Topology Control for Balanced Energy Consumption in Emergency Wireless Deployments

Alaa A. Abdallah Mohammed Hassan George S.-C. Kao Calin D. Morosan
Concordia University, Department of Computer Science and Software Engineering,
1455 de Maisonneuve Blvd. W, Montreal, QC, H3G 1M8, Canada, +1 (514) 848-2424-3109,
{ae_abdal, mo_hassa, geor_kao, cd_moros}@cse.concordia.ca

ABSTRACT
Wireless networks became an integral component of nowadays communication infrastructure and, due to their mobility and limited battery life, energy efficiency needs an important design consideration. Such networks are usually modeled by so called *mobile ad-hoc networks* (MANETs) models, further represented as simple graphs where the vertices have precise geometric locations and edges are straight lines.

Topology control is concerned with the assignment of different transmission power to wireless devices antenna such that the obtained ad-hoc networks satisfy some specific properties (connectivity, planarity, minimum energy, bounded degree, etc.). In this paper, we study the *energy-balanced topology control problem*, which is defined as follows: given a set of hosts in an ad hoc network, adjust the transmission power of each host so that the resultant network topology is connected and the maximum energy consumption among all the hosts is minimized. This problem has been solved by Ramanathan et. all [12] for static ad-hoc networks in a 2D environment.

We extend the algorithm from [12] for a dynamic environment in both 2D and 3D environment. We describe a communication protocol on top of this algorithm in order to ensure the connectivity and the energy balanced properties.

During the movement of nodes, the topology has to be changed. Since, in our protocol, each reconfiguration implies that all the nodes will transmit at maximum power, we study the influence of increasing the transmission radius of each node, by a fixed percent, over the number of reconfiguration needed, in order to maintain the network connectivity. Using an original network simulator, we show that the decreasing in the number of reconfigurations is exponential in terms of percentage of transmission radius increasing, which leads to a trade-off between the energy consumptions due to reconfigurations and due to the increased transmission radius. We also study the implication of other factors over the number of reconfigurations, such as node density, maximum transmission range, and different movement parameters (speed, changing of direction time).

PE-WASUN'05, October 10–13, 2005, Montreal, Quebec, Canada.

Categories and Subject Descriptors
J.m [**Computer Applications**]: Miscellaneous – *wireless communications*, *topology control*, *emergency communications.*

General Terms
Performance, Reliability.

Keywords
Topology control, MANET, energy efficient protocols.

1. INTRODUCTION
Wireless networks have witnessed an exponential growth in the last decade and they became an integral component of nowadays communication infrastructure. Such networks are usually modeled by *mobile ad-hoc networks* (MANETs) or *multihop wireless networks*.

A wireless ad-hoc network consists of a collection of transceivers where all communications among these transceivers are based on radio propagation. For each ordered pair of transceivers (u,v), there is a *transmission power threshold* associated, denoted by $p(u, v)$, which means that a signal transmitted by u can be received by v only if the transmission power of u is at least $p(u, v)$. The transmission power threshold for a pair of transceivers depends on a number of factors including the distance between the transceivers, antenna gains at the sender and receiver, interference, noise, environment, etc. [12]. Given the transmission powers of the receivers, we can model the network as a graph where a directed edge (u, v) is in this graph if and only if the transmission power of u is at least the transmission power threshold $p(u, v)$. Similarly, an undirected edge is in the graph if and only if, the transmission powers of both u and v is at least the transmission power threshold $p(u, v)$. We will restrict our study to the undirected model proposed in [3].

Topology control is the problem of computing and maintaining a network topology of different transmission powers with respect to some properties: connectivity, minimum energy, planarity, bounded node degree, bounded total edges weight. A large variety of such problems is described in [4] and [6].

The power transmission required to be assigned for a network topology is usually much smaller than the allowed maximal transmission power. Therefore, topology control can save energy and prolong the network lifetime. The topology control problems including both minimizing the total energy consumption and minimizing the maximum energy consumption are studied in [8] and [10].

The total energy consumption has been used as an important metric for evaluating the routing algorithms. However, the minimum total energy topology control problem has been proved to be NP-complete in [1]. Although in some cases that low total energy consumption implies energy-efficiency, having a minimum total energy does not necessarily produce a long-lived network since minimizing the total energy could lead to maximizing the energy consumption of a particular node. The premature failure of this node may consequently terminate the lifetime of the entire network due to its connectivity. Therefore, in some cases, balanced energy consumption is desired.

We study the *energy-balanced topology control problem* which is defined as follows: given a set of hosts in an ad hoc network, adjust the transmission power of each host so that the resultant network topology is connected and the maximum energy consumption among all the hosts is minimized. We will further refer to this problem as the *MinMax problem*. This problem has been solved by Ramanathan et. all in [12] for static ad-hoc networks in a 2D environment. They provided a global algorithm running in $O\left(n^2 \log n\right)$ to which we will further refer as the *MinMax algorithm*. Note that the *MinMax problem* can be also found in literature under the name of *energy-balanced topology control problem with symmetrical links* [5]. The symmetrical links model assumes that all the nodes have the same power threshold, which is based on the path loss model [11]. In this model the transmitting power $P_t = C \cdot d_{uv}^{\alpha}$, where d_{uv} is the Euclidean distance between u and v. If all the nodes have the same power threshold, we can normalize the constant C to 1 and assign to each link (u,v) a unique weight: $W\left(u,v\right) = d_{uv}^{\alpha}$. More than that, since the MinMax algorithm is insensitive to the value of α we will consider that the link weight is its Euclidean distance ($\alpha = 1$).

