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Short and Robust Communication Paths in Dynamic Wireless Networks

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Abstract. We consider the problem of finding and maintaining communication paths in wireless mobile ad hoc networks (MANET). We consider this problem as a bi-objective problem when trying to minimize both the length of the constructed paths and the number link reconnections. We propose two centralized algorithms that help analyse the problem from a dynamic graph point of view. These algorithms give lower bounds for our proposed decentralized ant-based algorithm that constructs and maintains such paths in a MANET.

1 Introduction

Mobile ad hoc networks (MANETs) define communication networks composed of mobile devices or stations able to communicate together with wireless media. When communicating in a peer-to-peer way, they do not rely on any infrastructure. The resulting communication network is decentralized. The volatility and the mobility are two major characteristics of these networks. The mobility comes with the nature of these stations that are usually small devices handheld by their owner or embedded in mobile vehicles. The volatility illustrates the idea that stations are not always turned on. They can be standing by and then reactivate to reappear in their neighborhood.

Stations volatility is the results of poor capacity batteries while radio communication need a lot of energy. As a result, energy saving is a key issue in the design of applications dedicated to MANETs that have to be careful with communication overheads. Two stations willing to communicate need to exchange preliminary information to set up the link. This initialization is called here, for seek of simplicity, "synchronization". Moreover, discovery times may also be considered (for instance, the Service Discovery Protocol in Bluetooth may be too slow for mobile networks). Synchronization processes need a lot of energy achieve and the number of new communication links may be minimized.

MANETs as well as classical networks need communication services like data routing. Yet, classical networks protocols for routing reveal to be useless in infrastructure-less communication systems. MANETs need dedicated algorithms for the routing of communication. A large panel of algorithms are proposed to perform routing in MANETs, taking into account different constraints such as the overhead of transmitted data [1], the quality of the communication links [2] or the geographical motion of the stations [3].

Here we address the problem of finding and maintaining communication paths between couples of stations in a MANET. We consider the problem of extra energy consumption that occurs when mobility and volatility force new synchronization processes. Our purpose is to minimize the number of these new synchronization processes by selecting communication paths that are less likely to disconnect. Such selected paths are called robust paths. In this paper we focus on a global analysis of this property in dynamic graphs with centralized algorithms (Sect. 2). This analysis gives clues to manage paths in a decentralized environment. Section 3 focuses on a decentralized ant-based approach that deals with the MANET issues. Simulations results are shown Sect. 4.

2 Global Analysis

The aim of this paper is to study the possibilities of creating and maintaining short and robust paths in mobile ad hoc networks. This global analysis aims at giving lower bounds to compare with the decentralized algorithm. Simulated ad hoc networks produce produce communication networks that can be considered as dynamic graphs where stations are nodes and effective communication links between stations are edges. These dynamic graphs are replayed and analyzed centrally. We propose some measurement for the problems we consider. First the length of paths is considered. Then for the robustness we suggest the *renewal rate* measurement: Let s be a subset of edges and nodes in the dynamic graph. s is said to be a structure. s is observed at to different dates—t_1 and t_2—during the evolution of the dynamic graph. Let S_{t_1} be the structure s at time t_1 and S_{t_2} the same structure at time t_2. Since the graph is a dynamic one, the set of edges and nodes that constitute s may change between t_1 and t_2. The renewal rate $t_r(S_{t_1}, S_{t_2})$ is the number C of changes (addition and removal of elements) in s between t_1 and t_2 divided by the cardinality of S_{t_1}: $RR(S_{t_1}, S_{t_2}) = \frac{C}{|S_{t_1}|}$.

We propose two centralized algorithms to produce lower bounds for the next decentralized approach.

Shortest Paths Minimal Set (SPMS). At each step of a dynamic graph one compute the minimal list of shortest paths between a given source and a destination. From the first step $i = 0$ the set of shortest paths is computed and is said to be the reference structure. Iteratively steps of the dynamic graph are applied. For each step a new shortest path structure is computed. If a path exists in this intersection structure then it becomes the new reference structure. The number of shortest paths cannot be larger in the new reference structure than in the older one since the new one is included in the old one. On the contrary, if the intersection between the new structure and the reference structure does not have a shortest path, then it means that the reference shortest path has been lost in this new step (t). Anyway we know that this structure is valid until the step $t-1$ so it is stored as the good one until the step $t-1$ and the number of shortest path structures in the solution set is increased by one. For this new step the new shortest path structure becomes the new reference and the process can go one

with another step. At the end of this process, only the minimal set of shortest path structures is stored.

