Improving ad hoc network performance with backbone topology control

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Abstract- **An important means to provide connectivity in areas where no access point is directly available is ad hoc networking. However, situations may occur where the connectivity of a set of nodes cannot be guaranteed (if they are too far apart); moreover, no QoS can be offered since the number of hops and the signal quality (thus the throughput) cannot be controlled. Therefore, we propose to deploy a controlled backbone in the ad hoc environment using movable mobile routers. This paper concentrates on two fundamental problems: on the one hand, global connectivity of the network is investigated, and on the other hand, we elaborate mechanisms that allow QoS support by setting an upper bound on the number of wireless hops. We describe the Mixed Integer Linear Programming (MILP) models for these deployment policies with respect to the constraints within these environments. Our approach suggested for backbone topology control allows one to achieve an efficient usage of resources.**

Keywords- ad hoc networking, connectivity, QoS, topology control, mixed integer linear programming.

I. INTRODUCTION AND RELATED WORK

An ad hoc network is a flexible and distributed system in which mobile nodes may act as routers relaying wireless communications. An ad hoc network can be autonomous, also called *infrastructure-less* or interconnected to an infrastructure (*infrastructured*). Due to the inherent mobility within the environment, network topology plays a key role on routing and network performance.

Topology control for ad hoc networks [11] [12] [15] is a recent focus in ad hoc networks. It is often based on the transmission power adjustment and aims at maintaining a specific network topology by controlling which links should be included in the network to achieve a set of session-specific objectives (such as reducing interference, reducing energy consumption or increasing the effective network capacity). These control techniques are centralized or distributed. In the centralized topology control algorithms [2] [11], a central entity computes the transmission power using node's position in order to achieve a topology with a strong connectivity. In the distributed algorithms [7] [12], mobile nodes adjust their transmission power according to local information to maintain a desired number of connected neighbors. However, in such approaches, QoS metrics are not considered.

Another approach to manage ad hoc network topology is based on the use of a subset of the network nodes to serve as a backbone supporting some functionalities [9] [1]. It is often called cluster based protocol, and consists in electing a set of cluster heads, every mobile node being associated to a cluster-head. Cluster election reduces topology maintenance in ad hoc networks. However, it has a negative impact on the cluster-heads, because a cluster-head consumes its energy more quickly than a normal node.

In [5], a mobile backbone network based architecture is introduced using two classes of network nodes: regular nodes using a single module radio with limited communications and data processing capabilities; and Backbone Capable Nodes (BCN) that use multiple radio modules. A subset of BCNs is periodically selected to meet quality of service objectives.

We proposed in [3] an intelligent ad hoc network providing connectivity, and performing terminal differentiation (link capacity, batteries and CPU). The network uses a set of autonomous mobile routers [14] that do not have mobility or resources issues. We have shown that the combination of cross-layer QoS and high quality wireless routing drastically improves the performance in the network, with real-time services support.

[8] proposed to enhance a sensor network by deploying a set of mobile 'swarms'. A swarm is a group of nodes having higher capabilities, and sharing the same mobility pattern. Once there is a hot spot, a swarm is directed to the intended area.

In this paper, we propose to control the ad hoc network topology through the deployment of dedicated mobile routers [14] depending on the nodes' locations. Thus, the network topology is hierarchical and based on a stable high quality mobile backbone formed by mobile routers having a long autonomy. Each node must be able to obtain its own coordinates by some means (triangulation or GPS [13] for example). We strive for one of the following goals, depending on the deployment policy:

- achieve a strong connected backbone, for global network connectivity,

- provide a QoS oriented topology control, by reducing the backbone network diameter, so that the maximum number of hops from a source to a destination is bounded. The use of classical QoS mechanisms combining layer 2 and layer 3 schemes may then be envisaged since the environment is stable enough.
Both infrastructured and autonomous ad hoc network configurations are considered in our study

The deployment in a dynamic environment, with a time varying network topology, will be studied in a future work.

