# Supply and Demand, a Dynamic Topology Control Method for Mesh Networks

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*Abstract*— **This work describes a distributed and flexible mechanism to perform network admission control and topology management for wireless mesh networks. The proposed method uses the concept of supply and demand to dynamically organize the wireless network. Mesh networks deployment and topology control is an interesting problem since the needs of two sites, even though using the same kind of equipment and protocol stack, may vary significantly. A network structure that suits perfectly to one site may be unacceptable to other. Typical examples of this are Safety Networks (PSNs). The number of nodes, movement pattern, traffic requirements and interconnections vary significantly from one site to another, even though the equipments, protocols and attending people are basically the same. Having one set of algorithms and protocols for each situation is not an option, giving its cost and deployment complexity. The technique, described here, successfully manages to maintain the desired topology and handle the different requirements, relying only upon a cost function to dynamically control the topology.**

***Keywords-** cluster heads; mesh networks; connection cost; topology control*

## I. INTRODUCTION

The deployment and management of topologies for wireless mesh networks (WiMesh) is a basic problem. Well defined and maintained network structure is an indispensable step to enable the creation of efficient higher layer algorithms [1]. For this reason topology control becomes a fundamental functionality to enhance scalability and capacity for large-scale wireless ad hoc networks [2]. It becomes even more interesting for networks such as Public Safety Networks (PSNs), since the requirements and modus operandi of these networks vary significantly for different disaster scenarios [3]. For example, the number of nodes, people served, mobility pattern, and target environment differ radically from forest fire site to an earthquake relief effort one. Other point to observe is that, in contrast to regular public access networks, the main concerns for deploying PSNs are rapid deployment and survivability [4]. This work presents a novel technique to perform adaptive topology control for wireless mesh networks.

For the general case, flat mesh networks are usually easier to deploy than hierarchical ones. However, flat networks are hardly scalable and appropriate to be used for large scale networks. Structured hierarchical networks, on the other hand, scale better, but the price to pay for this is the creation and the maintenance of the structure. This work focuses on hierarchical network topologies.

Even though the proposed method is general and adaptable to any wireless mesh network, we believe that we can benefit if we apply our method to highly dynamic and unpredictable networks, as is the case with public safety networks. As an example of network topology used for PSNs we can cite the CHORIST project [9] architecture. This project, funded by the European Commission, addresses Environmental Risk Management in relation to natural hazards and industrial accidents [9]. All components roles must be dynamically defined based only on local information. Nodes are also free to arrive and leave the network during all its life time. The same architecture is adopted for the mesh component by the project HNPS (Heterogeneous Network for European Public Safety)[13]. This project has the objective of developing a heterogeneous network concept for future European Public Safety communications based on the integration of different networks, including ad hoc deployable systems.

The next section presents some background concepts and references used in the development of this work. Section 3 discusses the problem, this work tries to solve. Section 4 introduces our proposal and its main characteristics. Section 5 shows the experimental results and Section 6 presents the conclusions and the future directions for this work.

## II. RELATED WORKS

To the best of our knowledge, no other work approaches the topology adaptability problem in the same way we do. Normally if the topology requirement changes a complete new algorithm must to be designed and deployed. For PSNs topology control, Midkiff and Bostian [5] present a two layer network deployment method. Their network consists of a hub and, possibly, many purpose specific routers to provide access to the nodes in the field. In some sense our work provides the same kind of topology, since we may face the clusters as a backbone to provide access for the end nodes, e.g. firefighters.

Sarrafi et al. present in [6] an interesting algorithm for topology control; however, they are mainly interested in the power consumption optimality of the network. Our objective here is distinct; we want to maintain a specific topology to enable robust and efficient communication.

In [10], Mainland et al. present the market-based macroprogramming paradigm to control the behavior of the nodes in a sensor network. Even though the main focus of both works is different, both have the same inspiration. We use the free market economic concept to control the network nodes' behavior and reach stable final configurations. The first welfare theorem states that a free market system will eventually reach Pareto optimality [11]. A Pareto optimal allocation is the one where no-one could be made better off without making someone else worse off. In other words, a Pareto allocation is a fair one. It is the best allocation one can expect to reach without hurting any of the participants.

