Enhanced Internet Connectivity for Hybrid Ad hoc Networks Through Adaptive Gateway Discovery

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Abstract

One of the key components affecting the overall performance of hybrid ad hoc networks is the algorithm used to discover and select Internet gateways. We have analytically modeled existing proposals (i.e. proactive, reactive and hybrid gateway discovery) showing that each of them is most suited only for a limited range of network parameters. We propose a new adaptive gateway discovery algorihtm called "maximal benefit coverage" based on the dynamic adjustment of the scope of the gateway advertisement packets. We show through simulation that ability of our proposed scheme to adapt to the changes on the network conditions allow it to outperform existing mechanisms alternatives over a variety of scenarios and mobility rates.

1. Introduction

The flexibility, self-configurability and easy deployment of mobile ad hoc networks (MANET) are making these networks an indispensable component in future mobile and wireless network architectures. In addition, with the advent of future wireless systems consisting of an integration of different heterogeneous wireless technologies, the interconnection of MANETs to fixed IP networks is one of the areas which are becoming of paramount importance. In such scenarios, commonly known as hybrid ad hoc networks, mobile nodes are witnessed as an easily deployable extension to the existing infrastructure. Some ad hoc nodes act as "gateways" which can used by mobile terminals to seamlessly communicate with other nodes in the fixed network. The challenge in interconnecting ad hoc networks to Internet, stems from the need to inform ad hoc nodes about available gateways in an extremely changing scenario while making a minimal consumption of the scarce network resources. So, an efficient gateway discovery for ad hoc networks becomes one of the key elements to enable the use of hybrid ad hoc networks in future mobile and wireless networks.

The different proposals to the issue of Internet connectivity for MANETs in the literature have used either a proactive gateway discovery or a reactive one. In the approaches based on a proactive gateway advertisements ([1], [2], [3]) the gateways periodically send advertisement messages which are flooded throughout the ad hoc network to inform all ad hoc nodes about available Internet gateways. Although these approaches achieve good connectivity, they have been usually criticized due to the high overhead they require and their limited scalability. In reactive approaches ([4], [5]) those nodes which require connectivity to the Internet reactively find those gateways by means of broadcasting some kind of solicitation within the entire ad hoc network. Although this approaches have been considered to require less overhead, we show in the next section that this process of finding gateways is as costly as the proactive advertisement. In fact, we show that reactive gateway discovery mechanisms scale poorly regarding the number of active sources willing to access the Internet.

There are also some works ([6], [7]) which propose hybrid gateway discovery approaches. In [6], the authors propose an scheme in which advertisements are only propagated up to a certain number of hops, and those nodes out of that scope will proactively find the gateways. However, as the authors show, the optimal TTL depends very much on the particular scenario and network conditions under consideration and so does the performance of this approach. In [7] the authors propose a more sophisticated approach in which advertisements are sent out only when changes in the topology are detected. However, they rely on the use of source-routing protocol, which limits the applicability and scalability of their approach.

In our opinion, existing approaches have neglected the huge overhead that the reactive gateway discovery scheme can have. The overall performance of the static approaches proposed so far can vary dramatically as the network conditions change. This is due to the strong performance dependence that they have on the scenarios under consideration (e.g. number of sources, number of nodes, degree of the network, etc.). We propose an adaptive gateway discovery approach based on the dynamic tuning of the scope of the gateway advertisements. Just by monitoring data packets, gateways will adaptively select the time to live of their advertisement that best suits the current network conditions. So, even when the network conditions change, the overall network overhead is reduced while still maintaining a good connectivity. In the authors' opinion, the main contributions of this paper are (i) an analytical study of the overhead of different gateway advertisement approaches showing the need for an adaptive scheme, and (ii) an adaptive gateway discovery scheme for hybrid networks which is shown to outperform existing alternatives.