In the next section, we describe the system model and formulate the problems of mobile router deployment to achieve connectivity or limited backbone diameter. The deployment in infrastructured network is then presented. In section IV, we provide some simulations and analyze the obtained results.

II. SYSTEM MODELING

A. Connectivity aware topology control

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

In order to achieve connectivity, we need to determine the locations of the mobile routers that maximize the number of covered mobile nodes. The deployment must ensure a connected backbone.

The parameters

We consider:

- N mobile stations (*MS*) to be covered by M mobile routers (*MR*), all located on a flat rectangular field of surface AxB.
- each mobile node MS_i is represented by the geometrical point P_i with coordinates (x_i, y_i),
- each mobile router MR_j is represented by the geometrical point Q_j with coordinates (a_j, b_j).
- R_r denotes the mobile router transmission range,
- R_m denotes the mobile station transmission range,
- $d(J,K)$ denotes the Euclidian distance between geometrical points J and K.

In order to be covered by a router, the distance between a mobile station and its closest router must be less than R_m. Two mobile routers are neighbors (i.e. adjacent in the backbone network) if the distance between them is less than R_r.

We define:

$$x_{min} = \min_{1\le i\le N}(x_i),\; x_{max} = \max_{1\le i\le N}(x_i)$$
$$y_{min} = \min_{1\le i\le N}(y_i);\; y_{max} = \max_{1\le i\le N}(y_i)$$

Variables:

For $i = 1,...,N$ and $j = 1,...,M$,

(a_j, b_j) denote the router's coordinates,

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

In other words, $\lambda_{i,j} = 1$ iff the mobile station MS_i is covered by the mobile router MR_j (ensures the connectivity between mobile node MS_i and mobile router MR_j)

For $i, j = 1,...,M$,

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

$\mu_{i,j} = 1$ iff MR_i is an adjacent router of MR_j in the mobile routers' backbone (ensures the connectivity between two mobile routers MR_i and MR_j)

The backbone network may be represented as a graph whose vertices represent the mobile routers, and whose the adjacency matrix is ($\mu_{i,j}$), $1 \le i, j \le M$

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

To check the backbone (formed by mobile routers) connectivity, we will test whether it is possible to create a route from any mobile router MR_s ($s=2,..., M$) to the router number 1 (MR_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

- find the locations of the mobile routers Q_i (a_i, b_i), for $i = 1,...,M$,

the $\lambda_{i,j}$ values, for $i = 1,...,N$ and $j = 1,...,M$

and the $\mu_{i,j}$ values, for $i, j = 1,...,M$

that maximize the following function:

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

$\sum_{i=1}^{N} \tau_i$ counts the total number of mobile nodes covered by a mobile router (which we want to be as high as possible),

We subtract $\sum_{i,j,s} z^s_{i,j}$ to force routes to be as short as possible in the backbone network.

Under the following conditions

a) Domain constraints

$$a_i \in [x_{min}, x_{max}],\; i = 1,...,M$$
$$b_i \in [y_{min}, y_{max}],\; i = 1,...,M$$
$$\tau_i \in \{0,1\},\; i = 1,...,N$$

$\lambda_{i,j} \in \{0,1\}, i = 1,...,N, \ j = 1,...,M$

$\mu_{i,j} \in \{0,1\}, \ i, j = 1,...,M$

$z^s_{i,j} \in \{0,1\}, \ i, j = 1,...,M, \ s = 2,...,M$

b) Coverage constraints (in order to ensure the connectivity between mobile nodes and mobile routers)

- $\lambda_{i,j} = 1 \Leftrightarrow d(P_i, Q_j) \le R_m, \ i = 1,...,N, \ j = 1,...,M$

(Node MS_i is covered by router MR_j)

- $\mu_{i,j} = 1 \Leftrightarrow d(Q_i, Q_j) \le R_r, \ i, j = 1,...,M$

(Router MR_i is connected to router MR_j)