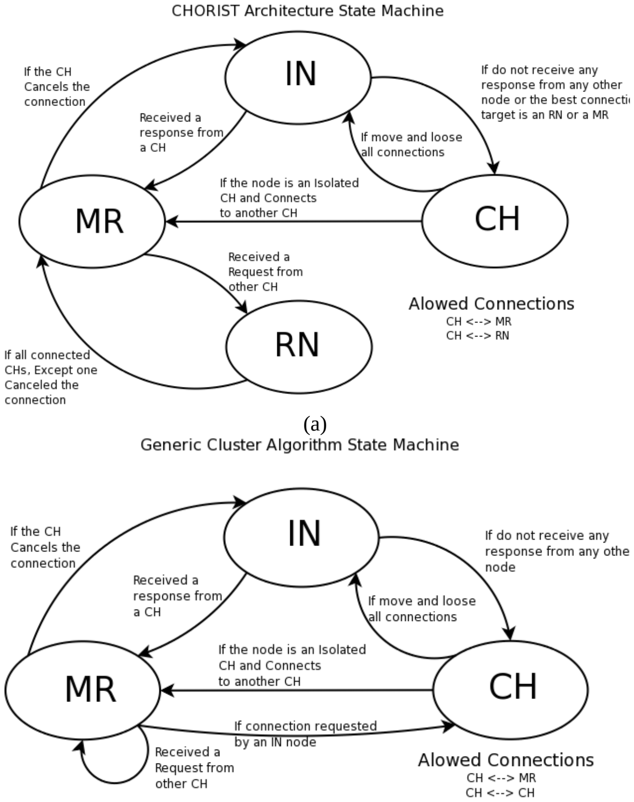
## III. PROBLEM DESCRIPTION

The main issue addressed in this work is the creation and management of stable topologies for wireless mesh networks. The technique described here intends to create and maintain well defined wireless mesh network architectures in a flexible and dynamic way. We want to be able, just adjust a set of parameters, to change the behavior of the whole network without deploying new equipments or protocols. The algorithm must be able to provide an easy way to change the network behavior, i.e. number and size of clusters, while respects the topology constraints. The proposed schema is general and can be adapted to any wireless mesh network architecture. As a proof of concept we applied the technique to the CHORIST architecture and we also defined simpler generic cluster based architecture. The method is adaptive and can organize the nodes connection in fairly different ways, going from the theoretical minimum to the theoretical maximum number of network clusters, in a distributed way.

The CHORIST network has a structure composed by an hierarchy in two levels. In such organization neither two Cluster Heads (CHs) nor two Relay Nodes (RNs) can be directly connected. For example, if a CH needs to exchange control data with another CH, the messages must be forwarded through a RN. On the architecture CHs are the nodes responsible for managing the radio resources for their clusters. RNs are the nodes that are part of two or more clusters and act as a bridge among them. Mesh Routers (MRs) are the nodes attached to CHs and they obey the CHs scheduling in order to communicate with other nodes. Nodes not yet attached to the network are called Isolated Nodes (INs). If required, the IN may become a CH or a MR. Fig. 1 (a) presents the state machine for the CHORIST architecture. Normally the first node to arrive becomes a CH and the other nodes should attach to this one.

If we reduce the CHORIST network to a graph, where the vertices represent the nodes and the edges the connections among them, finding the target network topology could be reduced to solving a two phases Weakly Connected Independent Dominating Set (WCIDS) problem [7].

The generic cluster algorithm is also a two layer one but simpler than the CHORIST architecture. CHs may be connected directly or through MRs, in this case there is no explicit RN role. The minimum number of CHs for this scenario is also a WCIDS, where the CHs are not in the range one each other, the message exchange should occur through a common MR. Fig.1 (b) shows the state machine for the generic cluster algorithm.



(a)

(b)

Fig.1. State machines for the two evaluated protocols

## IV. PROPOSAL

We base our solution on the economy laws of supply and demand to dynamically organize the network. The first law of supply and demand states that when demand is greater than supply, prices rise and when supply is greater than demand, prices fall. The power of such forces depends on how great the difference between supply and demand is. The second law of supply and demand, then, states that the greater the difference between supply and demand, the greater is the force on prices. The third law states that prices tend to an equilibrium point, where the supply is equal to the demand [12]. These three laws perfectly map the main requirements of a topology management algorithm.

