CLUSTERING FOR TRANSMISSION RANGE CONTROL AND CONNECTIVITY ASSURANCE FOR SELF CONFIGURED AD HOC NETWORKS*

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ABSTRACT

Ad hoc networks have been the new networking technology trend because of their promising characteristics. These characteristics fit better the requirements of today's army and the needs of today's commercial world. Most of the applications that have been referred in the bibliography assume devices that are of finite power. The latter is true because of the existing technology (web enabled cell phones, PDAs, laptops, PPCs). The goal for ad hoc networks is to accommodate light weight, battery powered portable devices. Because of the finite power limitation, we have to design efficient ways to use the existing power. A first step towards efficient utilization of power is to eliminate its unnecessary usage wherever possible. For a networking device, significant part of power is consumed for communications and more specifically for transmissions. In this work we focus on eliminating the transmission power consumed into the network subject to the network's connectivity. The assurance of network connectivity is essential in this problem since the usage of limited transmission power from the nodes may result in a partitioned network. We provide solutions to the efficient usage of transmission power by clustering the nodes based on their proximity and ensuring the intra-cluster and inter-cluster connectivity of the network. The algorithms presented in this paper achieve their objective as the collected results from their simulation show.

INTRODUCTION

In recent years there has been an increasing interest in ad hoc networks, because of their dynamic characteristics and their applications in the battlefield, in emergency cases and in the commercial world. A large number of researchers have focused on this topic trying to improve the efficiency, effectiveness and performance of those networks by identifying and proposing solutions to the 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 start failing fast and the network will partition. We have to introduce some ways to control the power consumed by the devices as long as they operate and perform their standard networking actions (e.g., routing). The power consumed depends on many factors like the power utilized from the operating system and the power consumed from transmitting and receiving packets. In this work we will focus only on controlling the transmission power of each node such that the network is connected and the utilized transmission power is minimized.

Since the transmitted power is proportional to the transmission range, we cluster the nodes based on their proximity. The nodes of a cluster communicate with each other on a regular basis (intra-cluster communication), so we want those nodes to be topologically close. When there is information that requires inter-cluster communication we let dedicated nodes (border routers - BRs) to forward this information among the clusters until it reaches the destination cluster. Based on the latter description one of the problems is not only to decide on clustering but also to select dynamically the BRs. The selection of BRs has to be done in such a way that the utilization of transmission power is improved. The connectivity of BRs is necessary for network connectivity, because if every cluster communicates with every other cluster then the network will be connected, given that the intra-cluster connectivity is ensured.

For the clustering of nodes we utilized simulated annealing (SA), which is a global optimization technique. The algorithm and characteristics of simulated annealing (SA) are described in section 3. In general, SA avoids local

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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 is related to the proximity of the nodes. In this work we assume that the positions of each of the nodes are known and can be utilized by SA. This information can be collected from GPS devices, attached to the nodes and can be stored in a database.

The selection of the Transmission Ranges to be assigned to each of the nodes is based on a heuristic algorithm, which also requires knowledge of the nodes' coordinates. Initially we apply the heuristic algorithm to each one of the generated clusters such that the transmission power required for intra-cluster connectivity is minimized. In order to ensure also network connectivity, it is necessary that the generated clusters are connected. After we have determined the set of candidate BRs, we apply the heuristic algorithm on this set, in order to decide the Transmission Ranges to be assigned on the BRs for inter-cluster connectivity. Description and characteristics of the heuristic algorithm are given in a subsequent section.

Even though the techniques we propose are based on a global optimization algorithm, we can apply this algorithm in the IP Autoconfiguration Suite (IPAS) [1] framework. 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). Inherently, IPAS has a module (Update Protocol - YAP) that collects network information into a centralized point and a central module (Adaptive Configuration Agent - ACA) that takes the configuration decisions. Taking advantage of this architecture, the Simulated Annealing algorithm can be hosted from the ACA module of IPAS.

In the following section we refer to some representative work related to the problem of clustering and transmission range control. In section 3 we present the simulated annealing algorithm, which is the basic gear to our proposed mechanisms. In section 4 we present the techniques and algorithms that we propose for clustering and transmission range control. By applying the clustering approach for controlling the transmission power and network connectivity, we obtain some very interesting results described in section 5. These results refer to the savings in transmission power by applying our mechanisms rather than using a common transmission range. Finally, in section 6 we conclude and describe future directions.