- $\lambda_{i,j} \le \tau_i \le \sum_{k=1}^{M} \lambda_{i,k}, \ i = 1,...,N, \ j = 1,...,M$

c) Route constraints

- $z^s_{i,i} = 0, \ i, s = 1,...,M$
- $z^s_{i,j} \le \mu_{i,j}, \quad i, j, s = 1,...,M$

(No traffic exchange between MR_i and MR_j if they are not connected)

- $$\sum_{j=1}^{M} z^s_{i,j} - \sum_{j=1}^{M} z^s_{j,i} = \begin{cases} 0 \ , if \ \ i \ne s, i \ne 1; \ \ i, s = 1,...,M \\ -\theta^s, if \ \ i = s; \quad i, s = 1,...,M \\ \theta^s, if \quad i = 1; \quad s = 1,...,M \end{cases}$$

(For flow conservation at mobile router MR_i)

where: $\theta^s = 1$ if $s = 2,...,M$,

$\theta^s = 0$ if $s = 1$

These constraints ensure the existence of a route between each two mobile routers (to keep the backbone connected)

The transmission range of the mobile routers R_r and mobile nodes R_m being constant, the complexity of the problem mainly depends on the number of mobile nodes N, and mobile routers M.

B. Quality of service oriented mobile routers deployment

In multi-hop wireless network, the network performance and the end to end delay of the communication mainly depend on the route's hop count.

We propose to manage the network topology, by limiting the diameter of the backbone graph. This reduces the end to end delay of the transiting communication, and provides a certain stability and control over the network. Thus, the use of a classical QoS scheme can be added, and the delay sensitive applications can be guaranteed.

In ad hoc networks, the end to end delay from a source MS_s to a destination node MS_d transiting H hops is:

$$D(s,d) = H \times (AverNodeDelay + T_{trans} + T_{prop})$$

Where:

T_{trans}: transmission delay (packet_len/data_rate)

T_{prop} : propagation delay (negligible).

$$AverNodeDelay = \frac{\sum_{k \in path(s-->d)} Nodedelay(k)}{H}$$

Nodedelay(k)= queue_delay(k)+MAC delay (k)

In the QoS oriented deployment, the backbone diameter constraints are added to the formulation of the problem: the maximum number of hops (set to H) between mobile routers is fixed to satisfy the worst case; we set the maximum tolerated delay (100ms) and consider the worst case delay per hop depending on buffer lengths, number of available mobile routers, and the network charge (amount of traffic in the network). On the one hand, if the network is not congested, a high value of H is allowed. On the other hand, this value is small when a longer delay is needed to relay packets at the IP (queue) and MAC layers, when congestion occurs.

This problem is slightly different from that formulated for the connectivity goal. An additional constraint is added to characterize the diameter of the backbone network (set to H hops). It is formulated as follows:

Diameter constraint:

$$\sum_{1 \le i,j \le M} z^s_{i,j} \le \frac{H}{2}, \ s = 1,...,M$$

C. Infrastructured ad hoc network case

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 formulation of the problems is almost the same as that of the autonomous ad hoc network.

Given that every router must have a route to the fixed gateway, it is sufficient to consider the gateway as the $(M+1)^{th}$ mobile router, having a predefined position. That is, $M+1$ mobile routers are considered in the model, we simply add a gateway position constraint expressed as follows:

$$\begin{cases} a_{M+1} = x_{gateway} \\ b_{M+1} = y_{gateway} \end{cases}$$

Hence, the problem can still be formulated as a MILP problem with this additional constraint. The network backbone connectivity or QoS purposes can still be satisfied as before.

In the following section, we will demonstrate the efficiency of the described models through simulations. The connectivity and QoS strategies are studied.

III. SIMULATIONS AND RESULTS

We use CPLEX [4], a mixed integer linear programming solver, to solve the studied models. The input files submitted to this solver, are described using the AMPL language [10].

