Connectivity aware topology control in ad hoc networks using mobile routers

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Abstract: - In order to provide an acceptable link quality and to improve the network performances in ad hoc networks, it is essential to add some control functions in the environment. This paper discusses a connectivity aware topology control strategy that uses a set of dedicated mobile routers to improve the network connectivity. The main issue consists in determining the best geographical location for the mobile routers in order to provide connectivity to a maximum number of nodes. Our study is focused on system modeling. We set the problem as an integer linear program (ILP), formulated using the AMPL language, and we solve it with a representative public-domain solver. We present several simulation results under various topological conditions that demonstrate the efficiency of our approach.

Key-Words: - Ad hoc networking, Connectivity, Topology control, Integer linear programming.

1 Introduction

An ad hoc network consists of a set of mobile wireless nodes communicating between them. When equipped with a wireless routing protocol, multihop communications are possible. In this case, the nodes act as routers to relay communications. Thus the ad hoc network is defined as a distributed system. An ad hoc network can be autonomous, also called infrastructure-less or interconnected to an infrastructure.

Topology control [1] [10] in ad hoc networks aims at maintaining a specified topology by controlling the links to be included in the network. The goal is to achieve a set of objectives such as: reducing interference or probability of detection, reducing energy consumption, and increasing the effective network capacity.

In this paper, we propose to control the ad hoc network topology using mobile routers. These mobile routers aim to build a robust connected backbone with high quality wireless links. The network performance can be enhanced and maintained at a minimum cost as a result of backbone construction. In our solution, two different network configurations are studied: an autonomous ad hoc network and a network interconnected to an infrastructure.

Our approach is original for several reasons. First, it consists in deploying a set of mobile routers based on the communicating mobile nodes' positions. It aims to ensure a global connectivity with a maximum overall quality, given the number of routers available. Secondly, we override the battery consumption problem of ad hoc networks since the routers [14] that will be used have a high autonomy. Moreover, they prevent other nodes from serving as routers and therefore reduce their battery level. In our proposition, the mobile routers' set is known in advance. Therefore no election algorithm for backbone construction is needed.

The main contribution of this work resides in the formulation of the system modeling that is validated using several network topologies. We consider the problem as an integer linear program, and formulate it using the AMPL language [9].

Our approach can be used for other applications, such as wireless infrastructure network dimensioning, when the average location of the users is known.

The remainder of this paper is organized as follows. In the next section we summarize the related work. In section 3, we present the system model and problem specifications. The problem of mobile router deployment is formulated in section 4. We consider the two configurations (infrastructure-less and infrastructured ad hoc network). In section 5, we describe the simulation model and analyze the results obtained, followed by conclusion and future work.

2 Related work

Topology control using energy consumption as a metric is a recent focus of wireless ad hoc network research. Due to the limited energy capacity of mobile nodes, the topology control algorithms are often used to manage energy consumption issues [11].

[15] studied the energy efficient QoS topology control problem that aims at determining a network topology that meets QoS requirements while minimizing the maximum transmitting power of nodes. When traffic demands cannot be splitted, the problem is formulated as an integer linear programming problem, where delay and bandwidth are considered. In the other case, when traffic demands are splittable, the problem was formulated as a mixed integer programming problem, using bandwidth requirements only.

Ad hoc network topology may also be managed using cluster based approaches [8] [1], in which an interconnected subset of the network nodes, called cluster heads, is elected to serve as a backbone. Every mobile node is then associated with a cluster-head. Such a mechanism facilitates topology maintenance.

Maximum covering problems arise in a variety of practical settings such as graphics, medical treatment, and spatial query optimization. In [2], a heuristic method for solving the maximum covering problem, called greedy randomized adaptive search procedure, is proposed. The quality of the solution is measured using an upper bound obtained by the resolution of a linear programming problem.