Robust Structures Minimal Set (RSMS). The constraint of shortest path is relaxed and only the existence of a path between a pair of nodes is considered. It is interesting in our case to look for the minimal set of paths that may link two nodes during the evolution of the graph. The algorithm constructs with the same behavior as above (algorithm SPMS) the minimal set of paths that link two nodes in a dynamic graph. Since several paths may link the nodes at any moment we consider structures that links them. We look for paths or structures that last as long as possible without changing—robust structures.

RSMS does not have optimal renewal rate; however experiments show that it is a good lower bound for the heuristic method presented next section.

Proposed algorithms give interesting measures for the deferred analysis of communication networks. These algorithms give lower bounds for the two objectives that we consider—short and robust paths. For now, after this global analysis, online constraints may be considered with a decentralized approach.

3 Ant-based Construction and Maintaining of Robust Paths

We now focus on applied constraints that lead to the conception of dedicated and decentralized algorithms in the field of mobile ad hoc networks. We consider networks where the mobility of stations may highly impact on the kind of service that can be delivered. We choose a realistic simulation mobility that corresponds to the mobility of pedestrians in an urban environment. Here, communication devices are handheld devices that may usually be shut down, so we consider a volatility model for the stations.

3.1 Description of the Model

The idea here is to design a decentralized algorithm that is able to handle the changes in the environment. Natural ant colonies have the ability to construct and maintain short path in changing environments. Even the loss of some ants is supported. The number of entities needed here is a key issue. Several previous works are related like AntNet [4] and Ant-Based Control (ABC) [5] in wired networks, and more precisely *AntHocNet* [6], DAR (Distributed Ant Routing) [7], or HOPNET [8] in wireless networks.

In this model, ants do not construct solutions to a given problem. They are just influenced by pheromone tails when making journeys in a dynamic network and also lay pheromone down the environment. On the wireless network field, the environment is the set of stations and pheromone trails are updated in stations local routing tables.

This algorithm uses the same local exploration formulas as defined in ACOs. For an ant k located on node i of a graph at date t, the choice for a next node j is made locally according the probability:

$$p_{ij}^{k}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha} \cdot [\eta_{ij}]^{\beta}}{\sum\limits_{l \in nbs(i) \backslash path(k)} [\tau_{il}(t)]^{\alpha} \cdot [\eta_{il}]^{\beta}} & \text{if } j \in nbs(i) \backslash path(k) \\ 0 & \text{else} \end{cases} \tag{1}$$

where:

- $\tau_{ij}(t)$ is the quantity of pheromone on edge (i, j) at step t,
- η_{ij} is the visibility on edge (i, j)—explained below;
- $nbs(i)$ is the set of neighboring nodes of i;
- $path(k)$ is the list of nodes that constitute the path already done by ant k;
- $neighbors(i) \backslash path(k)$ is the set of neighbors of i deprived of the node that are those node that are in the path of ant k;
- α and β are two parameters that relatively change the weight of pheromone trails in comparison to the visibility.

The two local information that are able to lead ants in the graph are the pheromone trails and the visibility. We want this information to be related to the two objectives we consider—short and robust paths. Pheromone trails are known to help ants construct short paths. The visibility is meant to be a local estimation of the quality of the path being constructed. Here the visibility is meant to give indications on the robustness of the paths being constructed. We need a local estimation of this robustness that is a global measurement, like the renewal rate (Sect. 2).

We propose to use a local heuristic based on the age of the edges to estimate their robustness. Let the number of appearances be the number of times a given edge appears in the dynamic graph. Let the overall age of this edge be the sum of the ranges of time it exists in the dynamic graph. We call volatility the ratio between the *number of appearances* of an edge and its *overall age*: $volatility = \frac{number\ of\ appearances}{overall\ age}$.

3.2 Algorithm

Ants move in the graph according to two modes—a forward mode when looking form the destination and a backward mode when the destination is reached. This model is common to several algorithms just like DAR, ARA or AntHocNet.