The remainder of the paper is organized as follows: section 2 provides an analytical evaluation of the different approaches and shows the need for adaptive gateway discovery alternatives. In section 3 we describe our proposed adaptive approach based on the maximal benefit coverage heuristic. The results of our simulations are shown in section 4. Finally, section 5 gives some conclusions and draws some future directions.

2. Analytical Evaluation of Existing Gateway Discovery Approaches

We consider as the baseline scenario for our analysis an hybrid network using the AODV [8] ad hoc routing protocol with an Internet connectivity approach similar to the reactive one proposed in [4]. We analyse that approach for the three existing gateway discovery mechanisms: reactive, proactive and hybrid.

2.1. Operation of existing approaches

The reactive approach is the basic approach described in [4]. RREP and RREQ messages are extended with a new flag ("I") which is used to differentiate usual RREP and RREQ messages from those used to discover routes to the Internet. We refer to the new messages as RREP_I and RREQ_I. A source willing to communicate with a node in the fixed network, will first attempt to contact it within the ad hoc network doing an extended ring search (as described below). If no answer is received after a network-wide search, then the source tries to find a route towards the Internet. So, it broadcasts a RREQ_I to the ALL_MANET_GW_MULTICAST address. Gateways, upon reception of this message will send out a unicast RREP_I message to the source. Then the source will select one of the gateways (based on the hop count) and will send the data towards the fixed node through that gateway.

The proactive approach introduces a new message called GWADV ("Gateway Advertisement"). Gateways will periodically broadcast within the ad hoc network these messages in order to inform all the nodes about the availability of that gateway. Upon reception of a GWADV message, mobile nodes will select their preferred gateway based on the hop count, and they will store a default route entry in their routing table. When a source wants to communicate with a destination, it tries first to find a direct route within the MANET, and if it does not manage to do it, it then uses its default route.

Finally, the hybrid approach we have implemented is basically the one described in [6]. Gateways will periodically flood TTL-limited GWADV messages which will only be forwarded upto a few hops away from the gateway. The sources within that flooding area, upon reception of the GWADV messages, will behave as in the proactive approach. Those nodes beyond that number of hops will find default routes proactively using the same RREQ_I-based reactive scheme described before. So, this approach is somehow a trade-off between the reactive and proactive approaches.

2.2. Analytical Model

In our model, we assume that N nodes are uniformly distributed in a rectangular lattice covering a certain area. Each vertex of the lattice is a possible location for a node, but only one node can be at a concrete vertex. An example of such a rectangular lattice is shown in Fig. 1. Given a node n in the lattice, there are $4k$ nodes at a distance of k hops from n. These nodes are placed in the k^{th} concentric ring centered on the node n. It is easy to show that the total number of nodes including n at a distance of k hops is given by (1). We also give the relation between k and N, in which $\lceil x \rceil$ is the standard ceiling operation meaning completion to the next integer. It is used in the expression for obtaining k because the last concentric ring might not be complete. So, given a broadcast message with time to live (TTL) equal to x, $N_r(x)$ will be the number of nodes forwarding that message if $x \leq (\sqrt{2N-1}-1)/2$ and N otherwise.

$$\begin{array}{rcl} N_r(k) & = & 1+\sum_{j=1}^{k} 4j = 1+2k(k+1), \\ k & = & \lceil (\sqrt{2N-1}-1)/2 \rceil \end{array} \tag{1}$$

Regardless of our gateway discovery mechanism, the approach used in [4] detects that a destination is a fixed node when the source does not receive any answer after a network-wide search. This network wide search is done using an expanding ring search. That is, the first route request message is only sent to the nodes at TTL_START hops. If no answer is received, a new message is sent with the previous TTL plus TTL_INCREMENT. This process is repeated up to a TTL of TTL_THRESHOLD. If no

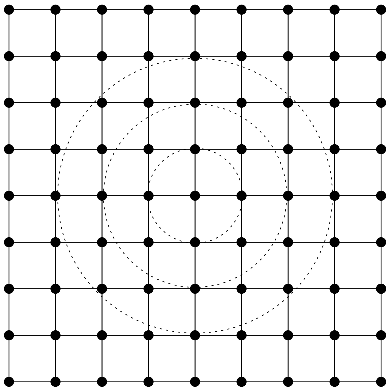

Figure 1. Rectangular lattice

answer is received, then the last request message is sent with a TTL equal to NETWORK_DIAMETER. The typical values defined for these constants in AODV specification are TTL_START=1, TTL_INCR.=2, TTL_THR.=7 and NET_DIAM.=30. Although we think that these values are not appropriate for hybrid networks, we have obeyed the original specification.

