (A-after self-organisation, B-before self organisation)

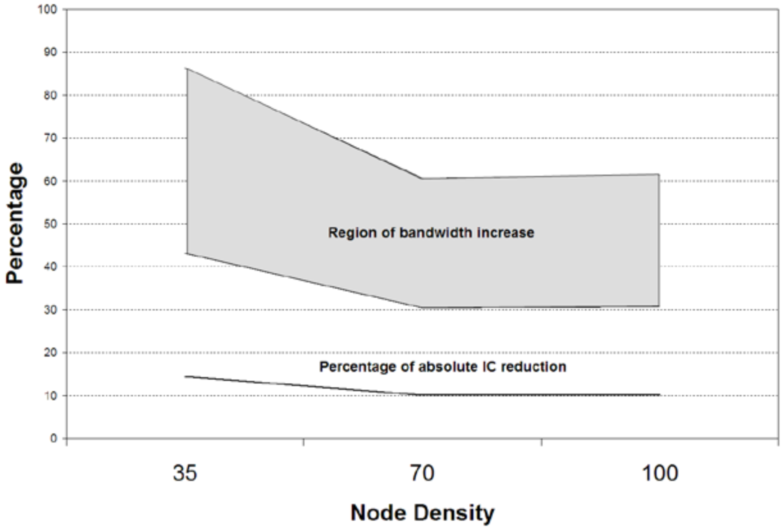

Figure 7: The shaded region indicates capacity increase by using random initialisation before the channel self-organisation is invoked- refer table 4. (Note: The line plot representing percentage of IC reduction and bandwidth increase region are illustrated together to show the significant capacity improvement that results by using random initialisation algorithm.)

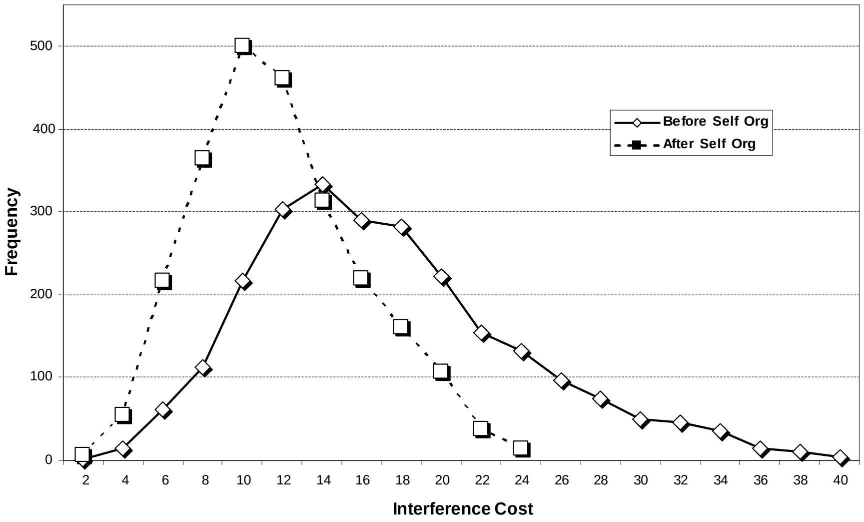

Figure 8: IC across the network before (diamond symbol points) and after (square symbol points) self-organisation–random initialisation algorithm.