The proposed method has three main objectives. The first one is to control the number of clusters and RNs of the network. We can use the first law of supply and demand to do this by controlling the prices of each kind of service offered in the network; we can control the number of elements offering such service. The second objective is to have a fast convergence to a stable state. This requirement is fulfilled observing the Second law, as big the differences among supply and demand the faster should be the convergence. Finally, the third objective is to maintain a stable, or at least as stable as possible, and well balanced network, while respecting the desired architecture. Clusters should not only have roughly the same size but we should have an easy way to control and fine tune the size of the clusters. Cluster heads must be able to optimally handle the communication among nodes inside their clusters and exchange key information with neighboring nodes fast and efficiently. However, the optimal number of nodes per cluster depends upon many factors, and even can vary according the network set up purpose. These issues are covered by the third law, since the final topology is expected to be a Pareto optimal arrangement [11] and hence it should be stable and fair among all the participants.

The basic mechanism of the evaluated protocols is as follows: whenever an IN arrives at the network, it broadcasts a connection request for the nodes nearby. This request is answered by all MR/RN/CH in the region. The neighboring nodes answer with their status, number of connections and link status. This information is used to define a connection cost to each one of the possible sponsor nodes. The information on the answer packets and the cost function determine to which node the IN will attach. The cost policy states that, considering all the given data, the lowest cost sponsor should be chosen.

To increase the network stability a node just gives up being a CH or a RN if it moves and loses all its connections, or if it moves and enters in conflict with other well established, lower cost, CH/RN in the region.

A node should always try to attach to the node that presents the lowest attachment cost. To decrease the number of CH, the chosen basic connection costs should give greater priority to CHs in detriment of the other kind of nodes. Only if there is no CHs around or they are completely overloaded an IN should decide to attach to a MR or a RN and became a new CH. In the same sense, to promote a more homogeneous load balance, the cost function guarantees that IN node will always attach to the less loaded, or the best suited sponsor.

The cost function can be as simple or as complex as one may need it. For this work our cost function considers basically the clusters load. However, other factors could be taken into account as well, e.g. perceived quality of signal, number of blocked nodes and mobility pattern. The used function can be described as:

$$C = \beta_k + \sum_{i=0}^{n} \varepsilon_i \qquad (1)$$

Where $C$ is the connection cost for one specific sponsor candidate, $\beta_k$ is the basic connection cost for each kind of server. Considering a free market, there is no difference between the services provided by two distinct servers. For this reason the basic connection cost for all servers, in the same class $k$, is the same. $n$ represents the number of nodes connected to this specific sponsor and $\varepsilon$ represents the individual cost for each one of the already sponsored nodes. On the case of our experiments we set $\varepsilon$ to be one for each connection the node has, but this value can be gauged according to the topology needs. The last part of the formula provides an adaptive behavior that enables nodes to choose the best servers for their needs, i.e. less loaded, or with more energy. We use a simple $\varepsilon$ in the formula just to validate the technique however this part of the formula could take into account any aspect that is important to the considered network.

The cost function calculation is a flexible way to control the network connections and the topology behavior. Fine-tuning the cost function one can, for example, decrease the number of connections of each CH and increase, or decrease, the size of the clusters. This flexibility is interesting, mainly for PSNs where different disaster sites may have different needs and the network operation can be shaped as desired. Changing and broadcasting a new basic costs vector, one can even change completely the behavior of an already established network without any full software or hardware update.

## V. EVALUATIONS

The evaluations were made using Sinalgo simulator [8] in a 2000x2000 $m^2$ area. We vary the number of nodes and the communication range of the nodes. All experiments were conducted using Linux Fedora Core release 6 in an Intel Xeon 1.86GHz machine with 16GB of RAM. All graphs are presented with a confidence interval of 99% and each point is the result of the mean of 34 runs with different network configurations. The nodes arrive randomly and are placed uniformly over the observed area. The centralized implementation works as an oracle, all nodes positions are known in advance and the algorithm creates offline the complete network graph to find the best possible roles for the nodes in the final network configuration. The results of the oracle are the best possible ones and unachievable with distributed algorithms, where nodes have only local information and new nodes arrive at different moments through out the network life time. However, the offline implementation shows us how far the proposed algorithm is from the theoretical minimal CH optimal solution.