When an ad hoc source tries to find a route towards a fixed node, it never gets any reply from any node within the ad hoc network. Thus, for each source S, the number of messages associated to realizing that a destination is a fixed node can be calculated according to (2).

$$\Omega_{FN} = \sum_{j \in \{1,3,5,7,30\}} N_r(j) \tag{2}$$

Similarly, whenever a source wants to reactively discover a gateway there is an overhead which is the sum of the number of messages required to do a network-wide distribution of the RREQ_I packet addressed to the ALL_MANET_GATEWAYS multicast address (N), plus the number of messages required to send an unicast RREP_I reply from every gateway to the source. Assuming that the gateways are in the borders of the lattice, it is easy to demonstrate that the mean path length is $\sqrt{N}-1$. Thus, the number of messages required to unicast the RREP_I to the source is 1 message sent by the gateway plus the $\sqrt{N}-1$ forwards of the mean path length. Thus, it makes a total of $\sqrt{N}$ for each gateway. If we denote the number of gateways by N_{GW}, the overhead of the reactive discovery of the gateways by one source can be computed as it is shown in (3).

$$\Omega_{r-gw} = N + N_{GW} \cdot \sqrt{N} \tag{3}$$

Let S be the number of active sources in the hybrid network communicating with fixed nodes, λ_{adv} the rate at which GWADV messages are being sent out by the gateways and t the duration of the time interval under consideration. The overhead of delivering each of this messages to the whole ad hoc network is $N+1$ messages; one forwarding by each of the N nodes (because of the duplicate messages avoidance) plus the message sent out by the gateway itself. In addition, if we take into account that initially all the sources in the network will need to realize that the destination node is a fixed node, then the total overhead in number of messages required by the proactive approach can be obtained using (4).

$$\Omega_p = S \cdot \Omega_{FN} + \lambda_{adv} \cdot t \cdot (N+1) \cdot N_{GW} \tag{4}$$

In the same way, if we denote by R_{dur} the route duration time in AODV[1]. Then, R_{dur} obeys an exponential random distribution with parameter λ_{dur}. Let N_{break} be a random variable representing the number of route expirations during an interval of t units of time. Then, N_{break} follows a Poisson distribution with an arrival rate equal to λ_{dur} so that $P[N_{break} = k] = \frac{e^{-\lambda_{dur}} \cdot \lambda_{dur}^k}{k!}$. So, the mean number of default route expirations per source will be given by $E[N_{break}] = \lambda_{dur} \cdot t$. Accordingly, the total overhead for the proactive route discovery will consist of the initial overhead to make every source aware that their destinations are fixed nodes, plus the overhead associated to the proactive discovery of the gateways whenever their default route expires or breaks. This overhead can be computed according to (5).

$$\Omega_r = [\Omega_{FN} + (\Omega_{r-gw} \cdot \lambda_{dur} \cdot t)] \cdot S \tag{5}$$

The hybrid gateway discovery scheme, has an overhead which is a combination of the overheads of the other approaches. For those sources located outside the area covered by GWADV messages, the overhead will be the similar to the overhead of the reactive approach. Thus, in order to asses the overhead of the hybrid approach it is of paramount importance, being able to calculate the mean number of sources which will be within the GWADV range.