Forward mode. The ant moves from node to node looking for the destination. It stores the constructed path. Next node is chosen according to Eq. (1).

Backward mode. When an ant in forward mode reaches the destination node, then it goes backward to the nest using the path created during the forward mode. It updates the pheromone trails. Similarly to ACOs the reinforcement of pheromone trails is made proportionally to the length of the constructed path.

Evaporation. As defined in ACO, the parameter ρ rules the evaporation rate of pheromone to be applied on each edge. With the constatnt Q, the quantity of pheromone (τ_{ij}) on edge (i, j) is: $\tau_{ij} = (1 - \rho)(\tau_{ij} - Q) + Q = \tau_{ij} - \rho(\tau_{ij} - Q)$.

3.3 Memory of the Pheromone Trails

Similarly to the volatility measurement that is computed from the logging of the appearances and disappearances of edges by nodes, the values of pheromone of an edge may be stored even when an edge disappears. This memory allows to give back to an edge its pheromone trail when it reappears. The idea is that if an edge has a high quantity of pheromone then it may a good point to quickly give it back its attractiveness when it reappears.

This heuristic may be discussed. A part of the simulations results are dedicated to the analysis of this mechanism and show its efficiency under some hypothesis. Experiments show that this memory of pheromone trails reveals to be very efficient for environments with high volatility.

4 Simulations and Results

We want to focus here on the simulation of realistic networks composed of handheld devices such as PDAs, cell phones or laptops that are able to communicate with *IEEE 802.11b* radio chips. We consider urban environments such as mall centers or streets or hallways. Tow different scenarios with different characteristics are proposed.

The first scenario called "hallway" is distinguished by a very high mobility of the stations but with no volatility—the stations move fast and their radio device is open. The environment is a hallway and the mobility is constrained by this hallway such that stations may only move from one part of the hall to the other in the two possible directions. The speed of the stations is correlated to the speed of walking people. All the parameters that identify the scenario are displayed Table 1.

The second scenario called "volatility" highlights a weak mobility and a strong volatility for its stations, as show parameter values in Table 1. Stations evolve in an open environment with a Random Way Point [9] mobility model.

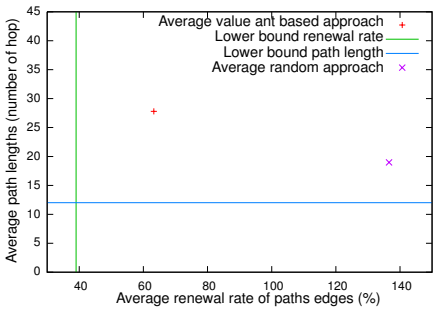
Table 1. Simulation parameters for scenarios "hallway" and "volatility".

scenario	"hallway"	"volatility"
Mobility	two directions	RWP
Environment	closed (hallway)	open
Area	$500m$ long hallway	$1km^2$
Stations	150	400
Station celerity	1.4 to $2m/s$	0 to $1m/s$
Volatility	no volatility	40% of stations
Radio radius	$20m$	$40m$

Simulations are based on a discrete time evolution by the simulator Madhoc (`litis.univ-lehavre.fr/~hogie/madhoc/`). Videos of these simulations are also available at `litis.univ-lehavre.fr/~pigne/these/`.

4.1 Multi-objective Optimization

Two objectives are considered in this problem: paths lengths and renewal rate of paths edges, both being minimized. Figure 1 gives a general overview of all the results obtained with the algorithm for simulations with the "volatility" scenario. Data here are average values for different parameter sets, 8 different pairs of source and destination, and 10 different random seeds. Four values are presented in the multi-objective space of solutions where x-axe gives the average renewal rate of the edges of a path and the y-axe gives the length of a path. The observation is that the produced results are less efficient than the random search in terms of path length. However the average renewal rate of the edges of the solutions generated by the ant-based approach is far more efficient than the random method.



- Horizontal line: average shortest path on each pair of source destination nodes.
- Vertical line: lower bound for the renewal rate given by the RSMS algorithm (Sect. 2).
- "+": average value for the solutions generated by the ant based approach.
- "×": average value for the solutions generated by a random centralized search algorithm.

Fig. 1. General solutions layout in the multi-objective solution space.