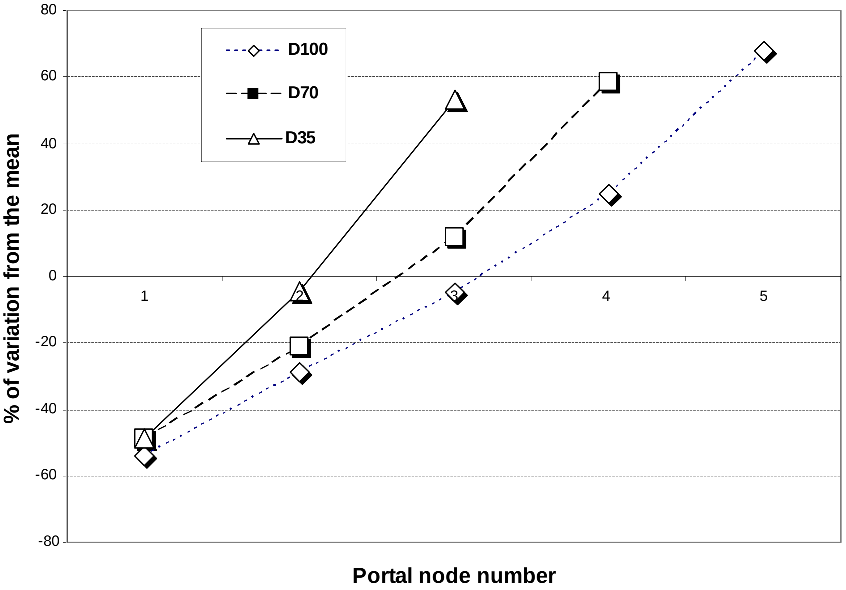

Figure 9: Variation in the distribution of client nodes

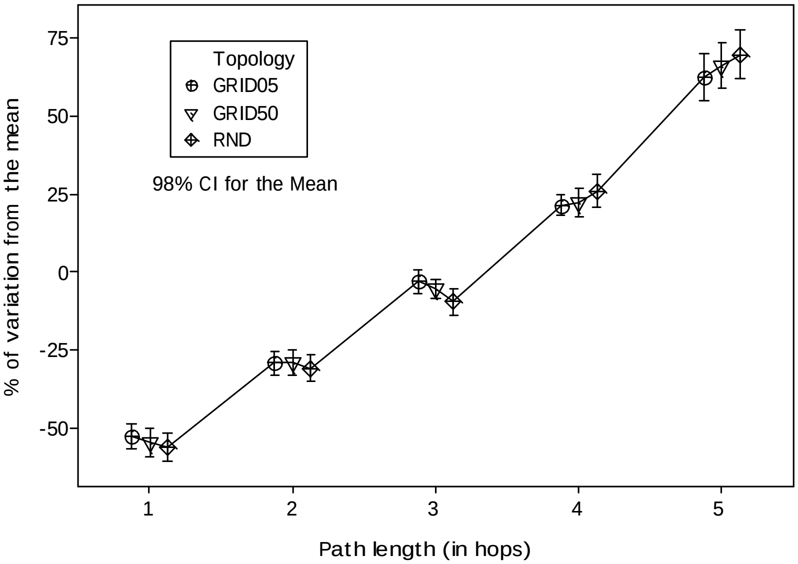

Figure 10: Percentage variation in the distribution of client nodes for 3 different topologies for 100 node density. **Note:** For the sake of clarity all the points for different topologies are not shown collocated per hop count. CI is the confidence interval.

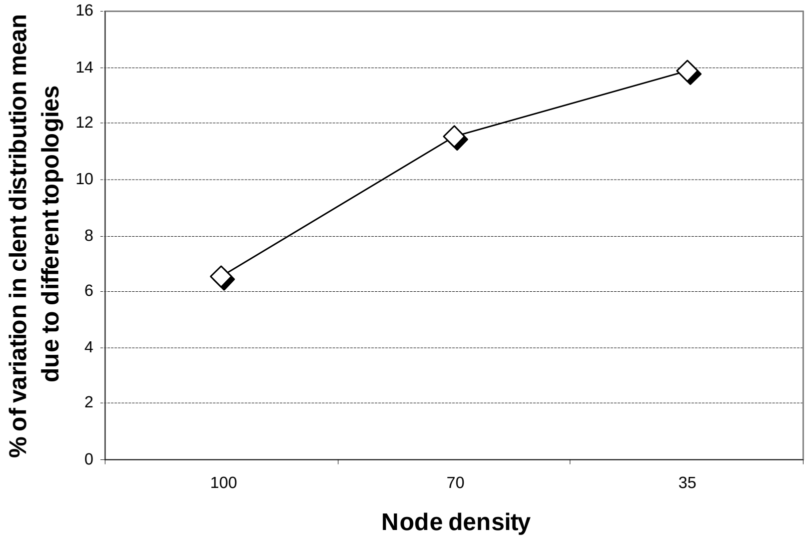

Figure 11: Variation in client distribution across topologies for different network densities.