Coverage and deployment were also studied recently in the sensor networks context [6] [13]. A deterministic coverage can be obtained when a static network must be deployed in a predefined coverage area. This problem is very similar to the art gallery problem (AGP) [5]. A grid based sensor placement for effective surveillance and target location was proposed in [6]. [13] proposed an optimal polynomial time algorithm for solving the best and worst case coverage. This algorithm is based on a combination of computational geometry and graph theory techniques, specifically the Voronoi diagram and graph search algorithms.

3 Context and system modeling

An ad hoc network is said to be *connected* if and only if there is a path between each pair of mobile nodes. Connectivity then depends on the existence of routes. It is affected by any changes in the topology due to mobility (link failure, route updates, rerouting, etc.).

In our approach, to achieve connectivity, we aim to solve the problem of deploying a set of mobile routers, characterized by a high autonomy and capacity, in the network area. The deployment is performed to create a connected backbone.

In the following, we will describe the environment characteristics and system modeling. We present then the deployment problem of mobile routers depending on connectivity and environment constraints.

3.1 System model

In this work, we consider an ad hoc network consisting of mobile stations and mobile routers. The network topology is hierarchical and based on a mobile backbone to be formed by the mobile routers. Each node must be able to obtain its own coordinates by some means (triangulation or GPS [12] for example).

We consider:

- N mobile stations (MS) to be covered by M mobile routers (MR), all located on a plane rectangular field.
- Each mobile station is represented by the geometrical point P_i with coordinates (x_i, y_i),
- Each mobile router is represented by the geometrical point Q_i with coordinates (a_i, b_i).
- R_r is the mobile router transmission range,
- R_m is the mobile station transmission range,
- $d(J,K)$ is the Euclidian distance between nodes J and K.

3.2 Assumptions and hypotheses

In order to be covered by a router, the distance between a mobile station and its closest mobile router must be less than R_m.

Two mobile routers are adjacent (are neighbors) if the distance between them is less than R_r.

We define:

$x_{\min} = \min(x_i)$, $x_{\max} = \max(x_i)$ for $i = 1,..., N$

$y_{\min} = \min(y_i)$; $y_{\max} = \max(y_i)$ for $i = 1,..., N$

where: $(x_{max} - x_{min}) \times (y_{max} - y_{min}) m^2$ represents the area surface where the mobile routers are deployed.

In the following, we consider two network configurations: an autonomous ad hoc network and network interconnected to an infrastructure via a fixed gateway. We will see that the problem formulation is not the same for the two cases. In the second case, at least one link to the fixed gateway must be guaranteed.

3.3 Router deployment in an autonomous ad hoc network

We aim to determine the location of the mobile routers so that a maximum number of mobile stations may be covered by a set of connected mobile routers. The number of mobile routers is known in advance.

We first formulate the problem in terms of cost minimization under connectivity constraints. We then develop an integer programming model to solve the mobile routers placement problem that achieves network connectivity.

Variables:

For $i = 1,\dots,N$ and $j = 1,\dots,M$,

$$\text{Let } \lambda_{i,j} = \begin{cases} 1 & \text{if } d(P_i, Q_j) \le R_m \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

In other words, $\lambda_{i,j}$ = 1 if the mobile station MS_i is covered by the mobile router MR_j. $\lambda_{i,j}$ denotes the connectivity between mobile node MS_i and mobile router MR_j

For $i, j = 1,\dots,M$,

$$\text{Let } \mu_{i,j} = \begin{cases} 1 & \text{if } d(Q_i, Q_j) \le R_r \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

$\mu_{i,j} = 1$ if MR_i is an adjacent router of MR_j in the mobile routers' backbone. $\mu_{i,j}$ denotes the connectivity between two mobile routers MR_i and MR_j .

The backbone network may be represented as a graph in which the positions of the routers correspond to the Q_j , *j=1,…, M* and the adjacency matrix is ($\mu_{i,j}$) , *i, j=1,…, M*

For $i = 1,\dots,N$, let $\tau_i = 1$ if MS_i is covered by at least one mobile router, that is, if there exists at least one mobile router MR_j for which $\lambda_{i,j}$ = 1.

