DYNAMIC CLUSTERING FOR TRANSMISSION RANGE CONTROL[1] IN AD HOC NETWORKS

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ABSTRACT

Ad hoc networks have being given a lot of attention in recent years. The problems associated with this kind of networks are many and difficult to solve because of their dynamic nature – networks with non-static topology and non-static infrastructure. A large number of the issues under investigation are related with the finite power of the mobile devices. In terms of the communication tasks that those devices perform, the transmission power that is utilized plays a very important role to the long-term survivability of the network. The issue of transmission power affects the connectivity of the network, in a way that when the utilized transmission power is small then the network may be partitioned. In this work the latter has equivalent importance with the case where the assignment of excessive transmission power, resulting in a very dense net of communication links. When we use large transmission power then the long-term survivability and connectivity of the network is jeopardized because the nodes use their finite power inefficiently. Our task is to adjust the transmission power to the level where both the connectivity of the network is ensured and the transmitted power is minimized among all participating devices.

INTRODUCTION

In the recent years there has been an increasing interest on ad hoc networks, because of their dynamic characteristics and their foreseeing applications in the battlefield, in emergency cases and potentially in the commercial world. A large number of researchers and institutes have focused in this topic trying to improve the efficiency, effectiveness and performance of those networks by identifying and proposing solutions of possible problems existing in their functionality at the various layers of the OSI model.

One of the most important problems is that the devices have finite power, so if this power is misused then the survivability of the network is jeopardized, because nodes will fail, the network will partition and will not be able to perform the appropriate tasks. So, we have to introduce some ways to control the power consumed from the devices as long they operate and perform their standard networking actions (e.g., routing). The power metric depends on many factors like the power consumed from the operating system and the power consumed from transmitting and receiving packets. In this work will not focus in every aspect of power but mostly on controlling the transmission power of each node in a way that the network is connected and the utilized transmission power is minimized.

The assumed network environment is an ad hoc network where the nodes are dynamically configured using IP Autoconfiguration Suit (IPAS). IPAS is a collection of protocols and modules that dynamically configure ad hoc networks with IP addresses and assign the appropriate capabilities to the configured nodes (e.g., DNS). One of the drawbacks of IPAS is that configures flat networks, so the scalability characteristics of the resulting autoconfigured network are debatable. A way to eliminate this drawback is the IPAS to generate a hierarchical network by applying dynamic clustering techniques. This hierarchy can be created by simultaneously trying to improve some of the performance metrics of the network. There are many techniques that optimize the clustering of data based on some cost functions but most of them are centralized as opposed to the distributed environment that we consider. The latter is not entirely true if we take advantage of the implicit centralized control that exists in IPAS. As we describe in the next section, the configuration decisions are taken at a central point, from a module called ACA (Adaptive Configuration Agent). Those decisions are based on the processing of configuration information collected and stored in a database. Obviously, by assuming the functionality of IPAS we can utilize the configuration information collected and extent ACA by incorporating a global optimization technique that uses the appropriate configuration information to reach in an

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optimal clustering decision subject to the cost function we will apply.

As we already mentioned one of the very important problems in the dynamic environments is how we can utilize efficiently the finite power of the participating devices. One aspect of this problem is what is the optimal transmission power (transmission range) assignment to the participating devices such that there is minimization of the transmission power among all over the participating devices subject to the constraint that the complete connectivity of the network is ensured. The latter description is the optimization problem that we try to solve by applying dynamic clustering.

Intuitively and since the transmitted power is proportional to the transmission range a promising approach is to cluster the nodes based on their proximity. So, we let the nodes that are closer to communicate with each other in a regular basis (intra-cluster communication), and when there is information that need to travel along the network we let specific nodes (border nodes) to communicate this information among the clusters until it reaches the destination cluster, where through the intra-cluster communication the information will be delivered to the destination. Based on the latter description one of the problems is not only to decide on clustering but also to specify dynamically the border routers, also in a way that is optimal in terms of the transmission power required for their connectivity, which will also ensure full network connectivity.

The global optimization technique that we utilize is the simulated annealing (SA) and is described in section 4. In general, SA avoids local minima by choosing in a probabilistic way to follow an intermediate solution that increases the cost instead of a solution that reduces it. Details of this method are given in a later section. The cost function that will be optimized will be related to the proximity of the nodes. In this work we assume that the positions of each of the nodes are stored in the configuration database and can be utilized by SA.