RELATED WORK

In this section we refer to some work done on the power control problem and on network clustering. The existing work related to the former problem comprises of techniques that try to identify the optimal transmit power to control the connectivity of the network. In [6], the power control problem is viewed as a network layer problem, and the COMPOW protocol is proposed. The work in [7] proposes, that each node has to adjust its transmit power such that its connectivity degree (number of one-hop neighbors) is bounded. ElBatt et. al. in [3], through the transmit power control, make an attempt to optimize the average end-to-end throughput by controlling the degree of the nodes. In [8] a distributed topology control algorithm is proposed. The latter technique is based on the utilization of direction information. Kawadia and Kumar in [12] propose the CLUSTERPOW algorithm, which aims on the increase of network's capacity by increasing spatial reuse. The algorithm consists of simply using the lowest transmit power level p, such that the destination is reachable (in multiple hops) by using power levels no larger than p.

By clustering, we organize the nodes hierarchically, so that they belong into similarity groups based on certain decision attributes, like the node IDs [5], or a small neighborhood of certain nodes elected as cluster-heads [4]. The selection of cluster-heads or the cluster set up phase utilizes metrics, such as transmission power, mobility, node degrees, node IDs or more elaborate node weights, which combine the above metrics, as in DCA [10], and in WCA [11]. The reasons for generating clusters could be the optimization of resources (i.e., battery power, available bandwidth), the lower complexity of addressing and network management, or the reduction of the overhead for route discovery.

SIMULATED ANNEALING

Simulated annealing (SA) [2] has been widely used for tackling different combinatorial optimization problems. The general algorithm is described below.

The SA algorithm has advantages and disadvantages, compared to other global optimization techniques. Among its advantages are the relative ease of implementation and the ability to provide reasonably good solutions for most problems (depending on the cooling schedule and update moves used). SA is a robust technique; however it does have some drawbacks.

Step I: Define
Initial Temperature T_0
Number of Clusters K
Number of Generations $N(T)$ per Temperature T
Step II: Initialization
Temperature $T = T_0$
Generate a clustering C
Calculate the cost $E = Cost(C)$
Define $E^* = E$ and $C^* = C$
Step III: *While* (stop criterion) $\neq$ satisfied ($T \neq 0$)
Step IV: *While* (number of generations) $< N(T)$
Generate a new clustering C
Calculate the new cost $E = Cost(C)$
Calculate the difference $\Delta E = E - E^*$
if $\Delta E \leq 0$ then $C^* = C$ and $E^* = E$
if $\Delta E > 0$ then
choose a uniformly distributed number $r \in [0,1]$
if $r < e^{-(\Delta E / T)}$ then $E^* = E$ and $C^* = C$
else (do not accept C^*)

Step V: Update the temperature
$T = CoolingSchedule(T, T_0, \text{number of Generations}(t))$ [1]
Step VI: Go to Step 3

To obtain good results the update moves and the various tunable parameters used (such as the cooling rate) need to be carefully chosen, 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 [9].

CLUSTERING AND TRANSMISSION RANGE CONTROL ALGORITHMS

In this section we will describe the algorithms and techniques we propose for clustering and transmission range control. Furthermore, the algorithms we propose achieve intra-cluster and inter-cluster connectivity. The algorithm for the selection of BRs is also presented.

[1] In our implementation we used the geometric cooling schedule, which is given from the following expression:

$$T = (0.99)^t T_0$$

A. Clustering of Nodes

For the clustering of the nodes we utilized the SA in order to get an optimal solution. The inputs to the optimization method are the position coordinates of the nodes, which are utilized by 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 $N(T)$ 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 problem is:

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

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

By fitting the above cost function to SA, a corresponding clustering map is generated. The latter step is followed by the selection of the transmission range to be assigned on each one of the nodes in a cluster. The objective is to achieve intra-cluster connectivity by improving also the transmission power utilization.

B. Intra-Cluster Transmission Range Assignment

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

$$f = \min \sum_{j=1}^{|C_i|} TmxRange(node_{ij})$$
subject to intra-cluster connectivity

Since the above problem requires an exhaustive search for the assignment of transmission ranges to the nodes of a cluster, we propose a heuristic algorithm. The objective is to assign to each node in the cluster the lowest possible transmission range so that the cluster remains connected.

Definition **Connected Cluster**: A cluster consisting of the set $\mathbb{S}$ of nodes is connected if $\forall \text{node}_i, \text{node}_j \in \mathbb{S}$ and $i \neq j$, there is always a path from node_i to node_j without going outside the cluster.