All experiments were conducted varying the communication range for 50, 100, 150, 200, 250, and 300 meters. However, as the final results for these variations did not present any meaningful difference, for this work we will present only the values obtained with the 200 meters communication range experiments. To evaluate the adaptability capacity of the proposed solution we defined different network configurations and nodes' cost. Considering the implemented cost formula (1), if one needs, for example, a network with less CH, it is only a matter of decreasing the basic CH connection cost and increasing the costs for other kind of nodes. In this way nodes will prefer to attach to an existing CH, as it is cheaper than to attach to other nodes to create new CH. For each different target scenario the, values should be adapted accordingly to the final desired network shape. The configurations used in the experiments for both topologies are:

- *Configuration 1*: favors the creation of clusters, as much as possible. It has high cost to connect to a cluster and low cost for connecting to other nodes. The basic connection cost values (*β)* are CH=20, MR=5, RN=1.
- *Configurations 2 to 5*: are variations over the standard configuration, smaller costs for attaching to CHs and larger ones for RNs and MRs. Here we want to evaluate if small variations of costs may affect the algorithm behavior. The *β* values are : *Configuration 2* CH=0, MR=2, RN=1, *Configuration 3* CH=0, MR=5, RN=3, Configuration 4 CH=0, MR=7, RN=5 and *Configuration 5* CH=0, MR=20, RN=5.
- *Configuration 6*: tries to shape the network as close as possible to the minimum WCIDS, the target configuration of the implemented offline approach. For this case *β* values are: CH=0, MR=50, RN=45

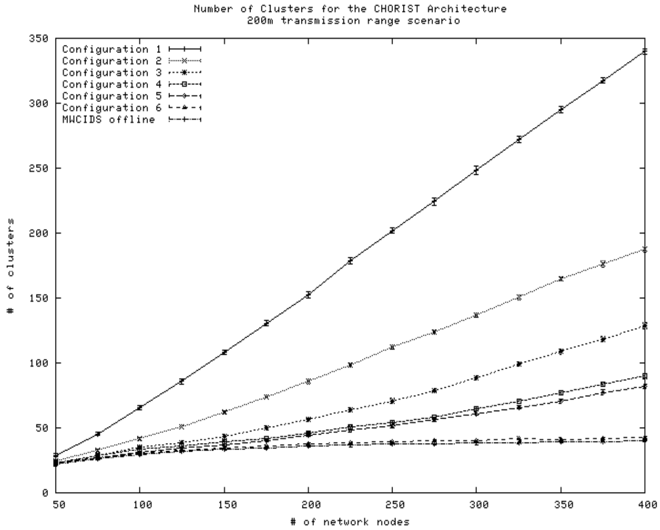


Fig.2. Number of Cluster Head nodes for the CHORIST topology

The configuration 1 and 6 are diametrically opposite in the sense that the first one aims to stimulate the creation of CHs while the second one aims to keep it as minimum as possible.