Let's assume that the gateways are located in the corners of the lattice as in our simulated scenario. In the hybrid approach it makes no sense sending GWADV at longer distances than $\sqrt{N}-1$ hops, because other gateways will be covering the area beyond that TTL. Then it is easy to derive an expression for the number of nodes which are at a scope of s hops from any gateway according to (6), with $s \in [0, \sqrt{N}-1]$.

$$N_r^{GW_i}(s) = \sum_{j=1}^{s} (j+1) = \frac{s(s+3)}{2} \tag{6}$$

Given a node n from the ad hoc network, the probability that this node will be able to receive a GWADV message from any of the gateways can be computed as shown in (7).

$$P_c(s) = \frac{\sum_{i=1}^{N_{GW}} N_r^{GW_i}(s)}{N - N_{GW}} \tag{7}$$

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[1] configured to be 10 seconds unless the route becomes invalid before (e.g. due to mobility)

Constant	N	λ_{adv}	N_{GW}	λ_{dur}	t
Value	25	1/5	2	1/10	900 sec

Table 1. Values for analytical evaluation

If we denote N_c as the number of sources being covered by any gateway when using a scope of s hops, then N_c is a random variable obeying a binomial distribution $B \sim (S, P_c(s))$. Thus, the mean number of sources being covered when gateways use a TTL of s hops can be computed as $E[N_c] = S \cdot P_c(s)$. So, the overall overhead of the hybrid approach consists of three different parts: the overhead associated to realize that the destinations are fixed nodes, the overhead associated to the propagation of GWADV messages over s hops by each gateway, and the overhead required so that those sources not covered by the GWADV messages can find the gateways and create a default route. An expression for that overhead is shown in (8).

$$\begin{aligned}\Omega_h &= S \cdot \Omega_{FN} + \lambda_{adv} \cdot t \cdot (N_r^{GW}(s) + 1) \cdot N_{GW} \\ &+ \Omega_{r-gw} \cdot \lambda_{dur} \cdot t \cdot S \cdot (1 - P_c(s))\end{aligned} \tag{8}$$

In the next subsection, we show numerical results from our analytical model to assess the effectiveness of each of the existing alternatives.

2.3. Analytical Evaluation

To compare the overhead of the different approaches, we have used the figures in table 1. As it was expected the proactive approach is less scalable regarding the number of nodes in the ad hoc network. This is because the higher the number of nodes, the higher the number of retransmissions which are required to propagate GWADV messages to the whole network. This is why usually proactive approaches have been said in the literature to have too much overhead. However, we can also notice that the process of discovering the gateways can be as costly as the process of propagating the GWADV messages. In fact, under certain network conditions the reactive approach can incur in higher overhead than the proactive one. In particular, we have found interesting to stress the poor scalability of the reactive approach as the number of sources connecting to Internet increase. This is supported by the graphs in Fig. 2(a) and Fig. 2(b).

As is it also shown in Fig. 2(a), the hybrid approach is somehow a trade-off between the reactive and the proactive approaches. Different values of TTL lead to different flavors of the hybrid approach. However, as it was also corroborated in [6], the optimal value of TTL is something that strongly varies from one scenario to another. In fact, as depicted in Fig. 2(b), there are situations in which a proactive approach performs better than an hybrid approach and vice versa. Thus, the definition of an universal hybrid gateway discovery approach seems to be unrealistic without adding some degree of adaptability. We describe our proposed adaptive approach in the next section.