The algorithm for the minimum transmission range selection for intra-cluster connectivity, operates on each cluster individually. The algorithm is described below and assumes that we operate on cluster C_k:

Step I: Order the distances of each pair of nodes in the cluster in ascending order. Store it in the vector *SortedPairDistances*
Step II: Pick the first entry (lowest distance) from the *SortedPairDistances* and then store the corresponding pair of nodes in the *ConnectedList list* and the link in the *LinksList* list. Remove this entry from the *SortedPairDistances.*
Step III: Until the $|ConnectedList| == |C_k|$
Step IV: Pick the first entry – link $(\text{node}_i, \text{node}_j)$ from the *SortedPairDistances* such that one of the following is satisfied:

1. $\text{node}_i \in ConnectedList$ & $\text{node}_j \notin ConnectedList$
2. $\text{node}_i \notin ConnectedList$ & $\text{node}_j \in ConnectedList$

Remove this entry from the *SortedPairDistances*
Step V: Add the nodes $(\text{node}_i, \text{node}_j)$ in the list *ConnectedList*
Step VI: Add the link to the *LinksList* list
Step VII: Go to Step III

Upon the completion of the above algorithm the selected links of the connected cluster are stored in *LinksList* along with their distances. A sample entry of this list is the following:

node_i	node_j	$dist_{ij}$

Based on the entries of the *LinksList* we determine the Transmission Range to be assigned to each participating node in the cluster. The selection algorithm follows:

```
for (each entry of the form (node_i, node_j, dist_ij))
{  if (node_i has not been assigned a TxRange_i)
      TxRange_i = dist_ij
   else {
      if (TxRange_i < dist_ij)
         TxRange_i = dist_ij
   } }
```

In general terms among all the distances in the *LinksList* of a node to other nodes in the cluster the algorithm selects the maximum of them. Following this logic we end up having bidirectional links and the cluster is ensured to be connected.

After having applied the above algorithms each node in the cluster has been assigned a Transmission Range that can be translated to a specific Transmission Power. Using the specific range the nodes can deliver packets in any node in the cluster. Apart from the intra-cluster connectivity, we have to ensure network connectivity. For connections outside the cluster (inter-cluster connectivity) responsible are the Border Routers (BRs). The BRs are selected among the border nodes of the cluster and are the exits and gates from and to the cluster. In the following paragraphs we present the selection of BRs algorithm and the assignment of Transmission Range to them such that inter-cluster connectivity, which is necessary for the network connectivity is ensured.

C. Selecting 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 inter-cluster connectivity. The clusters communicate with each other through a set of BRs. The problem that arises is how we can select those BRs, such that the network is connected and the transmission range required for inter-cluster communication is minimized.

