Impact of Topology Control on the Performance of a Self-Organization Scheme for Wireless Mesh Networks

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ABSTRACT

Multi-radio wireless mesh networks (MR-WMN) with a smart channel assignment scheme can be used as a viable cost-effective alternative for a last mile broadband access. The channel assignment algorithm should be such that it reduces the overall interference and increases the aggregate capacity of the network. In this paper, we have concisely presented the key results of our *work in progress*, which pertain to the evaluation of self-organization algorithm for multi-radio mesh networks. Specifically, the study focuses on the impact of *initialization process* on the self-organization algorithm performance as it involves mesh node selection for channel assignment. The initialization process results in a topology control of MR-WMN by way of spatial distribution of connectivity between the mesh nodes. The process for initiating the topology of self-organized mesh networks is also described. In order to conclusively show the merits of our initialization process, we have carried out this study for realistic densities of the mesh nodes and their topologies varying from completely random to being ordered in a grid.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design – *Wireless Communications*

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design – *Distributed networks*

General Terms

Algorithms, Performance, Design.

Keywords

Self-organization, Mesh networks, Multi-radio routers, Performance evaluation.

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1. INTRODUCTION

Multi-Radio Wireless Mesh Networks (MR-WMN) have spurred a lot of research interest in academia as well as in the industry. This is primarily because of the several beneficial attributes offered by MR-WMN such as cost effectiveness, redundancy of paths and scale of deployment. Each hop in a multi-radio WMN has a throughput that is dependent mainly on the radio type, distance between the transmitter and receiver, the data rate and interference. However, if the channels are not assigned smartly there is a strong likelihood of co-channel and adjacent channel interference across the mesh networks.

Our self-organization mechanism assigns the channels intelligently in the mesh so that the interference between the channels of mesh routers in its *interference range* is decreased. Furthermore, our algorithm provides an 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-organization 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.

Our work involves also the study of the impact on the self-organization algorithm performance by the way in which the mesh nodes are selected at initialization (start-up) for channel assignment. The initialization process results in a *topology control* of MR-WMN by way of spatial distribution of connectivity between the mesh nodes.

In this paper, our contributions are twofold. We: (i) propose an initialization process for our self-organization algorithm and (ii) present and discuss key Java based stochastic simulation results that reflect the impact of the initialization process on our self-organization algorithm. These results we have obtained for different MR-WMN node densities and typical topologies.

This paper is organized as follows: In Section 2, we summarize the significance of our work by categorically comparing the attributes of our proposed self-organization method with the corresponding attributes of the other methods. Section 3 outlines our self-organization algorithm along with the measurement techniques and operational parameters that could be adopted from 802.11a/b/g/k. Section 4 explains the process for initialization of channel self-organization in the MR-WMN along with the simulation results that show the impact of initialization process on the self-organization algorithm performance. Conclusions are stated in section 5.

2. REVIEW OF RELATED WORK AND COMPARISON TO OUR PROPOSAL

We have carried out an extensive literature review in the area of WMN that uses distributed algorithms for self-organization and with a focus on the attributes of scalability and stability. These algorithms do not require changes at the 802.11 MAC layer. Due to space limitation we can not provide the entire review herein so instead Table I summarizes the key attributes of the solidly proposed algorithms [1-3] that we have identified. Furthermore, in Table I we have compared the key aspects of significant algorithms with our self-organization algorithm so as to draw out our contributions.

In [1] the authors extend their proposal with the usage of a virtual control network instead of a dedicated interface-channel on each router. The virtual control in [1] means that a certain fraction of bandwidth is used on each channel for channel assignment purposes rather than reserving one exclusive channel. Reference [2] proposes the 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.

Reference [2] uses integer linear programming to obtain bound of optimal solution and evaluate the proposed algorithm. The main drawback of the proposal in [2] is the scalability since a centralized algorithm is used.

In [3] the authors have created a self-stabilizing distributed protocol for channel assignment. The main limitation of their proposal, as well as those in [1] 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 et al. [3] assumes that the interference is symmetric and is based up to a range of three hops. The method results in improvements 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.

Table I: Comparative study between our and other key proposals.

Literature / Attributes	***Raniwala et al.[1]***	***Ko et al.[3]***	***Subramanian et. al [2]***	***Our work***
Type of algorithm	Distributed/ Centralized	Distributed	Centralized & 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
Capacity analysis	Not specified	Not specified	Not specified	Will be specified

3. PROPOSED SELF-ORGANIZING ALGORITHM OVERVIEW

The proposed algorithm is outlined below in different steps that correspond to the different states of the system [4].

3.1 Initializing the system

This procedure initializes 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. The exact process for cluster formation is explained in [4].

(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 3.2.

3.2 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.

3.3 Self- Organization: Proactive Logic

3.3.1 Method for adjusting the channels - 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 which is explained in [4] is a development of the ideas in [3]. 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.

3.4 Self- Organization: Reactive logic

Reactive reasoning is concerned with 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. Due to space constraints this is not discussed here.

3.5 Triggering criterion for Proactive logic

The radio-aware routing metric has been proposed in the IEEE 802.11s amendment and is called as the airtime link metric. If the airtime link metric calculated by a node on the basis of the actual received parameters is greater than the expected airtime link metric by some pre-assigned margin then the node (interface) will decide to trigger the proactive logic as explained above. 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.

3.6 Self-Organization Algorithm: Adoption of measurement techniques and parameters from 802.11a/b/g/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/k. Below we tabulate the specific parameters and techniques from each of the stated 802.11 standards [5] 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
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)
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 Initialization, Interference cost measurement
Location Configuration Information report request	802.11k	Physical location of the station	Link Initialization

4. Revised Initialization Algorithm

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 neighboring 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 neighboring 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 initialization algorithm is that an initialization 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 initialization 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 initialization process simultaneously and autonomously.