3. Proposed Adaptive Gateway Discovery Mechanism

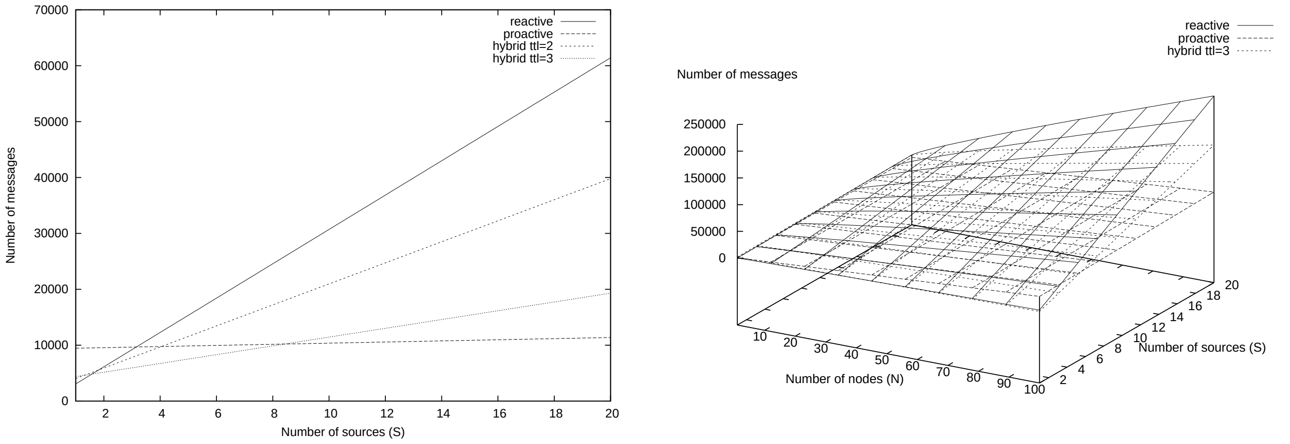
Given the conclusions of our analytical study, we believe that an adaptive gateway discovery mechanism being able to dynamically change its proactiveness or reactiveness can reduce the overhead of the gateway discovery without jeopardizing the overall network performance. Hence, in this section we propose a new adaptive gateway discovery approach based on the dynamic adjustement of the TTL of GWADV messages.

Our previous study has shown that the scope of the advertisements has a strong impact on the proactiveness or the reactiveness of the scheme. Thus, it seems reasonable to use the TTL of the GWADV messages as the parameter to adjust depending on the network conditions. The higher the TTL, the higher the overhead due to the periodic advertisement and the lower the overhead associated to the reactive discovery of the Internet gateways. That is, the higher the TTL the higher the proactiveness of the approach. In fact, a TTL = 0 corresponds to the totally reactive approach whereas a TTL = NETWORK_DIAMETER corresponds to a completely proactive scheme.

There are different criteria to determine when the TTL should be adjusted. For instance, the rate at which neighbors change or the mean duration of the links can be an indication of the network mobility. However, these kind of metrics are not usually easy to interpret. In addition, they do not capture one of the key parameters according to our model which is the number of sources.

For a gateway to be aware of the total number of sources communicating with nodes in the Internet it is required some kind of signaling mechanism facilitating such information to the gateway. However, that would incur in extra overhead and it is something which can require changes to the routing protocols. So, we propose to use simpler metrics being able to convey the required information without any additional overhead. In our proposal, each gateway will only know about the sources which are accessing to the Internet through them. This scheme is very convenient because that information is very easy to learn by the gateway provided that it is routing those datagrams that it would receive anyway.

The gateways will keep track (using a structure like the one which is shown in Fig. 3) of the number of hops at which each of its active sources is located. This information is easy to extract by simply looking at the IP header.



(a) Overhead vs. number of sources

(b) Overhead vs. number of nodes and number of sources

Figure 2. Analytical overhead of the different approaches.

IP address	TTL	Time learnt
....		

Figure 3. Table to store source TTL entries

This table will be periodically purged so that stale entries do not influence the TTL of the next advertisement.

In the next subsection we propose an heuristic algorithm for the determination of the TTL to be used for the next gateway advertisment. It relies soleley on the local information contained in the aforementioned table.

3.1. Maximal Benefit Coverage

In the maximal benefit coverage, the gateways will select the TTL of their advertisements so that the overhead savings are maximized. That is, the gateway will select a TTL t so that the overhead of flooding GWADV messages up to t hops plus the overhead associated to the discovery of gateways by sources at distances longer than t hops is minimized.