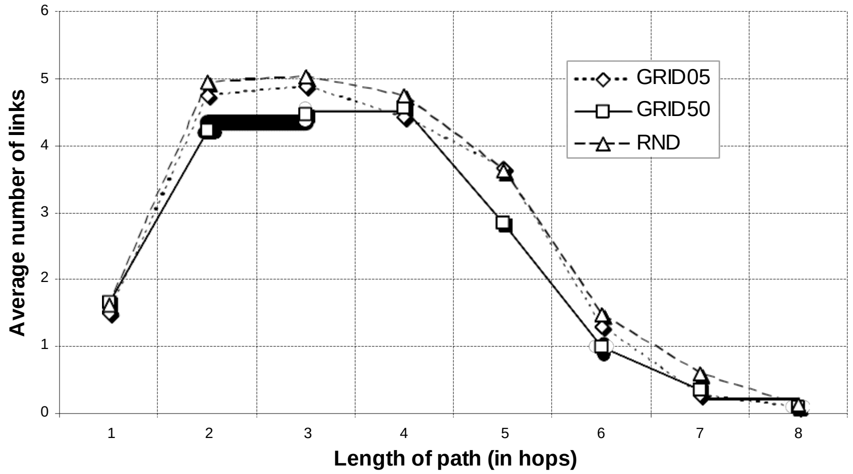

Figure 12: Mean number of links vs. hop count for different topologies (for 100 node density)

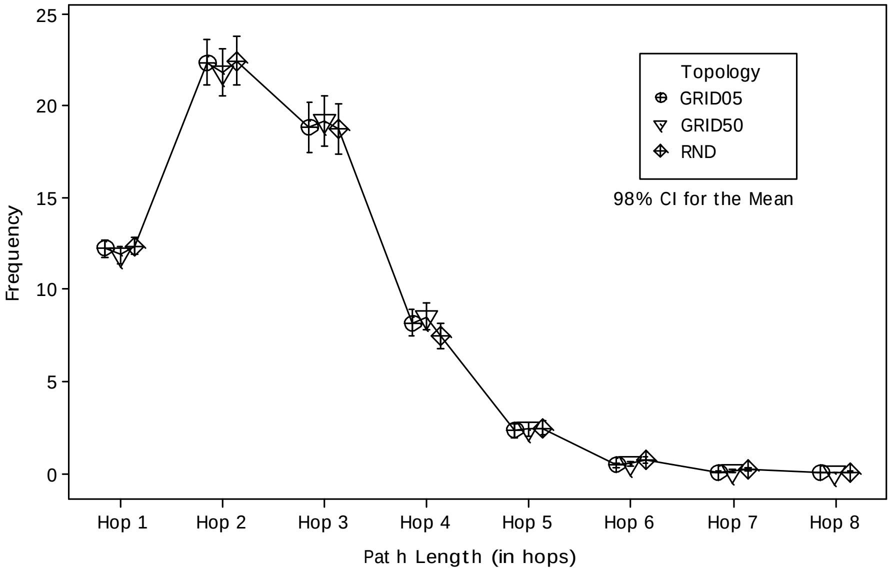

Figure 13: Frequency distribution of the path length (in hops) for different topologies at 100 node network density– different topologies types are shown by distinct symbols. **Note:** For the sake of clarity all the points for different topologies are not shown collocated per hop count.

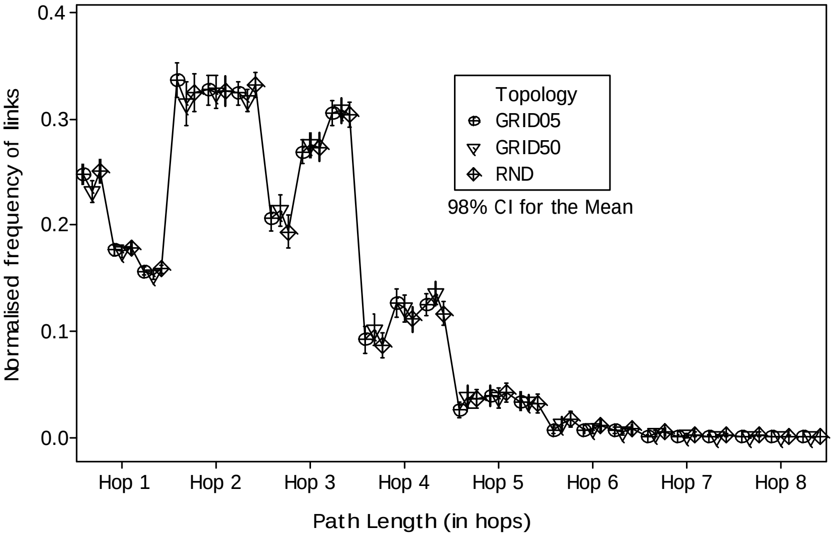

Figure 14: Frequency of links normalised with respect to network densities (35,70,100) as a function of path length (in hops) for different topologies. **Note:** For the sake of clarity all the points for different topologies are not shown collocated per hop count.