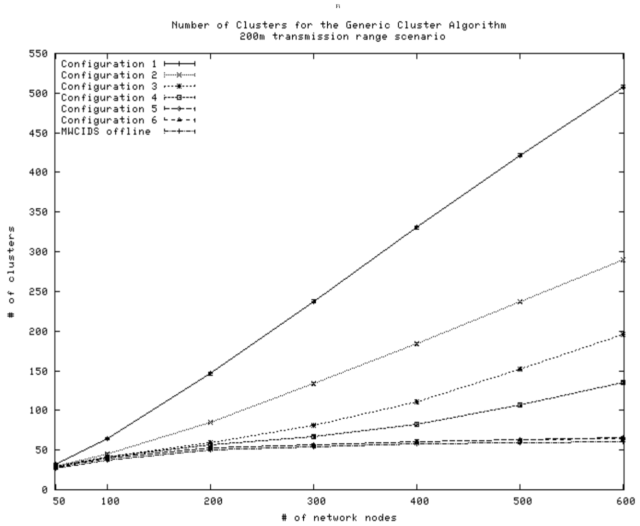


Fig.3. Number of Cluster Head nodes for the generic clustering topology

The graphs of Fig. 2 and Fig.3 show the number of CHs for different network sizes for the two evaluated architectures. As we can observe the number of cluster heads changes in the way they were expected to. The small changes in the cost values also show that using the technique one can even make a fine grain control of the network shape. Regarding the minimum CHs configuration, the values reached by the Configuration 6 are really close to the ones found by the minimum WCIDS one, being normally inside the 99% confidence interval range. However, worth to remember that the offline implementation, not only has the complete view of the network, but also it has to work with the final configuration. This kind of approach could hardly be implemented in the real world managing real topologies. We use these results just to compare our results to a theoretical minimum. Our approach, on the other hand, works only with local information, the CHs are assigned dynamically, the algorithm does not need to know the entire topology in advance, nodes arrive to the network at different moments during the simulation time as it happens in the real world. This means that it is easily implementable in a distributed system.

Other interesting characteristic we can notice from the graph of Fig. 2 and Fig.3 is the slope of the curves, for Configuration 1, where the CH attachment cost is abusive, the slope is more accentuated, when the cost to attach to a CH decreases, the slop of the curve is given by the increase in the cost of the attachment to MRs and RNs. The differences between the two graphs are also expected since the evaluated protocols are different and have different elements. So the proportional connection costs are different.

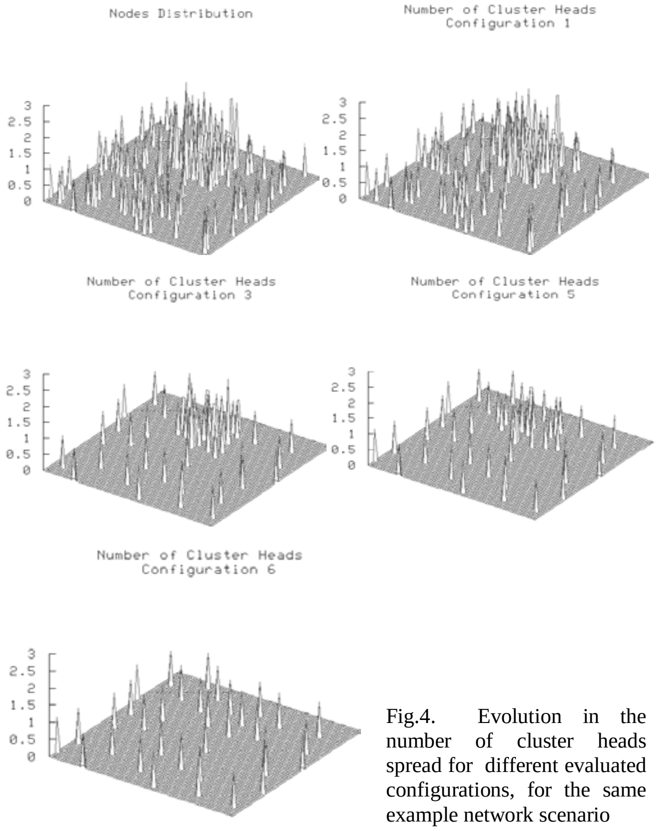


Fig.4. Evolution in the number of cluster heads spread for different evaluated configurations, for the same example network scenario

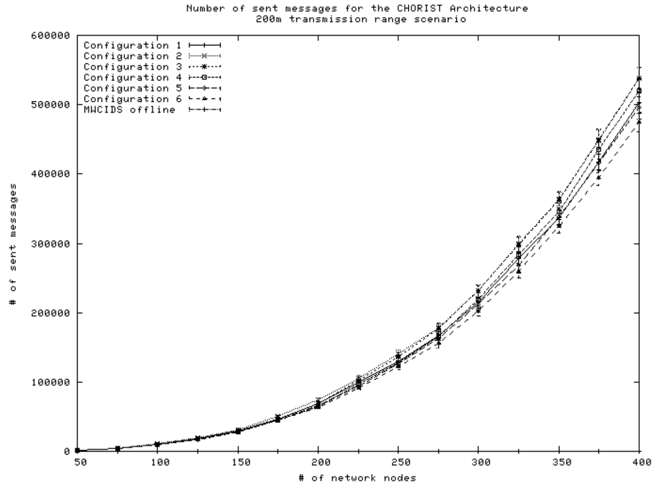


*Fig. 5. Number of sent messages through the network nodes for the CHORIST topology*

The graphs presented in Fig. 4. show the evolution of the CH numbers in a more visual way. We can see that at Configuration 1 the distribution of CHs is similar to the nodes distribution. The CHs concentration decreases, as expected, until reaches the Configuration 6 where the CHs distribution is close to the minimum one. The supply and demand laws take care of load balancing the clusters and control the volume of each kind of node.