Initially, in this section we will present how we select the BRs and in the following one we will describe how we decide on the appropriate transmission range of each one of those. Our algorithm for the selection of BRs is based on the 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,...,K-1
    for j= i+1, ...,K
        determine the node_ij and the node_ji
        among all the nodes of cluster i and
        cluster j respectively, such that
            min(dist(node_ij – node_ji))
    end
end
```

The above algorithm determines the set

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

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 select the minimum set of BRs that ensure inter-cluster connectivity (e.g., there is always a path from every cluster i to every other cluster $j\,(i \neq j)$) subject to the minimization of the transmission power usage. The solution that we propose for this problem is described in the following section.

D. Inter-Cluster Transmission Range Assignments

Since we have the set $\mathbb{B}$ of the candidate border routers, we want to assign to them transmission ranges such that all clusters are connected. For that purpose we will reuse the algorithm presented above for the assignment of transmission ranges to the nodes in a cluster such that intra-cluster connectivity is ensured. We can view the set $\mathbb{B}$ of candidate border routers as a cluster, so the above algorithm is applied without any major modification. The only modification to the algorithm is the termination condition. For the intra-cluster connectivity the algorithm terminates when all nodes in the cluster are connected but for inter-cluster connectivity the algorithm terminates when all clusters are connected.

Following the set of algorithms above we end up with a connected hierarchical structured network and at the same time we have achieved to lower the transmission power consumed from the participating nodes. The validation of the latter statement is done in the next section, where we present simulation results related to the algorithms proposed.

RESULTS

We implemented the algorithms that ensure network connectivity by minimizing the transmission range utilized by the participating nodes. The gain from the application of those algorithms is presented in the following figures. Initially, we compare the network topology resulting from our algorithms with the case of assigning the lowest common transmission range to the nodes such that the network remains connected. For the experiments we assumed 100 nodes uniformly distributed in an area of (1000m x 1000m). The number of clusters being generated is 6.

By comparing figures 1 and 2 the gain from applying the proposed methods is obvious, since the density of the links in the latter figure proves that a large number of links are unnecessary for achieving connectivity. Most of those links have been eliminated in figure 1, while the network still remains connected, which proves the effectiveness of our methods.

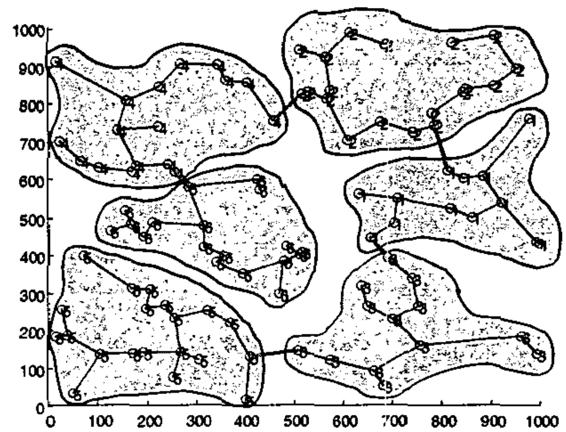

Figure 1: Network Topology by applying clustering and transmission range control

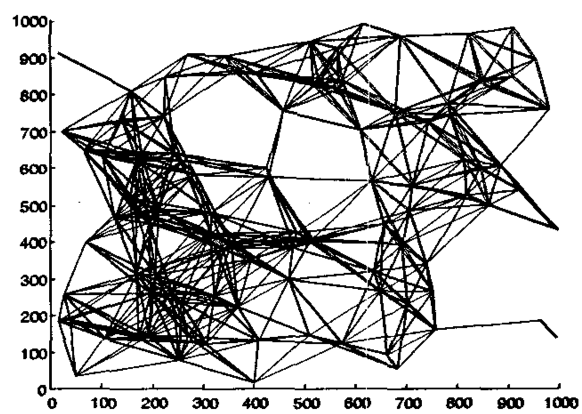

Figure 2: Network connectivity with common TxRange

The following figure is a comparison of the lowest (e.g. such that the network remains connected) common transmission range scenario with the scenario of variable transmission ranges assigned to the various nodes in the network such that connectivity is ensured and the utilization of transmission power is minimized. Those results correspond to the case of 6 clusters, and 100 nodes uniformly distributed in an area of (1000m x 1000m).

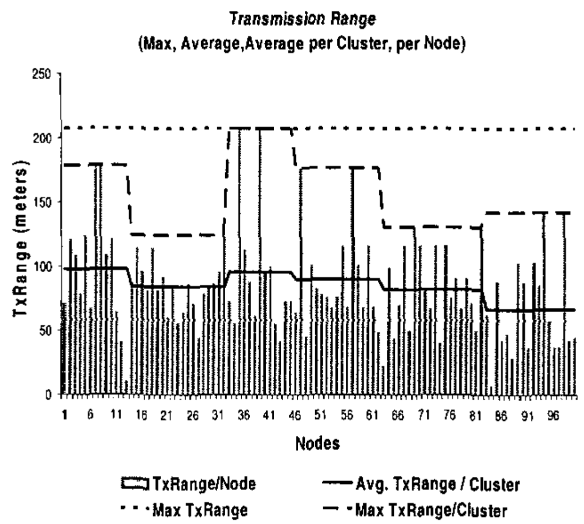

Figure 3: Transmission Range (max per cluster vs. avg. per cluster vs. node per cluster)

We plotted the maximum transmission range assigned (e.g., equals the lowest common transmission range required, so that the network is connected), the maximum transmission range assigned per cluster, and the average transmission range per cluster. The gain is obvious, when we compare the average transmission range assigned with the maximum one. By lowering the transmission power of the nodes we conserve energy and we make the network more survivable. Also, the techniques proposed affect the scalability of the network, since the generation of clusters creates an inherent hierarchy. A final important comment is that the smaller the density of the communications links the better it is for the MAC protocol (especially if we assume 802.11b), since fewer nodes will compete for accessing the shared media.

CONCLUSIONS

The results that we collected by simulating the proposed mechanisms are a convincing proof that they utilize efficiently the finite power of the participating devices and improve the survivability and scalability of the ad hoc networks. The latter is achieved by generating a hierarchical topology into the network through the clustering process. The novel approach we propose has been proven effective as the evaluation of the simulation results collected shows. For the improvement of the described mechanisms, we have to modify/extent the techniques in order to respond fast and efficiently to the topology changes. One way to succeed on the latter is to make the techniques distributed, so they can fit better to dynamic environments like MANETs.

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