To formulate the backbone connectivity problem, we will check that it is possible to create a route from any mobile router *s* (*s=2,…, M*) to the mobile router number 1.

Hence, we define $z^s_{i,j}$ as: $z^s_{i,j} = 1$ if the route from the router *s* to the router number 1 goes through the link (i, j), otherwise $z^s_{i,j} = 0$.

The optimization problem consists in finding:

- the locations of the mobile routers Q_i (a_i , b_i), for $i = 1,\dots,M$,
- $\lambda_{i,j}$ values, for $i = 1,\dots,N$ and $j = 1,\dots,M$
- and $\mu_{i,j}$ values, for $i, j = 1,\dots,M$

while maximizing the following function:

$$\sum_{i=1}^{N} \tau_i - \sum_{i,j,s} z^s_{i,j} \quad (3)$$

The function terms denote the total number of mobile node connected to a mobile router, while the backbone formed by the mobile routers still connected.

Under the following conditions:

a) Domain constraints to define the area delimitation, and binary variables:

$$a_i \in [x_{min}, x_{max}], i = 1,\dots,M \quad (4)$$

$$b_i \in [y_{min}, y_{max}], i = 1,\dots,M \quad (5)$$

$$\tau_i \in \{0,1\},\ i = 1,\dots,N \quad (6)$$

$$\lambda_{i,j} \in \{0,1\}, i = 1,\dots,N,\ j = 1,\dots,M \quad (7)$$

$$\mu_{i,j} \in \{0,1\},\ i, j = 1,\dots,M \quad (8)$$

$$z^s_{i,j} \in \{0,1\},\ i, j = 1,\dots,M,\ s = 2,\dots,M \quad (9)$$

b) Coverage constraints represent the connectivity between mobile nodes and mobile routers:

- $\lambda_{i,j} = 1 \Rightarrow d(P_i, Q_j) \le R_m,\ i = 1,\dots,N,\ j = 1,\dots,M$ (10)
- $\mu_{i,j} = 1 \Rightarrow d(Q_i, Q_j) \le R_r,\ i, j = 1,\dots,M$ (11)
- $\lambda_{i,j} \le \tau_i \le \sum_{k=1}^{M} \lambda_{i,k},\ i = 1,\dots,N,\ j = 1,\dots,M$ (12)

c) Routes constraints (backbone connectivity): These constraints ensure the existence of a route between each two mobile routers:

- $z_{i,i}^{s} = 0$, $i, s = 1, ..., M$ (13)
- $z_{i,j}^{s} \le \mu_{i,j}$, $i, j, s = 1, ..., M$ (14)
- $\sum_{j=1}^{M} z_{i,j}^{s} - \sum_{j=1}^{M} z_{j,i}^{s} = 0$, if $i \neq s, i \neq 1; i,s = 1, ..., M$ (15)
- $\sum_{j=1}^{M} z_{i,j}^{s} - \sum_{j=1}^{M} z_{j,i}^{s} = -\theta^{s}$, if $i = s$; $i, s = 1, ..., M$ (16)
- $\sum_{j=1}^{M} z_{i,j}^{s} - \sum_{j=1}^{M} z_{j,i}^{s} = \theta^{s}$, if $i = 1$; $i, s = 1, ..., M$

  where: $\theta^{s} = 1$ if $s \neq 1$, $s = 1, ..., M$ (17)

Given that, when the transmission range of the mobile routers R_r and mobile nodes R_m are fixed, we note that the problem complexity depends mainly on the mobile nodes number, and the surface area.