By following the approach described above for dynamically clustering the nodes for controlling the transmission power and ensuring at the same time full network connectivity, we reach in very interesting promising results that we describe in section 6. In the following paragraph we revisit some representative work related to the problem trying to solve, so we prove in that fashion that our approach is a novel one. In the third section we give a description of IPAS that will be useful for the understanding of the network environment and the justification of the validity of our approach to use a centralized technique. In section 4, we present the details of simulated annealing, which is the basic gear to our proposed mechanisms. In section 5 we present the techniques and algorithms that we propose for dynamic clustering and transmission power control and in section 6 we give some of the results concerning the savings in power by applying our mechanisms rather than using a flat transmission range. Finally, in section 7 we conclude this presentation along with some words for future directions that we explore.

RELATED WORK

In this section we refer to some work done on power control problem. The existing work related to this problem comprises of strategies to find an optimal transmit power to control the connectivity properties of the network or part of it. Power control is conceptualized as a network layer problem in [7], and the COMPOW protocol is proposed. It is proposed in [9], that each node adjust its transmit power so that its degree (number of one-hop neighbors) is bounded. A distributed topology control algorithm using direction information is proposed in [10]. [3] proposes using transmit power control to optimize the average end-to-end throughput by controlling its degree.

The clustering problem pertains to classifying the nodes hierarchically into equivalence classes according to certain attributes. These attributes could be node addresses [5], geographical regions or zones [8], or a small neighborhood (typically 1 or 2 hops) of certain nodes elected as cluster-heads or leaders, as in [4]. The leader election or the cluster set up phase uses heuristics like jode addresses, node degrees, transmission power, mobility or more sophisticated node weights combining the above attributes, as in WCA [15], and in DCA [14]. The goal of clustering could be to reduce route discovery overhead, (by address space aggregation or by localizing control messages), to optimize resources like battery power and network capacity, or for ease of addressing and management.

IP AUTOCONFIGURATION SUITE (IPAS)

Rapidly deployable and survivable networks are very important requirements in the Objective Force. Thus, in order to support these requirements, the entire tactical battlefield network, possibly consisting of thousands of hosts, routers and MANET nodes, must be autoconfigured. Moreover, the networks must be rapidly reconfigured as conditions or requirements change. In this section, we present an approach to plug-and-play and survivable networking using the Autoconfiguration Protocol Suite (IPAS) [1][6]. We describe the IPAS protocol architecture, its elements and their functionalities.

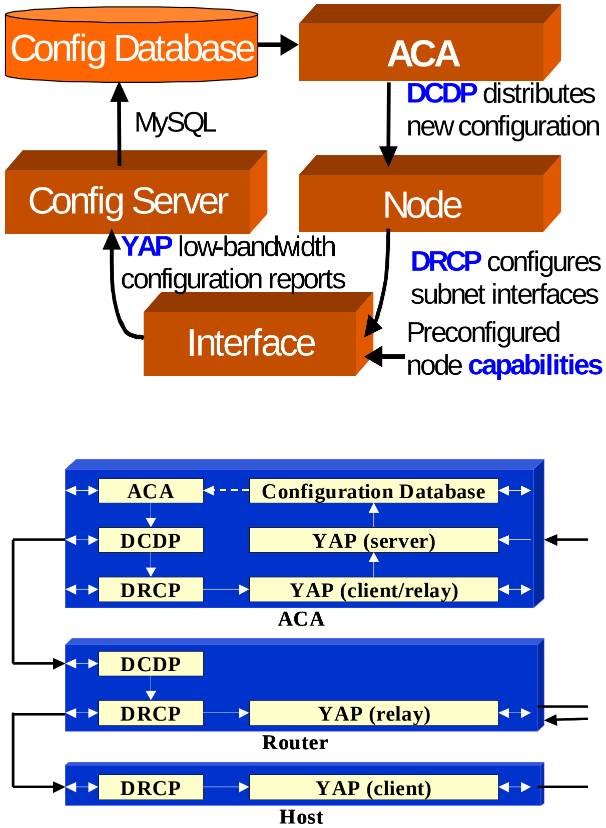

Figure 1: IPAS model

The above figure shows the IPAS components and how they relate to each other. At its heart is the new Dynamic Configuration Distribution Protocol (DCDP). DCDP is a robust, scalable, low-overhead, lightweight (minimal state) protocol designed to distribute configuration information on address-pools and other IP configuration information (e.g., DNS Server's IP address, security keys, or routing protocol). DCDP was designed for dynamic wireless battlefield, operating without any central coordination or periodic messages. Moreover, DCDP does not require a routing protocol to distribute information or any interface to be configured (except for the link-local information in IPv6).