We first show a deployment example of the mobile routers in an ad hoc network satisfying the connectivity goal. Then, we study the relationship between the network topology (number of mobile node *N*, field size *A*x*B*, and router's transmission range R_r) and the optimal number of routers (*M*) required to cover the mobile nodes.

In order to see the impact of the QoS based deployment of routers on traffic performance (end-to-end delay and throughput) we use the NS-2 [6] tool. When the locations of the mobile routers are obtained by the CPLEX solver, they are introduced in the NS-2 simulation model. The purpose of these experiments is to show that the QoS oriented deployment of routers can improve the network performance efficiently, while using an optimal and limited number of routers.

Figure 1 illustrates a deployment example of routers in an autonomous network to ensure connectivity. In the example: field is of size 1000x1000m^2, the number of mobile nodes is *N*=100 (randomly generated), and the node and mobile router transmission range are respectively R_m=150m, R_r=220m. We find that *M*=11 mobile routers are required to achieve the connectivity. We note that, depending on the configuration of the network the mobile routers deployment is different.

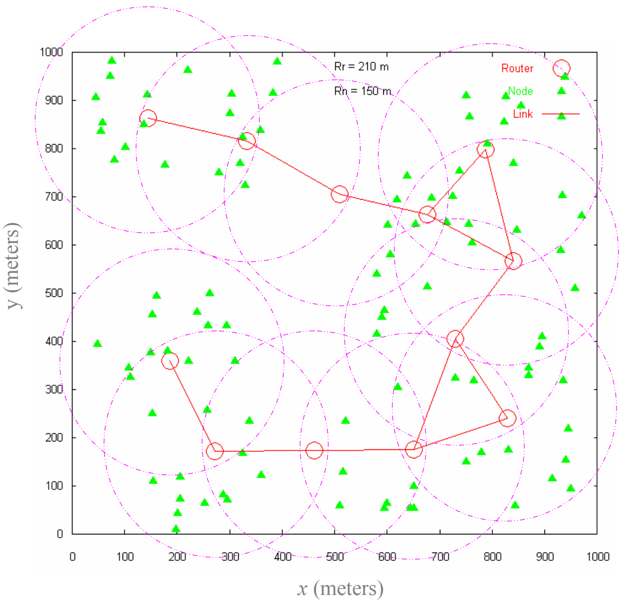

Figure 1. Connectivity aware topology control in an infrastructure-less ad hoc network

We studied networks topologies with 30 (respectively 60 or 100) mobile nodes in a field of size 500x500m^2 (respectively 750x750m^2 or 1000x100m^2). In each case, we randomly generated 20 networks and represent the average values computed from the obtained results. The transmission range of the mobile routers was 150 m, 225m or 300m. In Figure 2, 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 router's transmission range (disproportional). We find that, *M*=15 mobile routers with a transmission range R_r of 150 meters are required to achieve connectivity in a topology of *N*=60 nodes in a field of 1000x1000m^2; this number decreases with a higher transmission ranges of the routers (*M*=9 mobile routers for a R_r=300m).

In a realistic ad hoc network application, our model provides an efficient tool to determine the number of routers to deploy in a given area with a predefined number of mobile nodes.