In this paper, we extend the MinMax algorithm for moving nodes in both 2D and 3D environments. We describe a communication protocol on top of this algorithm in order to ensure the connectivity and the energy balanced property. Also we extend the algorithm for multiple connected components.

Using an original network simulator, we show that the decreasing in the number of reconfigurations is exponential in terms of percentage of transmission radius increasing, which leads to a trade-off between the energy consumptions due to reconfigurations and due to the increased transmission radius.

We also study the implication of other factors over the number of reconfigurations, such as node density, maximum transmission range, and different movement parameters (speed, changing of direction time).

The paper is organized as follows. In section 2 we describe the MinMax algorithm from [12] and our modifications, in section 3 we describe the communication protocol that we added on top of the MinMax algorithm, in section 4 we present the simulation environment and the results, in section 5 we draw the conclusions, section 6 is dedicated to the acknowledgements, section 7 contains the references and in section 8 we present the graphs containing the simulation results.

2. THE MINMAX ALGORITHM

Since our protocol is based on the algorithm provided in [12], we consider opportunely recalling its main parts. The algorithm is a global algorithm, based on the minimum spanning tree construction, which can be summarized in three steps.

Step 1 - The algorithm starts by constructing the UDG graph (Unit Disk Graph) [7]. UDG is defined as the graph $G(V, E)$ in which there exists an edge (u, v) between two nodes $u,v \in V$ if and only if the Euclidean distance between u and v is less than one unit. The authors from [12] considered that the maximum transmission range is not bounded and, consequently, the entire UDG is connected. We have found this assumption unrealistic and, therefore, we modified their algorithm by fixing limited power transmission for each node such that we deal with more disconnected components of UDG.

Step 2 - In this step a spanning tree like algorithm is run on the UDG obtained in Step 1. The obtained graph is close to a minimum spanning tree for each connected component. Note that, in a wireless environment, running a spanning tree algorithm will not necessarily produce a tree structure. The transmission power in each node will be adjusted accordingly to the length of the new edges.

Step 3 - During this step, the algorithm will minimize the power assignment for each node, maintaining the connectivity of each component. The graph obtained is connected and per-node minimized.

3. THE COMMUNICATION PROTOCOL

Since the MinMax algorithm has to be run locally at each node of the network, we implemented a proactive communication protocol on top of it, in order to maintain the connectivity in a moving environment. This protocol works under the assumptions of the emergency wireless deployments:

Small number of nodes. SEAL, Coast Guard, mountain rescues, fire fighters, disaster intervention, etc., they all have teams formed by less then 50 "independent" communication units. The meaning of "independent" in this context is that there is no hierarchical structure in the communication network (or a network backbone) and all the nodes are equivalent from the point of view of routing. Also, it is hard to believe that someone will send an emergency team with more then 50 units on the field without setting a hierarchical communication network, with a precise infrastructure.

The imperious need for connectivity. This is imposed by the emergency character of operations. Our protocol will ensure the connectivity of the network in conjunction with the MinMax algorithm.

The imperious need for conserving energy individually. Indeed, as we stressed in the introduction, wireless deployments deal with scarce energy resources, often battery powered.

The need of knowing the other nodes location. This is due to the "team oriented" decisions that have to be made regardless the ad-hoc character of the network.

Smart wireless devices. They have to be able to run algorithms, store data, and to be GPS equipped. These objectives are not realistic for the large public but are usual for such teams not dealing with a limited budget.

High probability of moving. This is another intrinsic characteristic of the emergency deployments. Most of the previous papers dealing with this problem assumed a quasi-static ad-hoc network, which is far from being realistic. Therefore, we implemented the protocol using both high-speed moving and static or quasi-static nodes in the same ad-hoc network.

Most of the requirements described above imply that each node has knowledge about other nodes locations. At a glance, this goal seems to be impossible since we are dealing with a mobile network. Nevertheless, this is possible due to the different meaning of connectivity in a wireless network than a wired one. Indeed, in a mobile ad-hoc network, a node can travel without taking care about the link with its neighbor until it has to transmit a packet or until the probability that it is out of range is higher than a threshold value.

The observations above leaded us to the following communication protocol in two phases: a gossip phase and a reconfiguration phase.

3.1 The Gossip Phase

In this phase, all the nodes are exchanging information consisting solely in their physical location, by transmitting and receiving using the maximum power available. The only packets transmitted are the *control packets*, containing the node ID, a time-stamp, and the coordinates of the node. The time-stamp is used to identify the gossip session. Although the gossip phase can be triggered by only one node, it is possible that two or more gossip phases are triggered simultaneous from different locations of the network. When a node triggers a gossip phase, it attaches a time-stamp to this first message and it sends to its one-hop neighbors. If a node receives two or more control packets, it forwards the one with the latest time-stamp. Also, each node updates its list with the coordinates of the other nodes.