DCDP relies on the Dynamic and Rapid Configuration Protocol (DRCP) to actually configure the interfaces. DRCP borrows heavily from DHCP, but adds features critical to roaming users. DRCP can automatically detect the need to reconfigure (e.g., due to node mobility) through periodic advertisements. In addition, DRCP allows for: a) efficient use of scarce wireless bandwidth, b) dynamic addition or deletion of address pools to support server fail over, c) message exchange without broadcast, and d) clients to be routers.

The Configuration Database Update Protocol (YAP) is a simple bandwidth efficient reporting mechanism for dynamic networks. YAP has three elements: 1) YAP Clients running on every node, 2) YAP Relays forwarding information from YAP clients to a server, and 3) a YAP Server. YAP clients periodically report its node's capabilities, configuration, and operational status to the YAP relay agents. The capabilities say, for example: "This node can be a DNS server with priority 0" or "a YAP server with priority 3" (priority reflecting a node's willingness to perform a function). Other YAP information include the node's: 1) name and IP address, 2) Rx/Tx packets, bit rate, link quality, 3) routing table, and 4) address pool. The YAP server stores this information in a configuration database (see Figure 1).

The brain of IPAS is the Adaptive Configuration Agent (ACA). It observes the state of the network in the Configuration Database (filled by YAP) and can perform some actions, such as server reconfiguration, based on some rules or policies. The ACA can also reset the network and can distribute an address pool from human input or from a predefined private address pool (e.g., 10.x.x.x).

SIMULATED ANNEALING

Simulated annealing (SA) [2] has been widely used for tackling different combinatorial optimization problems. The general algorithm is described below. A comprehensive discussion of the theoretical and practical details of SA is given in [11][12]. It suffices here to say that the elementary operation in the Metropolis method for a combinatorial problem such as scheduling is the generation of some new candidate configuration, which is then automatically accepted if it lowers the cost (C), or accepted with probability $\exp\left(-\frac{\Delta C}{T}\right)$, where T is the temperature, if it would increase the cost by $\Delta(C)$. In the description of the algorithm below, s is the current schedule and is a neighboring schedule obtained from the current neighborhood space N_s by swapping two classes in time and/or space.

Thus the technique is essentially a generalization of the local optimization strategy, where, at non-zero temperatures, thermal excitations can facilitate escape from local minima.

The SA algorithm has advantages and disadvantages compared to other global optimization techniques. Among its advantages are the relative ease of implementation, the applicability to almost any combinatorial optimization problem, the ability to provide reasonably good solutions for most problems (depending on the cooling schedule and update moves used), and the ease with which it can be combined with other heuristics, such as expert systems, forming quite useful hybrid methods for tackling a range of complex problems. SA is a robust technique, however, it does have some drawbacks. To obtain good results the update moves and the various tunable parameters used (such as the cooling rate) need to be carefully chosen (e.g., some of them considered are listed in the following paragraph), the runs often require a great deal of computer time, and many runs may be required. Depending on the problem to which it is applied, SA appears competitive with many of the best heuristics, as shown in the work of Johnson [13].

ALGORITHMS AND TECHNIQUES

In this section we will describe the algorithms and techniques we propose for clustering the nodes and specifying the transmission power of each one of them. Since the latter two actions will ensure only intra-cluster connectivity along with reduction in the transmission power utilized from the nodes per cluster, we will describe also the algorithms we propose for ensuring full network connectivity through the specification of the border routers that allow inter-cluster connectivity along with the algorithms used for assigning the appropriate transmission range to those nodes for full network connectivity subject to transmission power minimization used from the border routers.