The graph of Fig. 5 shows the number of messages sent through the entire network during the simulation time for each one of the defined configurations. As expected the bigger the size of the network the larger the number of messages exchanged among nodes. However, among the configurations the volume of messages does not vary expressively. Even though the network shape varies, the message cost to generate and maintain a network, with the minimum and maximum number of CHs, is basically the same. The messages for the offline approach in this graphic has no meaning, they are represented just to keep this graph with the same representation of the others.

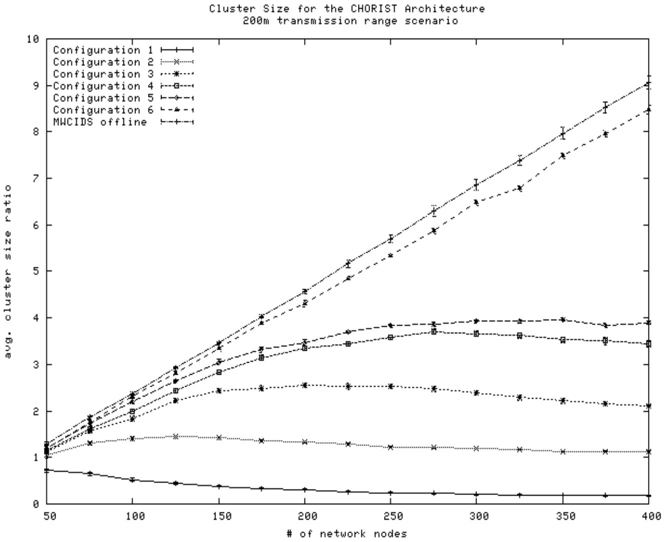


Fig.6. Number of nodes per cluster for the CHORIST topology

The graphs of Fig. 6 and Fig. 7 show the average size ratio of clusters when the network size increases. We define cluster size ratio as: *CSR=(nMR+nRN)/nCH*. Where *CSR* is the cluster size ratio, *nMR*, *nRN* and *nCH* are, respectively, the number of mobile routers, relay nodes and cluster heads of the whole network scenario. The average is the average of all the evaluated scenarios. From these graphs we can perceive that fine tuning the costs we can model the clusters behavior. The offline approach has the biggest cluster size ratio since its main goal was to reach the minimum number of clusters, so the clusters increase in size. The standard deviation for the cluster sizes, for all evaluated configurations, is typically below 0.05, this means the clusters are indeed well balanced, as we first intended. More over, we can control the clusters size changing the cost function. We can perceive from the graphs that the different configurations reach a stable point in the ratio of MR + RN and CHs.