At a glance, this phase can be seen as an impediment to the regular data traffic and a communication bottleneck. Nevertheless, studies over gossiping in ad-hoc networks show that this can be done quite efficiently in small networks (under 50 nodes, as we have mentioned above). We further direct the reader to [2] and [9] for a more detailed analysis of the gossiping process in ad-hoc networks. Note that, regardless the fact that in the worst case the gossip phase can take at most $O(n^3)$ forwarded messages, in [9] is described a technique which can reduce with up to 94% the number of messages needed in order to accomplish this phase.

3.2 Reconfiguration phase

In this phase, the MinMax algorithm is run locally at each node of the network and the topology is configured accordingly. Also, each node constructs and stores its routing table according to the new topology. The complexity of MinMax algorithm in $O(n^2 \log n)$, which takes by far shorter time comparing to the time needed to accomplish the gossip phase.

3.3 Protocol analysis

The gossip phase can be triggered by two events:

- **Explicit pinging:** this occurs whenever a node *u* is outside the transmission range of a node *v*, with which was previously connected during the configuration phase. We deal with this case by letting node *v* to ping node *u* each time *v* is at a vector distance from the previous ping-location greater than a configurable threshold value. This makes sense since a node traveling around a fixed location has a great probability to maintain the connection with its neighbors.
- **Implicit pinging:** this occurs whenever a node *v* has to transmit a packet to one of its neighbors according to the routing table stored in *v*. Since every packet has to be acknowledged, implicitly the absence of an acknowledgment will trigger a gossip phase. In our simulations we implemented only explicit pinging.

A great advantage of this protocol is that, once the topology is computed, the routing protocol will not need any extra messages since a routing table is stored in each node. This will need a small amount of memory for a network with at most 50 nodes.

Also, another advantage of using a proactive protocol for such a network is that it requires much less computations comparing to a reactive protocol which needs a route discovery for each packet sent. As long as the number of reconfigurations in time is much less then the number of packets sent, we can claim that this protocol is more efficient then a reactive one.

A natural question arises: how often a mobile ad-hoc network has to change its topology in order to keep the two properties: minimizing the maximum power consumption and keeping the connectivity? Let us consider the simplified situation in which three nodes are connected as in Figure 1.

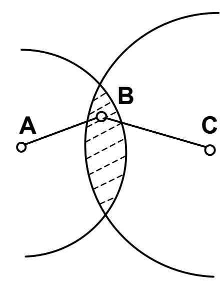

Figure 1 – Node B is connected to A and C as long as it is inside the hatched area

We can see that, as long as node B stays in the hatched area, it will be connected to nodes A and C. Once node B will be outside that area, the connection will be lost and a new reconfiguration phase is triggered (Figure 2).

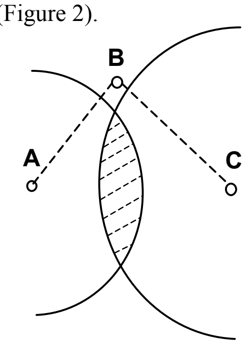

Figure 2 – Node B is not connected to A and C if it is outside the hatched area

Let us assume now that we increase the transmission radius of each node by a percent δ (Figure 3). In this case, the area in which B can move without losing the connection will increase by a percent ($2\delta + \delta^2$), which is quadratic in terms of δ. The main question is if the number of reconfigurations needed to keep the network connected will decrease by the same amount. This question comes from the fact that we are dealing with two contrary effects:

– Increasing the transmission radii leads to a smaller number of reconfigurations, which consequently leads to smaller power consumption due to the gossip phase. Recall that, during the gossip phase, all the nodes have to transmit at maximum power.

– On the other hand, increasing the transmission radii leads to an overall increasing of the power consumption for the whole network.

In this paper, one of our goals is to study the cumulative effect of these two phenomena, and to prove that there exist a trade-off between decreasing the power consumption due to reconfiguration phases and increasing the power consumption due to increasing the transmission radii.

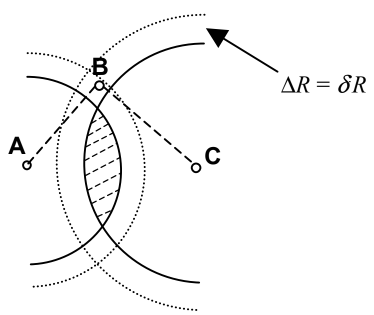

Figure 3 – Node B becomes connected to A and C if A and B increase the transmission radius

A trade-off can be proven if the sum of the two power consumptions function of the increasing radius percent δ will have only one minimum. Since for the increasing power transmission we had an explicit quadratic dependence, for the number of reconfigurations we had to do simulations to extract the behavior of this value function of the increasing radius percent. More than that, even a trade-off exists, its optimality raises another question: is this a "good" trade-off? A possible positive answer can be given if the decrease in the number of reconfiguration is much faster than the increase in the transmission power. As you will see in the next section, our simulations show an exponential decreasing in the number of reconfigurations over the increasing in radius percentage, which sustains the hypothesis of a "good" trade-off.