The difference between our approach and those provided in existing literature is that we do not focus on graph theoretical optimization, heuristics based on graph theory or even TPC. Instead we target scalability and robustness as the primary desired features by way of a best attempt method based on light weight agents.

Our revised initialization algorithm operates along the following steps:

- We designate the node, which wants to establish connectivity with the neighboring nodes as the link creator (LC) node.
- Instead of sequentially connecting to the neighboring nodes each LC node in the WMN creates a pool of neighboring nodes interfaces. It then selects randomly one of the neighboring node's interfaces.
- The selected interface of the neighboring 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 initialization process is then continued iteratively until all the nodes in the WMN are connected.

A) Blocking Process in Random Initialization

We consider the *blocking* process to be of two types- neighboring nodes blocking and node self-blocking. The operation of neighboring 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 neighboring 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 neighbors. 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.

4.1 Results and discussion

We state first the key attributes of the simulation model:

- 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:
    1. Simple grid - routers were positioned from each other in a uniform grid with their in-between distances randomly varying by 5%.
    2. Random grid – same as simple grid but with a 50% random variation in the in-between distances.
    3. Completely random grid – in this topology the arrangement of the routers was generated completely randomly.

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.

4.1.1 Performance Evaluation

Table 3 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 initialization algorithm in comparison to the sequential algorithm which translates to an improvement in the overall capacity.

Table 3: Absolute IC difference before self-org between sequential (SEQ) and random (RND) initialization.

Initialization	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

4.1.2 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 initialization algorithm before and after self-organization is invoked. This is shown in Fig 1 where the solid lines are for before self-organization and the dashed lines are after self-organization is invoked. It can be seen that after self-organization 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.

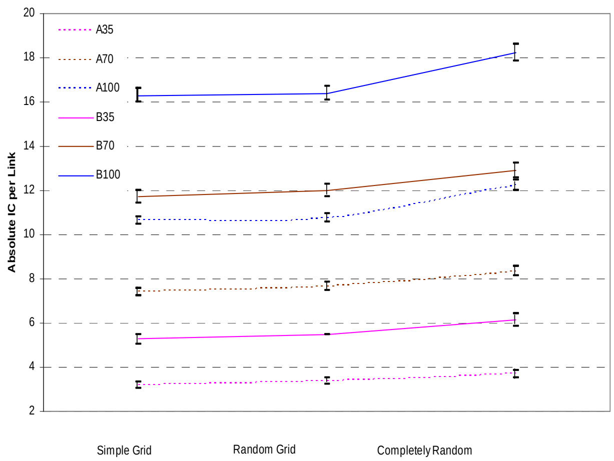

Figure 1: 98% bounds of absolute interference cost per link (A-after self-organization, B-before self organization)

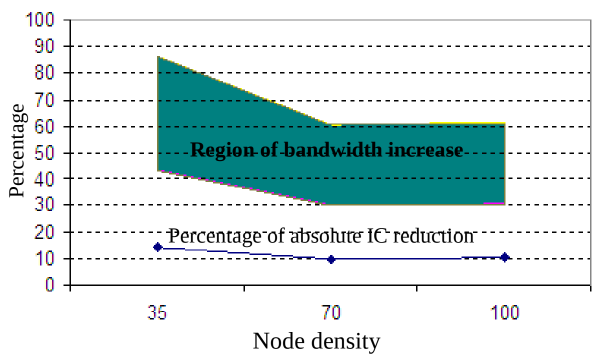

Figure 2: Green region shows capacity increase by using random initialization before the channel self-organization is invoked – (refer 4.1.1). Note: The percentage of IC reduction i.e. blue line and bandwidth are illustrated together to show the significant improvement that results by using random initialization algorithm.

4.1.3 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-organization algorithm is invoked. Results in Fig. 3 were obtained when random initialization algorithm was used. 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 that caused more interference after the self-organization than it had caused before the self-organization was invoked.

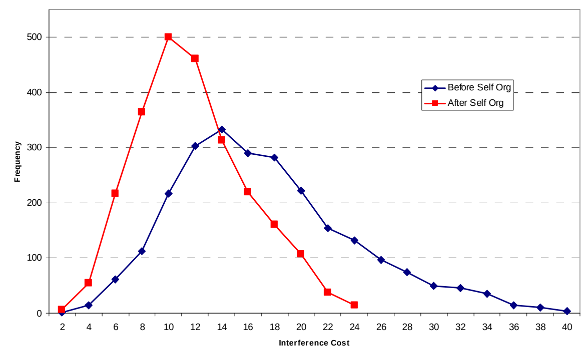

Figure 3: IC across the network before (blue) and after (red) self-organization–random initialization algorithm.

5. CONCLUSIONS

An overview of our self-organizing algorithm for wireless mesh networks (WMN) was provided. The algorithm provides scalability by progressively assigning the channels to nodes in clusters during the WMN system start up phase. Stability is obtained by means of the proactive and reactive logic of the algorithm. An improved initialization approach for the self-organizing algorithm in multi-radio wireless mesh networks (MR-WMN) was discussed and its effectiveness in further reducing channel interference was shown. The initialization process results in a *topology control* of MR-WMN by way of spatial distribution of connectivity between the mesh nodes. The performance results obtained have conclusively shown the positive impact of the initialization approach for different node densities, topologies and across different parts of the MR-WMN.

6. ACKNOWLEDGMENTS

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