4.2 Parameters and Results

Metaheuristics are usually criticized for their important set of parameters to be tuned. Our proposed model also suffers criticism; however dependencies between parameters allow simplifications in the system. Relative importance parameters α and β (Eq. (1)) are relative one on the other. α is set to 1 and the evolution of β is observed. Then we consider ρ, the evaporation rate of the pheromone trails. It may strongly impact the algorithm's behavior changing the attractiveness of the paths. Other parameters are tuned experimentally as shown in the table of Fig. 2. This figure shows the results obtained by our proposed algorithm with the simulation of the "volatility" scenario. Each point on the figure is the average value of the paths constructed by the algorithm when ran on the network with 8 different pairs of source/target nodes and 6 random seeds (48 different runs). From one point to another only the values of the parameters β and ρ differ.

Parameter	Description	Value
Q	initial pheromone	1
ρ	evaporation rate	variable
$nbAnts$	number of ants	40
k	node jumps per step	100
α	pheromone strength	1
β	visibility strength	variable
TTL	ant max lifetime	100

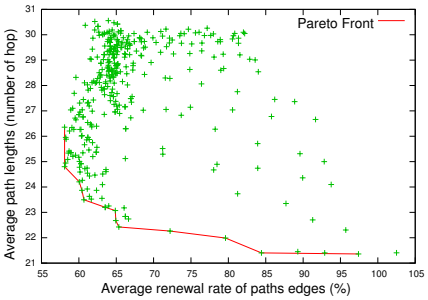
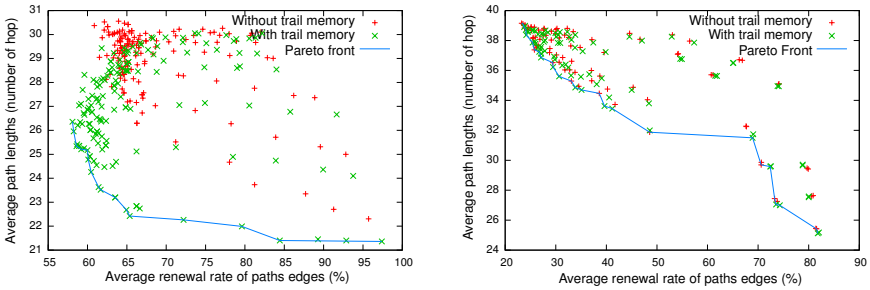


Fig. 2. Parameters and solutions for the "Volatility" scenario.

4.3 Analysis of the Pheromone Trail Memory Heuristic

The proposed heuristic is to use a memory to recall pheromone values on edges that reappear after having disappeared. The hypothesis is that an edge with a strongly loaded pheromone trail is probably an important edge that has to get his attractiveness back as quickly as possible. In the "volatility" scenario edges that disappear have a high probability to reappear since the mobility is low. In this case the heuristic seams appropriated. Figure 3(a) shows the undeniable superiority of this approach. On the opposite the memory heuristic is not appropriated to the "hallway" scenario where edges that disappear have nearly no chance to reappear. Figure 3(b) illustrates this.



(a) "Volatility" scenario. (b) "Hallway" scenario.

Fig. 3. Pheromone trail memory heuristic on the two scenarios.

5 Conclusion

The purpose we were given here was to address the problem of finding and maintaining robust and short communication paths in dynamic and decentralized environments such as mobile ad hoc networks. This problem leads us to

consider the problem as a two objective problem. Swarm intelligence and especially ant-based approaches have shown efficiency in evolving and decentralized environments. We proposed such an ant-based models that only depends on local heuristics and is able to adapt to the changes in the environment.

A study of the problem with centralized algorithms has been performed and allows identifying key issues in the problem. This analysis helped the formulation and the evaluation of the decentralized ant based algorithm.

Two original propositions show up in this field. First the use of the local volatility measurement of the edges allows—as shown by the simulations—to lower the renewal rate of the paths edges constructed by the ants. This means in terms of mobile wireless that the overhead communication needed to reconnect communication links is lowered. The second original proposition is that a local heuristic computed by the stations of a mobile network leads to store pheromone trails of communication links that disappear so as to give them back there pheromone value if they ever reappear. This last heuristic shows it efficiency when stations are volatile and communication links have chances to disappear and then reappear.

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