4. SIMULATIONS

In our experiments we simulated the deployment of moving mobile hosts in 2D and 3D. We considered a variable number of points (between 20 and 80), leading to different node densities. The points have been uniformly randomly generated in this space. The simulations have been placed in a 340x340 square for the 2D experiments, or 340x340x340 cube for the 3D experiments.

In order to emulate a "natural" movement of the nodes, beside randomly generated speed and movement angles we provide two original features: *time-to-live* and *distance-to-live*. After expiration of either one of the two parameters, each node receives new movement parameters (speed, direction, time-to-live, and distance-to-live).

Also, we study the implications of having high-speed moving nodes among quasi-static ones. The experiment time is also variable and we study the implication of this parameter over the results. All the experiments have been done in 2D and 3D as well. The results from 3D confirmed the expectations that the behavior of the number of reconfigurations must be the same as in 2D, of course scaled to a bigger space.

The network simulator system is using an original *dynamic time slicing*, based on an event-driven technique. This will ensure that all possible events are taken into account. Practicaly, we are computing the time to the proximal event and we stop the simulator according to this time. The possible time events are: expiring of time-to-live, expiring of distance-to-live, and out of the ping distance of a node.

We provide 7 separate analyses, each of them in 2D and 3D. In these analyses we study the number of reconfigurations versus the following parameters: increasing in the percentage of the transmission radii, point density, maximum transmission radius, experiment time, ping distance, time-to-live, and maximum speed. For the seek of clarity, the confidence interval is represented only for one curve in each graph.

4.1 Number of Reconfigurations Versus Increasing Percentage of Transmission Radii

This represents the main result of our paper and proves that there is a "good" trade-off between the decreasing in the power consumption due to the reconfiguration phases and the increasing in the power consumption due to the increasing in the transmission radii.

As you can see in Figure 4 (2D case) and Figure 5 (3D case) the number of reconfigurations decreases exponentially with the increasing in the transmission radii. We repeated the same experiment for different number of points (from 20 to 80) and we have obtained the same result.

We can see that the number of reconfigurations drops to nearly a half for an increasing in transmission radii under 5%. This effect is even more accentuated in 3D due to an increased number of disconnected components and, consequently, a smaller dependence between nodes and a small average degree.

Summing now the two contrary effects we obtain the graph from Figure 6, where the yellow line represents the cumulative power consumption. Although the two curves have different scales, they can differ only up to a multiplicative constant, which will affect only the location of the trade-off minima.

4.2 Number of Reconfigurations Versus Point Density

In Figure 7 we can see the influence of the point density over the number of reconfigurations. We scaled the density of points in 2D multiplying by 10^4 (pink) and in 3D multiplying by 4×10^6 (blue).

As it was expected, the number of reconfigurations linearly increases with the density of nodes.

4.3 Number of Reconfigurations Versus Maximum Transmission Radius

In Figure 8 (2D) and Figure 9 (3D) we show the influence of the maximum transmission radius over the number of reconfigurations. The reason of this analysis is the first step of MinMax algorithm in which we are constructing the UDG after which we are applying step 2.

Excepting very small maximum transmission radii, the number of reconfigurations is relatively insensible to variations of this parameter. The accentuated decreasing in the number of reconfigurations for small maximum transmission radii and small number of points is due to the increasing number of components (blue and pink curves in Figure 7). Also, the deviations from linearity in Figure 8 and Figure 9 are due to a relatively high standard deviation (around 6%). We show this for only one curve by vertical bars (Figure 8, brown line, 80 points).

4.4 Number of Reconfigurations Versus Experiment Time

In Figure 10 and Figure 11 we show the influence of the experiment time over the number of reconfigurations in 2D and 3D respectively. This could be a measure of the bias induced by an inadequate experiment time chosen to draw other analyses.

As it was expected, the dependence is linear, showing a better linearity in the higher domain and for a higher number of nodes.

4.5 Number of reconfigurations versus ping distance

The ping distance is another important parameter in our communication protocol. This is the vector distance that a node has to parse in order to ping its neighbours. A smaller ping distance could lead to high communication overhead, but a higher ping distance will increase the probability that the network is disconnected.

As you can see in Figure 12 (2D) and Figure 13 (3D), the number of reconfigurations decreases faster for small values of ping distance that for greater values of the ping distance. This is an expected result since a greater value of ping distance means that a node will not ping its neighbors as often as for a smaller value.

4.6 Number of Reconfigurations Versus Time-To-Live

As we have mentioned before, one of the features of our simulator is a parameter called *time-to-live*, which has been introduced in order to simulate a "real life" movement in which the nodes suddenly changes their direction and their speed.

The graphs from Figure 14 and Figure 15 show that the number of reconfigurations is practically insensible to this parameter, for small number of nodes, and has a very weak dependence for higher number of nodes. Also, in Figure 16, for 80 nodes we show the standard deviation that affects this curve (around 5%).