A. Dynamic Clustering

For the clustering of the nodes we utilized the SA in order to get a global optimal solution. The inputs to the optimization method are the coordinates of the position of the nodes, which are utilized from the cost function to be minimized. Also inputs to SA are the number of clusters to be generated K, the initial temperature $T_{\max}$ and number of generations per temperature T. Our intension is to cluster together nodes that are close, since we expect that this will minimize the transmission power utilized from the nodes (e.g., transmission range proportional to transmission power). The formulation of the optimization problem is:

$$\min \sum_{i=1}^{K} \sum_{j=1}^{|C_i|} \left\| x_{ij} - z_i \right\|$$

K : The number of clusters to be generated

$|C_i|$: The cardinality of cluster i

x_{ij} : The coordinates of the j^{th} node of i^{th} cluster

z_i : The coordinates of the center of the i^{th} cluster

By fitting the above cost function to the SA, the algorithm produces the clustering scheme that minimizes the above given cost function. Following this step is to determine the transmission range that each of the nodes in a cluster has to achieve in order to have per cluster full connectivity. The full network connectivity and the inter-cluster actions are described later.

B. Intra-Cluster Transmission Range Control

Since we have defined the clusters, we will describe the technique we propose for assigning the appropriate transmission range in each of the nodes per cluster, such that the transmission power is minimized and at the same time full intra-cluster connectivity is ensured. The optimization problem that we try to solve here is described as follows:

$$f = \min \sum_{j=1}^{|C_i|} TmxRange\left(node_{ij}\right)$$

subject to intra-cluster full connectivity

In order to minimize f we have to minimize the path that connects all the nodes in the cluster. From the above description, the problem is the same with the Traveling Salesman Problem (TSP), which provides us with the minimum path that connects all the participating nodes. Based on the latter observation we reuse SA to solve the TSP problem, which is the first step to the determination of the appropriate transmission range for each of the nodes in the cluster.

The second step, which follows the determination of the minimum path that connects the nodes of the cluster under consideration is the following algorithm that utilizes the minimum path and determines the transmission range that each node in the cluster has to achieve for minimizing the transmission power and ensuring at the same time the intra-cluster connectivity.

Assume that the minimum path among all the n nodes of the i^{th} cluster is described as follows:

$$x_{i,1}, x_{i,2}, \ldots, x_{i,n-1}, x_{i,n}, x_{i,1}$$

Each node x_{ij} has two immediate neighbors $x_{i,j-1}$ and $x_{i,j+1}$ (in the case of $x_{i,n}$, the neighbors are the nodes $x_{i,n-1}$ and $x_{i,1}$). The transmission range that the node x_{ij} has to achieve is determined as:

$$\max\left(\left\|x_{i,j}-x_{i,j-1}\right\|,\left\|x_{i,j}-x_{i,j+1}\right\|\right)$$

Even though this is not the minimum transmission range that a node can be assigned for intra-cluster connectivity, this value reduces (e.g., as we will prove later in the results section) the transmission range that a node in the cluster has to achieve in order to have intra-cluster-connectivity but also the generated links are bi-directional. We want bi-directional links because many of the popular routing algorithms assume that the links are undirected (i.e., AODV).

C. Assigning Border Routers

Having determined the clusters and the appropriate transmission range of each node in a cluster for intra-cluster connectivity, we have to ensure also that we have network connectivity. Each cluster communicates with the rest of the clusters through a set of border routers. Only those nodes are used for inter-cluster communication. The problem that arises is how we can determined those border routers for a cluster among the nodes of this cluster, such that the network is connected and the transmission range required to be achieved from the border routers in order to have network connectivity is minimized.

Initially, in this paragraph we will present how we determine the border routers and in the following we will describe how we decide on the appropriate transmission range of each one of those. Our algorithm for the determination of border routers is based on the general idea that for a pair of clusters the nodes that we choose to act, as border routers are the pair of nodes that have the minimum distance among all the pairs of nodes between the two clusters. The algorithm that determines the border routers for each cluster is as follows:

$for\ i=1,\dots,K-1$
  $for\ j=i+1,\dots,K$
    Deteremine the $node_{ij}$ and the $node_{ji}$
    among all the nodes of cluster i and
    cluster j repsectively, such that
      $\min\left(dist(node_{ij}-node_{ji})\right)$
  end
end

The above algorithm determines the set

$$\mathbb{B}=\left\{\mathbb{B}_{C(1)},\mathbb{B}_{C(2)},\cdots,\mathbb{B}_{C(K-1)},\mathbb{B}_{C(K)}\right\}$$

where,

$$\mathbb{B}_{C(i)}=\left\{node_{ij}:\ \min\left\|node_{ij}-node_{ji}\right\|,\forall j\neq i\right\}$$

of border routers that are candidates for being responsible for the inter-cluster communications. Our task is to minimize this set of candidate nodes since with the above algorithm we have determined a border router per every other cluster. Obviously, we do not need this density in the inter-cluster connections, so we have to find the minimum set of border routers that ensure network connectivity (e.g., there is always a path from every cluster i to every cluster j ($i\neq j$)) subject to the minimization of the transmission range assigned to border routers for inter-cluster connectivity. The solution that we propose for this problem is described in the following paragraph.