3.4 Router deployment in an Ad hoc network interconnected to an infrastructure

When the ad hoc network is considered as an extension of an existing infrastructure (it constitutes a means to access the fixed network), the model must take into account the fact that at least one mobile router is connected to the infrastructure. The problem formulation is slightly different from the autonomous ad hoc network. Given that every router must have a route to the gateway, it is sufficient to consider the gateway as the $M+1^{th}$ router constituting the backbone, having a predefined position. That is, $M+1$ mobile routers are considered in the model, we simply need to add a gateway position constraint that can be expressed as follows:

$$\begin{cases} a_1 = x_{gateway} \\ b_1 = y_{gateway} \end{cases} \quad (18)$$

Hence, the problem can still be formulated as an ILP problem with this additional constraint and router number parameter. The network backbone connectivity still satisfied following the constraints defined for the autonomous ad hoc model.

4 Experiments and results

In this section, the models formulated above are tested using simulations. We will show that mobile routers can be efficiently deployed in the environment depending on the network topology and configuration (autonomous or not).

To determine the mobile routers positions in the network area, we solved the formulated problems using the FortMP [4] solver available on the NEOS server [3]. The input files submitted to this solver, were described using the AMPL language [9].

In these simulations, we used a set of network topologies, while varying the number of mobile nodes, the number of mobile routers, the surface area, and the transmission range of mobile routers. The impact of these parameters on the network connectivity is shown. In addition, the optimal number of mobile routers required to cover a network is studied. The optimal number of mobile routers is the number of routers needed to guarantee the connectivity of more than 95% of mobile nodes in the network.

Fig.1 shows the mobile routers deployment in an autonomous ad hoc network with 100 mobile nodes randomly located in an area of size $1000 \times 1000 m^2$. For this topology, using a transmission range of the mobile router of 220 meters and a mobile node transmission range set to 150 meters, 11 mobile routers are deployed. Following the optimization results, each router is placed so that to maximize the number of directly attached (one hop neighbors) mobile nodes. Local connectivity is guaranteed in each cluster (with a mobile router as a cluster head). Furthermore, the mobile routers are connected.

In Fig.2, following the area limits constraints (field of size $800 \times 800\ m^2$), and number of mobile nodes (50), Rm=150 m, Rr=200m; 7 mobile routers are required to achieve connectivity in the ad hoc network. We illustrate that depending on the configuration of the network: infrastructure or infrastructure-less network, the mobile routers deployment is different. Note that in the interconnected network, one of the mobile routers is deployed near the fixed gateway. That is done to satisfy the connectivity of the backbone network (to connect the two clusters) and to provide an extension of the fixed network (to achieve the connectivity to the fixed gateway constraint).

As shown in Fig.1 and Fig.2, the backbone network formed by mobile routers depends on the ad hoc network configuration and topology.

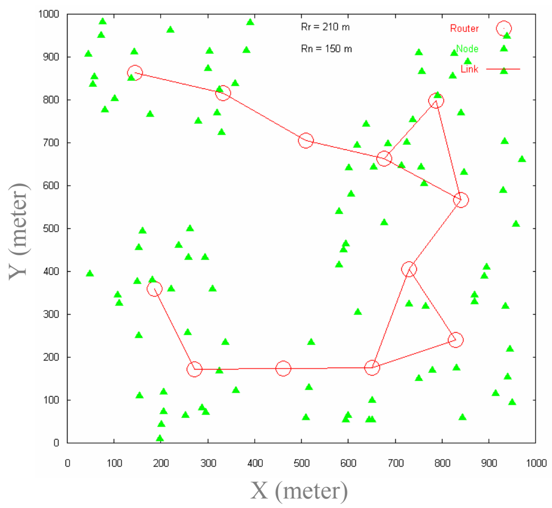

Fig.1 Mobile routers deployment (autonomous network)