4.7 Number of Reconfigurations Versus Maximum Speed

The last analysis is concerned with the influence of the *maximum speed* of a node in the network over the number of reconfiguration needed in order to keep the network connected.

This dependence is depicted in Figure 16 for 2D case and in Figure 17 for 3D case. We have considered a wide range of the maximum speed (between 5 and 40 pixels per second) compared with the experiment area (340x340 pixels). The simulation results confirm our expectations showing a nearly linear dependence of the number of reconfigurations by the maximum speed in 2D and 3D as well.

5. CONCLUSIONS AND FUTURE WORK

In this paper we study a topology control problem under two concurrent constrains: minimizing the maximum energy consumption of individual nodes in a mobile ad-hoc wireless network while keeping the connectivity of the network. We analyze mainly the influence of increasing in the power transmission over the number of reconfigurations.

Using an original network simulator we implemented an improved version of the MinMax algorithm from [12] in 2D and 3D, adding a communication protocol on top of it. One of the advantages of using this protocol is that no additional routing protocol is needed. Since most of the routing protocols in MANET are using different kind of flooding, this will significantly decrease the power consumption due to route discovery. Also the protocol is quite simple and connectivity and minimizing the maximum power consumption are ensured. However, the drawback is that a node has to "guess" when the gossip phase is ended. This can be avoided by using the number of connected nodes from the previous gossip phases. Also the gossip time rapidly increases with the number of nodes. Therefore, for an increased number of nodes, a hierarchical structure seems to be more suitable.

By extended simulations in different environments we show that the decreasing in the number of reconfigurations is relatively exponential to the percentage of increasing the transmission radii. This shows that there exists a trade-off between the energy consumptions due to reconfiguration phases and due to the increasing in the transmission radius.

It is our interest to further investigate the performance of the proposed topology control protocol in terms of work throughput, transmission delay, and other communication parameters. Also it is interesting to complete the simulations with implicit pinging events (due to data traffic). A separate analysis can be done regarding the energy consumption during the gossip phase, which can be completed by considering random appearance and disappearance of some nodes in time.

6. ACKNOWLEDGMENTS

We are grateful to Dr. Lata Narayanan for her support during this project.

7. REFERENCES

[1] W.-T. Chen and N.-F. Huang. The strongly connecting problem on multihop packet radio networks, *IEEE Trans. Comm.*, 37(3):293–295, 1989.

[2] Z. Haas, J. Halpern and L. Li. Gossip-based ad hoc routing, in *IEEE INFOCOM*, 2002.

[3] L.M. Kirousis, E. Kranakis, D. Krizanc and A. Pelc. Power consumption in packet radio networks, in *Proc. of the 14th Annual Symposium on Theoretical Aspects of Computer Science (STACS 97)*, *Lecture Notes in Computer Science*, 1200:363–374, 1997.

[4] X.-Y. Li. Algorithmic, geometric and graphs issues in wireless networks, *Wireless Communications and Mobile Computing*, 3(2):119-140, 2003.

[5] Y. Li, X. Cheng and W. Wu. Optimal Topology Control for Balanced Energy Consumption in Wireless Networks, *J. Parallel Distrib. Comput.*, 65:124–131, 2005.

[6] N. Li and J. C. Hou. Topology control in heterogeneous wireless networks: Problems and solutions, *INFOCOM, 2004*.

[7] D. Li, X. Jia and H. Liu. Energy-Efficient Broadcast and Multicast Routing in Ad Hoc Wireless Networks, *IEEE Transactions on Mobile Computing*, 3(2):144-151, 2004.

[8] E. L. Lloyd, R. Liu, M.V. Marathe, R. Ramanathan and S. S. Ravi. Algorithmic aspects of topology control problems for ad hoc networks, *Mobile Networks and Applications*, 10(1-2):19-34, 2005.

[9] X.-Y. Li, K. Moaveninejad and O. Frieder. Regional gossip routing for wireless ad hoc networks, *Mobile Networks and Applications*, 10(1-2):61-77, 2005.

[10] R. Rajaraman. Topology control and routing in ad hoc networks: a survey. *ACM SIGACT News*, 33(2):60-73, 2002.

[11] T. S. Rappaport. *Wireless Communications: Principles and Practice*, Prentice-Hall, Englewood Cliffs, NJ, 1996.

[12] R. Ramanathan and R. Rosales-Hain. Topology control of multihop wireless networks using transmit power adjustment, in *Proceedings of IEEE INFOCOM*, Tel-Aviv, Israel, pp. 404–413, 2000.