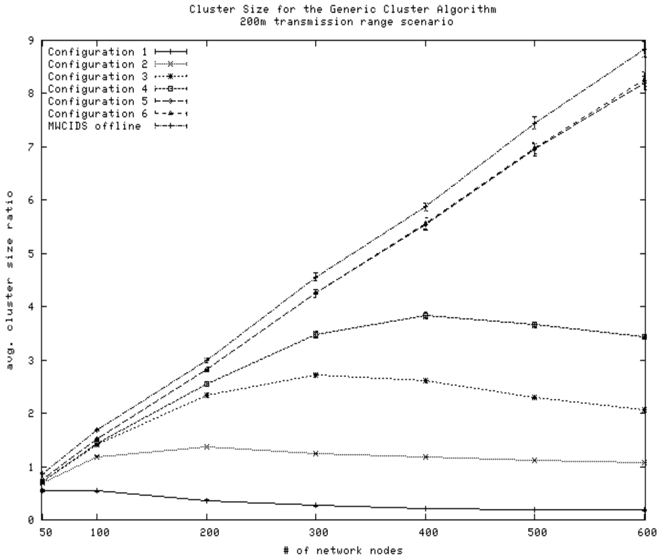


Fig. 7. Number of nodes per cluster for the generic clustering topology

For all CHORIST evaluated cases, our technique increases the number of relay nodes more than the minimum value, given by the offline implementation. The first reason for this is that, the technique does not have a global view to decide the best global RNs. Second, as we create more clusters it is only natural to have more RNs to interconnect them. However, the most important factor is that CH nodes chose their RNs in a selfish manner. They chose the best suited nodes, in their point of view, not in the network one. In this way, it is possible to have, for example, two different nodes acting as RN between the same two CHs, just because each CH chose their RN in a selfish manner. In this case instead of having one RN acting as a gateway between these two CHs, as it is the case in the offline approach, the network will have two RN. Each one acting as a RN for one of the CHs involved. So, the increase in the number of RNs has some advantages; first the cost function could take into account the channel reliability and, in this case, maybe two RNs would increase the network stability. However, increasing the number of RNs we increase also the diversity in the paths, enabling the existence of smaller routes between nodes.

## VI. CONCLUSIONS AND FUTURE WORKS

This paper presents a technique to perform network admission control and topology management for structured mesh networks. The results show that by handling only local information and without the complete final configuration, the proposed method guarantees the correct clustering formation and role attribution for the nodes. The technique is also able to shape fairly distinct final network configurations. For example, just controlling the cost function one can go, in a distributed way, from a completely clustered network to the one that has the minimum possible number of clusters.

The cost function, responsible for modeling the network shape, can be as simple or as complex as one needs it. For the results presented here, we choose to focus on the number of clusters, however, other factors could be taken into account. The important point to consider is that the cost function calculation is a flexible way to control the network topology behavior. This flexibility is an interesting asset, for networks such as public safety networks, were different disaster sites could have different network requirements and the network operation can be shaped as desired. The cluster sizes are homogeneous; the technique enables a load balance among clusters in a dynamic and simple way

The next steps for this work would be implementing the proposal in a real environment to evaluate how it behaves in a real world trial. Other work that needs to be done is the calibration of the cost function to control the number and quality of CHs and RNs in a more precise way. We want to evaluate also if it is possible to have different cost functions for different areas, in this case we could have different parts of the same network with different topology configurations.

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## REFERENCES

[1] R.Rajaraman, Topology control and routing in adhoc networks: a survey, SIGACT News, vol. 33, pp. 60-73, Jan.2002

[2] P. Santi, Topology Control in Wireless Ad Hoc and Sensor Networks, WILEY, July 2005

[3] Y. Huang, W. He, K. Nahrstedt, W. C. Lee, Incident Scene Mobility Analysis, IEEE Conference on Technologies for Homeland Security, Waltham, MA, May 2008

[4] J. Q. Bao and W. C. Lee, Rapid deployment of wireless ad hoc backbone networks for public safety incident management, in Proc. IEEE Globecom, Nov., 2007

[5] S. F. Midkiff and C. W. Bostian. Rapidly-deployable broadband wireless networks for disaster and emergency response. In Proc. First IEEE Workshop on Disaster Recover Networks, June 2002

[6] A. Sarrafi, M. H. Firooz, and H. Barjini, A Cluster Based Topology Control Algorithm for Wireless Ad-Hoc Networks. International Conference on Systems and Networks Communication , Oct., 2006

[7] Teresa W. Haynes, S. T. Hedetniemi, Peter J. Slater, Fundamentals of Domination in Graphs, CRC; 1 ed., Jan, 1998

[8] http://dcg.ethz.ch/projects/sinalgo/, last visited Jun. 2010

[9] http://www.chorist.eu/, last visited Jun. 2010

[10] G. Mainland, L. Kang, Sébastien Lahaie, D. C. Parkes, M. Welsh: Using virtual markets to program global behavior in sensor networks. ACM SIGOPS European Workshop, Leuven, Belgium, Sept., 2004

[11] Xiaokai Yang,Economics: New Classical Versus Neoclassical Frameworks, Wiley-Blackwell, Jan 2001

[12] Hubert D. Henderson, Supply And Demand, Kessinger Publishing Company, July 2004

[13] http://dcg.ethz.ch/projects/sinalgo/, last visited Jul. 2010