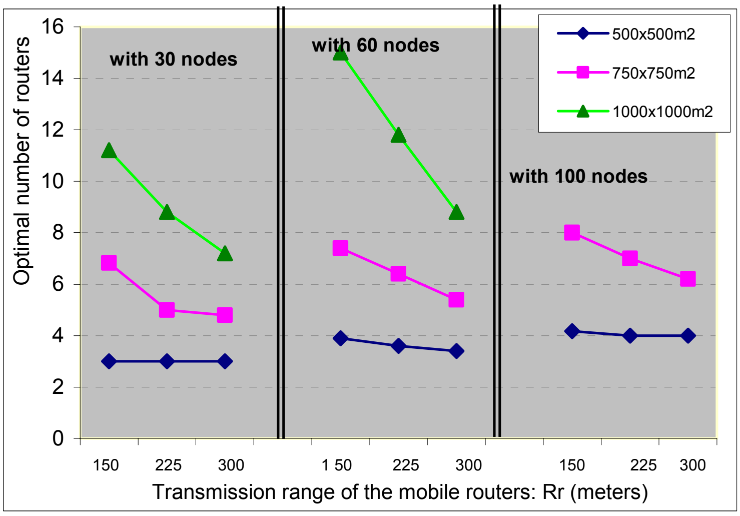

Figure 2. Optimal number of routers, surface size and router transmission range.

To show the network performance of the QoS based deployment, we have done a series of simulations using NS-2. Simulations are driven for 7 network topologies of 50 nodes in a field of size 800x800 m^2 using the wireless 802.11 MAC layer. All mobile routers have 11 Mb/s data rate. Other mobile nodes have (randomly) 2 or 11Mb/s data rate. The DSDV routing protocol is used. For each network topology, the mobile routers positions are obtained by the CPLEX solver following the QoS oriented model.

For each network topology, we randomly generate 17 CBR applications with 32kbps data rate and packet size of 512 bytes, during a simulation time of 300 seconds.

The aim of our simulations is to compare the performance of the network under different conditions. Table 1 shows the average end to end delay, average delivery ratio and average loss ratio of the considered traffics:

a) Without using mobile routers
b) With a cluster based approach by electing mobile node having a high data rate as cluster head [9]
c) Using our QoS oriented deployment model (see Section II.B)
d) Using a fixed number of mobile routers uniformly distributed in the simulation area, so that to cover the whole simulation field

Table 1. Traffic performance comparison

	Average end to end delay	*Average delivery ratio*	*Average loss- ratio*
a) Classical ad hoc network	806ms	84,58%	16,42%
b) Cluster based approach	584ms	86,1%	13,9%
c)Our approach: QoS oriented deployment	220ms	93,95%	7,05%
d)Uniform deployment of mobile routers	200ms	93,88%	6,12%

In the case of a classical ad hoc network, no high capacity links are available and hence the routes become rapidly congested. Consequently, the average end to end delay is high and the global throughput is not satisfied.

For the cluster based approach, Table 1 shows better performances. In such an approach, high capacity links may be elected to relay communications, thus reducing delay and packet loss.

With the QoS based deployment, results show a better end to end delay (less than 220 ms) and a reduced loss ratio (7,05%). In this case, mobile routers are deployed according to the other nodes in the network. They keep the backbone diameter limited and provide shortest routes. In addition, since mobile routers are dedicated for routing, they have a high transmission range and high link capacity. Therefore, the throughput and delay of the transiting traffics is improved. Note that, if a service differentiation is performed at IP or MAC layer, the real time application requirements can be met.

In the last approach, when a great number of mobile routers is deployed uniformly to cover the simulation field, the network performance is improved. However, this deployment is not optimal in terms of number of routers and is area dependant, as opposed to our approach (dependant of mobile nodes position). Our approach shows almost the same performance, with a reduced number of routers wisely deployed.

IV. CONCLUSION AND FUTURE WORK

We have presented a topology control mechanism using the deployment of a set of high capacity mobile routers in a static environment. The goal of our approach is to achieve strong network connectivity or bounded backbone diameters. For each strategy, the problem was set as a mixed integer linear programming problem. The infrastructured and infrastructure-less ad hoc networks are considered in our study. Simulation results show that the proposed approach significantly improves the performance of the ad hoc network. The next steps of this work concern:

- An experimental study to evaluate this approach for the two strategies in a real life application,
- Refining the models to take into account other parameters like signal power level and power management,
- Dynamic mobile routers deployment following the network topology changes.

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