8. SIMULATION GRAPHS

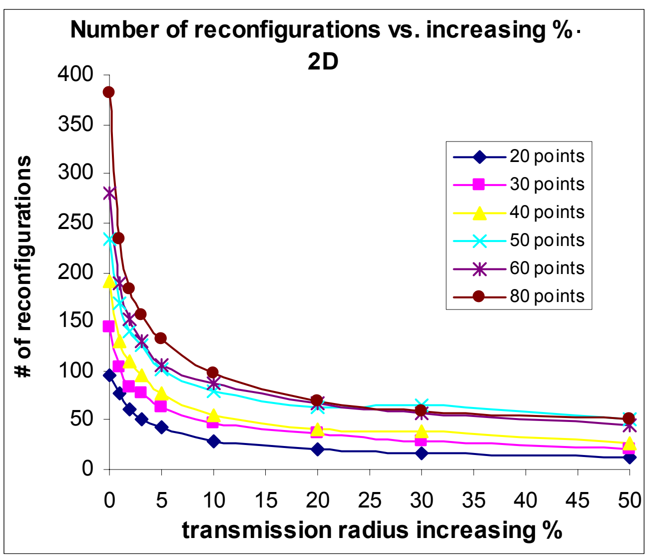

Figure 4 – Number of reconfigurations vs. increasing percentage of the transmission radii - 2D

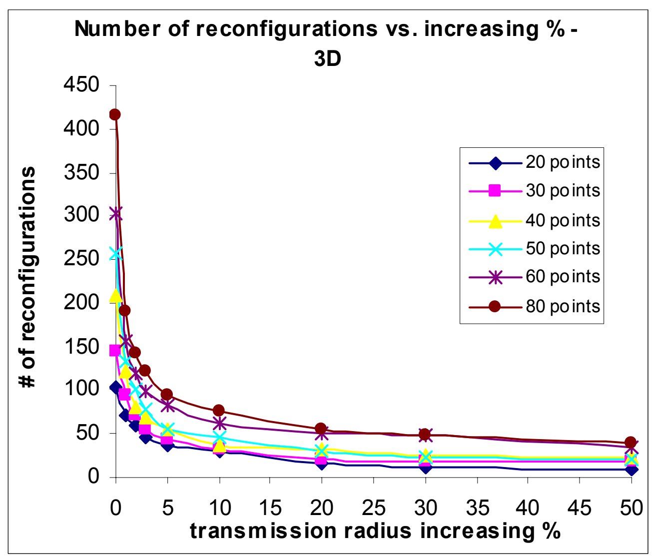

Figure 5 – Number of reconfigurations vs. increasing percentage of the transmission radii - 3D

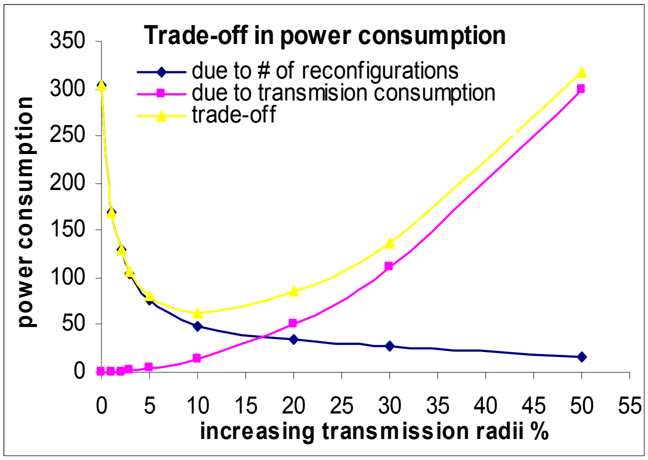

Figure 6 – A trade-off (yellow) between the power consumption due to the number of reconfigurations (blue) and due to increasing percent of the transmission radii (pink)

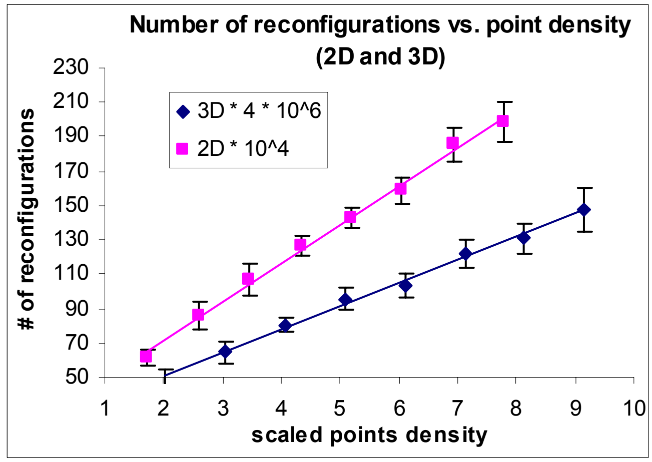

Figure 7 – Number of reconfigurations vs. point density (2D&3D)