D. Inter-Cluster Transmission Range Control and Minimization of Border Routers

Since we have the set $\mathbb{B}$ of border routers, we want to specify the minimum transmission range for each one of those such that they are fully connected. In order to reach to a solution we can handle set $\mathbb{B}$ as a single cluster of nodes and by applying the same algorithm as the one, which determines the minimum transmission range for intra-cluster connectivity we can determine the value of transmission range to be achieved by each candidate border node (e.g. we have to solve the TSP problem for the nodes in $\mathbb{B}$).

What we described above is the first step. The second step is to eliminate from the minimum distance path the border routers that are unnecessary. Those border routers are the ones that do not contribute to the inter-cluster communication, or in other words are the border routers that are essentially after the transmission range assignment from the first step, connected to other border nodes in their own cluster. We proceed to this elimination by checking the neighbors of the border routers. A border router

$b_k \in \mathbb{B}_{C(i)}$ is eliminated if its neighbors $b_{k-1}, b_{k+1} \in \mathbb{B}_{C(i)}$, too.

Obviously, by applying the same algorithm for determining the shortest path among the border routers (TSP) and eliminating the ones that do not contribute to the inter-cluster connectivity results in the elimination of the unnecessary border routers and the unnecessary inter-cluster communication links, since we assign to the border routers the shortest transmission range such that we have a fully connected network. The results on the transmission range savings that we get from the proposed algorithms along with results concerning the network connectivity and the border routers' assignments, are presented in the following paragraph.

RESULTS

We implemented the above described, sequence of steps that ensure full network connectivity by minimizing the transmission range to be achieved by the participating nodes. The benefits of applying those mechanisms are obvious in the following figures, which represent the resulting network connectivity when we apply clustering and transmission range control. We compare the latter with the corresponding network where we assume flat transmission range to ensure network connectivity. The following results were collected by assuming 40 nodes uniformly distributed in an area of (500m x 500m). The number of clusters we generated was 4.

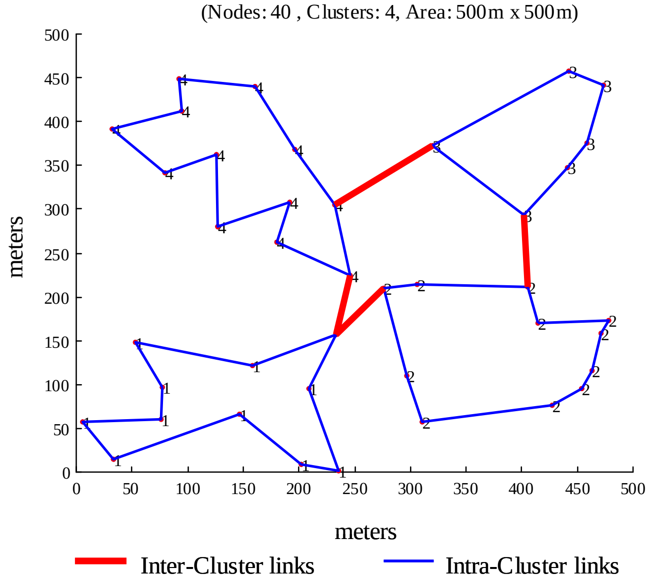

Figure 2: Network connectivity by applying clustering and transmission range control