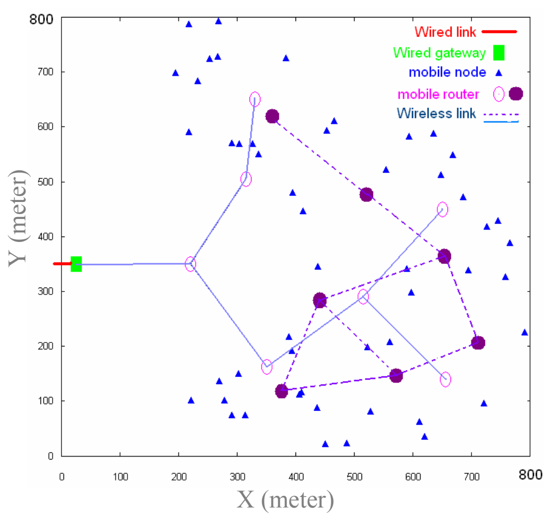

Fig.2 Mobile routers deployment: in infrastructured and infrastructure-less network

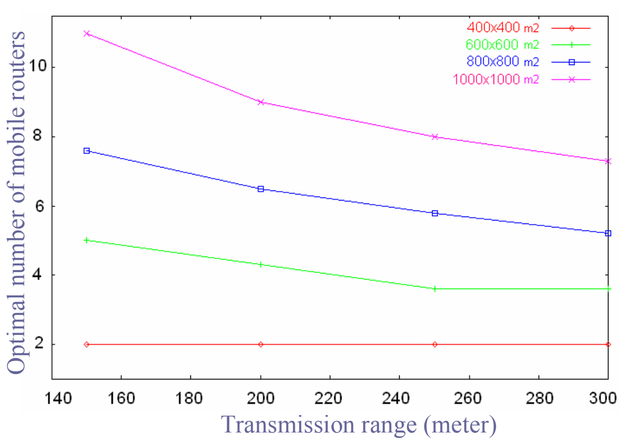

Fig.3 Optimal number of mobile routers Vs transmission range Vs field size

In Fig.3, the optimal number of mobile routers required to achieve connectivity in an ad hoc network is studied. 20 networks with 30 mobile nodes were randomly generated in respectively a field of size $400\times400m^2$, $600\times600m^2$, $800\times800m^2$, and $1000\times1000m^2$. For each field, the transmission range of the mobile routers was varied. Results show that the optimal number of mobile routers needed to ensure connectivity is a function of: the field size (proportional), the number of nodes (proportional) and the mobile routers' transmission range (disproportional). On the one hand, 8 mobile routers with a transmission range of 250 meters are required to achieve connectivity in a field of $1000\times1000m^2$; this number decreases with higher transmission ranges. On the other hand, the optimal number needed in a small field still reduced (2 routers only for field $400x400m^2$ independently of their transmission range (Fig.3)).

However, due the energy constraint in ad hoc network, mobile routers using a high transmission range consume more power (therefore, they have less autonomy) and decrease the network capacity.

In ad hoc networks, the per node throughput under optimal circumstance is given as in [7]: $\Theta\left(\frac{W}{\sqrt{n}}\right)$, where n is the number of mobile nodes, and W the bandwidth capacity. Hence, the per node throughput decreases while the number of nodes increases. In our situation, having a router with a high transmission range increases the number of mobile nodes attached to it. As a result, the per cluster node number is increased, degrading thus the per node throughput.

5 Conclusion

We have presented a new connectivity based topology control scheme for ad hoc networks. We proposed to deploy a set of high capacity mobile routers that form a backbone network depending on the existing network topology, in order to provide an optimal connectivity. Two situations have been studied: an autonomous network and a network interconnected to a fixed infrastructure. The problem was formulated as an integer linear programming problem and we presented the results obtained with this model.

The next step of this work concerns:

- The dynamic deployment of mobile router following the network topology variations,

- Router deployment oriented quality of service constraints (limit network backbone diameter)
- An experimental study to evaluate this approach, using a localization approach, where a refinement phase of mobile routers positions will be needed, taking into account signal power levels as a metric.

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