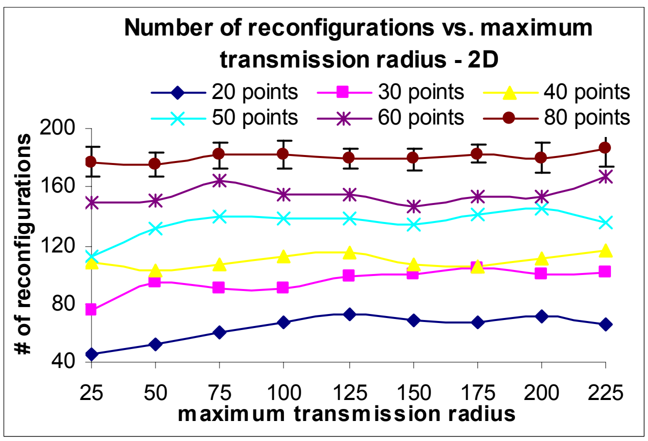

Figure 8 – Number of reconfigurations vs. maximum transmission radius – 2D

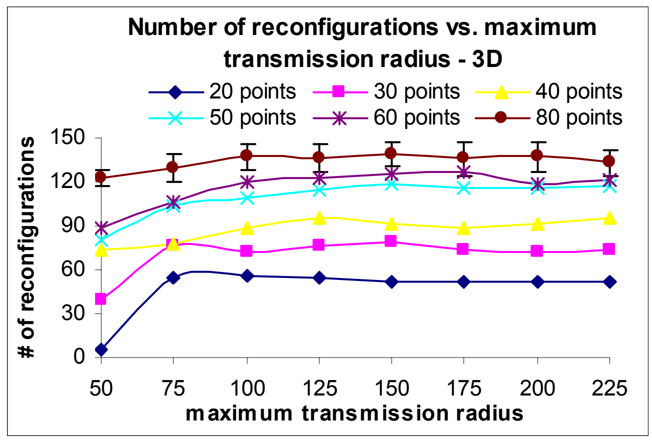

Figure 9 – Number of reconfigurations vs. maximum transmission radius – 3D

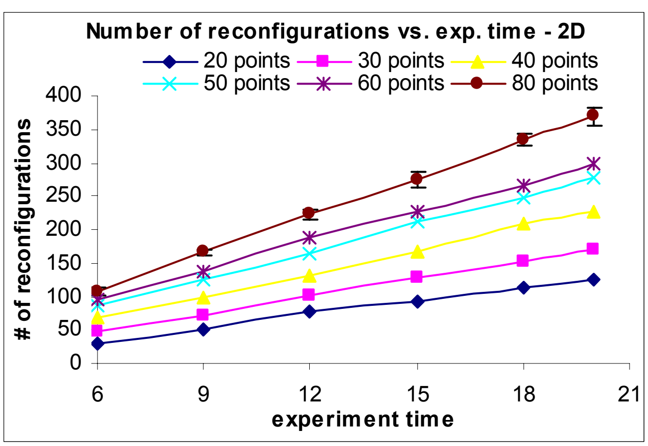

Figure 10 – Number of reconfigurations vs. experiment time – 2D

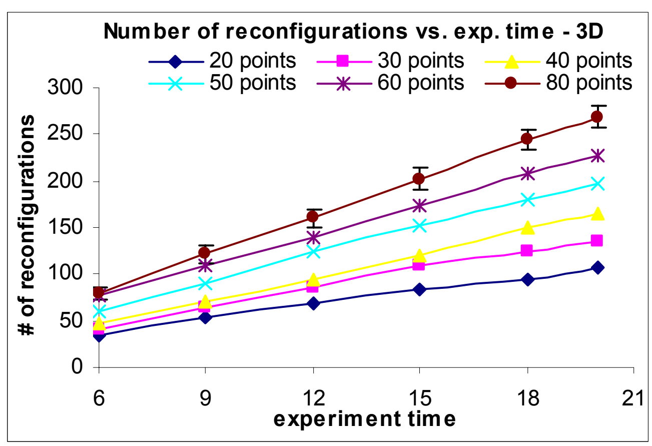

Figure 11 – Number of reconfigurations vs. experiment time – 3D

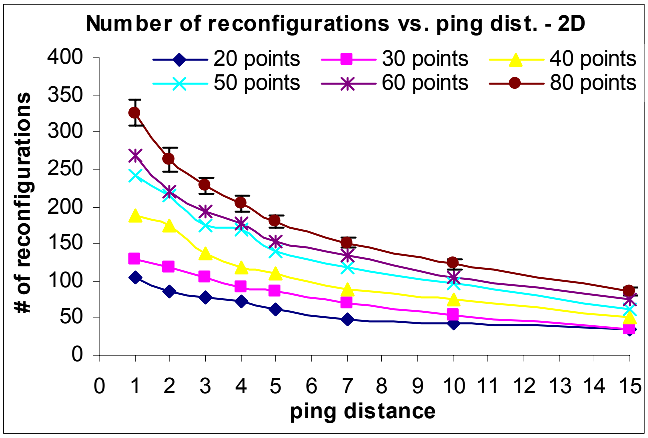

Figure 12 – Number of reconfigurations vs. ping distance – 2D