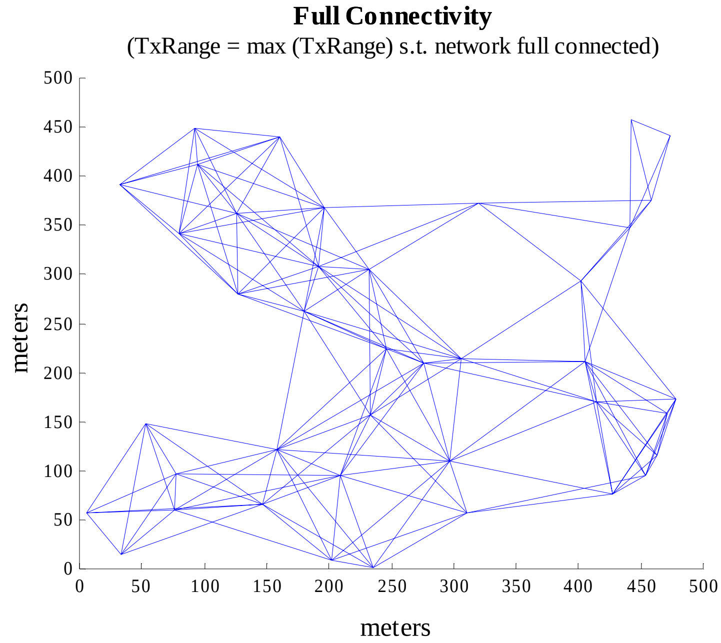

Figure 3: Full network connectivity with flat transmission range

Comparing figure 2 and 3 the benefits from applying the proposed methods are obvious, since the density of the links in second figure proves that a large number of links are unnecessary for achieving full connectivity and also that the assignment of flat transmission power to the nodes for full connectivity is characterized as inefficient.

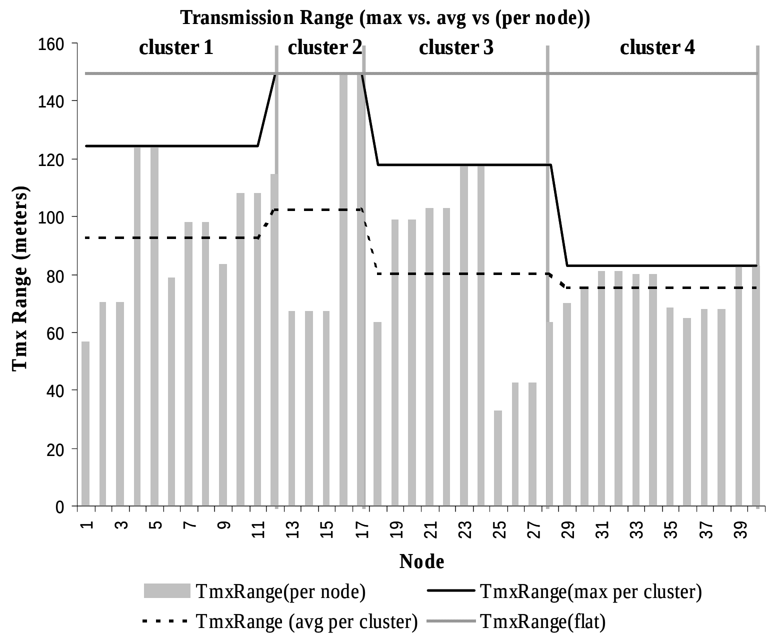

Figure 4: Transmission Range (max per cluster vs. avg. per cluster vs. node per cluster)

The above figure 4 is a representation of the transmission ranges assigned to the various nodes in the network such that the full connectivity is ensured and the transmission power is efficiently utilized. Those results correspond to the case of 4 clusters, and 40 nodes uniformly distributed in an area of (500m x 500m).

Also, in figure 4 we draw the maximum transmission range assigned, the maximum transmission range assigned per cluster, and the average transmission range per cluster in order to get a view of the benefits of using the combination of clustering with transmission control. By assigning less power for transmission to the nodes we conserve energy and we make the network more survivable. Also, the techniques proposed affect also the scalability of the network, since the generation of clusters creates an inherent hierarchy in the network. A final comment is that the smaller density of the communications links in the network helps the MAC protocol (especially if we assume 802.11) to perform better, since fewer nodes will compete for accessing the same media.

CONCLUSIONS

Obviously, the results that we collected by enforcing the proposed techniques for clustering and transmission range control is a convincing proof that those mechanisms have the potential to improve both the efficient utilization of the finite power of the mobile devices and improve the survivability and scalability of the mobile ad hoc networks by implying a hierarchical topology into the network. Furthermore, this is the first approach to enforce transmission range control through the clustering of the nodes and as we mentioned it is proven that those techniques proposed are promising and efficient.

Apart from the promising indications and results, we have to improve the techniques to respond fast and efficiently to topology changes. One important issue that requires investigation is the extension of the techniques mention above to become distributed, so they can fit better to dynamic environments like the MANETs are.

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