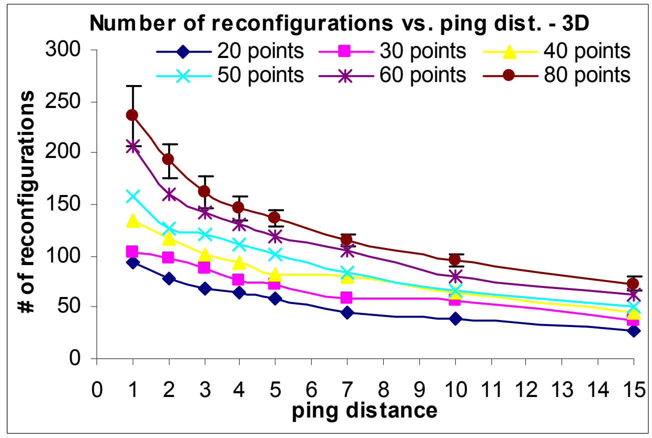

Figure 13 – Number of reconfigurations vs. ping distance – 3D

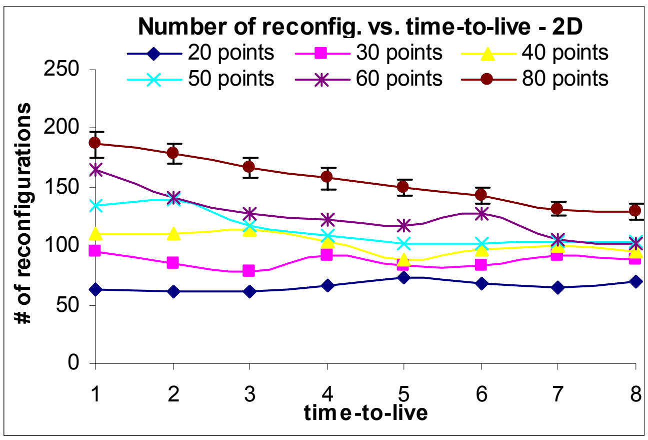

Figure 14 – Number of reconfigurations vs. time-to-live – 2D

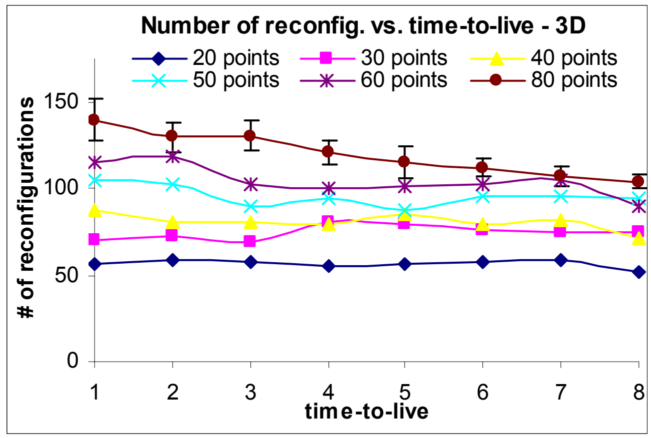

Figure 15 – Number of reconfigurations vs. time-to-live – 3D

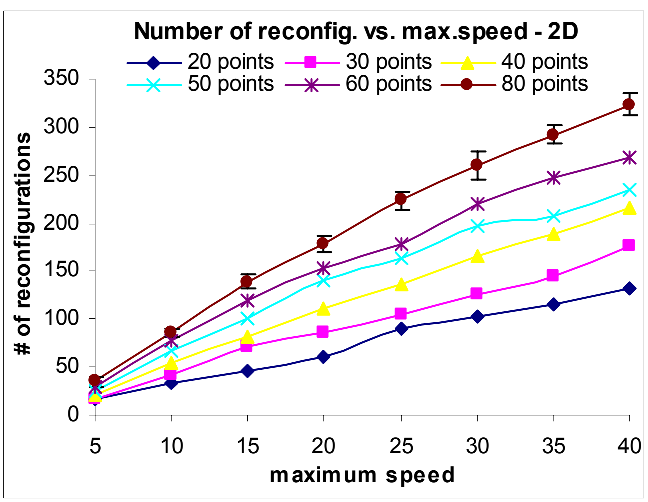

Figure 16 – Number of reconfigurations vs. maximum speed – 2D

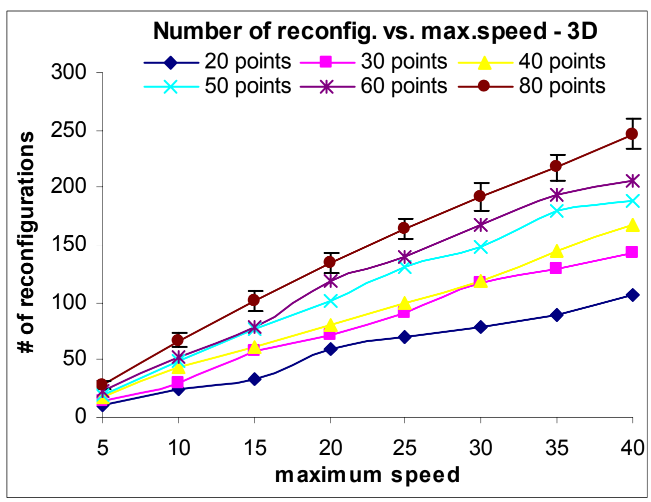

Figure 17 – Number of reconfigurations vs. maximum speed – 3D