In order to accurately compute that optimum, the gateway would require complete information of the topology, number of nodes, etc. However, the overhead required to make all this information available to the GW can be higher than the benefit it can obtain. So, in our case, the gateway will use an heuristic to aproximate the benefit even if there is incomplete information.

To compute the benefit of using a $TTL = t$ for GWADV messages, each gateway will use the expresion shown in (9). In this equation N represents the cost in messages of a network-wide flooding and $S(s)$ is a function representing the number of active sources for that gateway at a distance less or equal to s. The numerator of (9) represents the cost in terms of number of messages associated to not covering the sources (a network-wide flood for each of them), and the denominator represents (according to our model in section 2) the cost of flooding up to a scope of s hops. Note that the function $S(s)$ is accurately known by the source because it is stored in the aforementioned ”Source TTL” table, and the information in the table is maintained up-to-date with no overhead, because it is directly extracted from data packets that each gateway would receive anyway.

$$\beta(s) = \frac{N \cdot S(s)}{s(s+3)} \tag{9}$$

This approach considers the additional flooding cost of covering a source when selecting the TTL. This is clearly shown in (9) in which the benefit decreases as a function of the number of nodes required to propagate the GWADV messages and it increases as the number of sources at that number of hops is higher.

So, the problem of finding the most appropriate TTL for the next advertisement can be formulated as finding $s \in [1..t_{max}]$ so that $\beta(s) = \max_{1 \le x \le t_{max}} \beta(x)$, where t_{max} is the TTL of the source which is furthest away from the gateway. This problem is a simplified dynamic program-

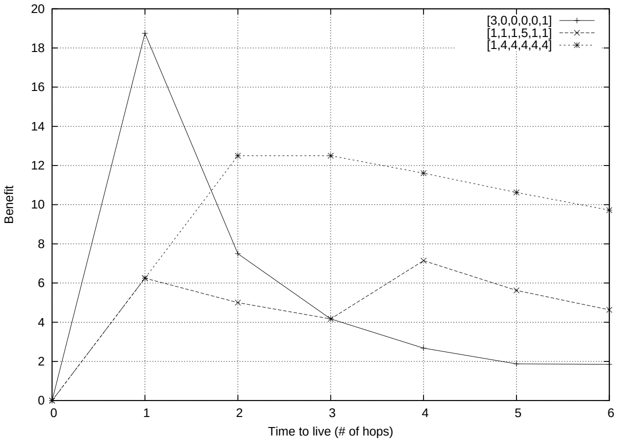


Figure 4. Examples of benefit functions.

ming problem, which can be easily solved in $O(S)$ (a single pass on the table with S sources).

Fig. 4 shows the benefit for different TTLs of some combinations of sources. The combinations in the legend of the graph which are in the form $[s_1, s_2, \ldots, s_n]$ represent a particular case in which there are s_1 sources at TTL=1, s_2 sources at TTL=2, and so on. As the figure depicts, the benefit function is not prone to those suboptimal cases of the previous algorithm. In addition, it is also shown how the higher the TTL, the bigger should be the number of sources at that TTL so that covering them is cost-effective in terms of overhead.

In the next section, we will show through simulations that the proposed scheme is able to outprform existing ones.

4. Performance Evaluation

In this section, we present the evaluation of the proposed approach and we compare it with the reactive, proactive and hybrid ones. For this evaluation we have conducted extensive simulations of the different schemes under a variety of networking scenarios.

4.1. Simulation Environment and Scenarios

All of the gateway discovery mechanisms have been implemented and simulated in the NS-2 [9] network simulator. The simulated scenario consists of 25 mobile hosts randomly distributed over an area of 1200x500 m. The radio channel capacity for each mobile node is 2Mb/s, using the IEEE 802.11b DCF MAC layer and a communication range of 250 m. In addition, there are two gateways; one located at the coordinates (50, 450) and (1150, 50) respectively. In the hybrid approach both of them use a TTL = 2 for their advertisements as it is recommended in [6] for the kind of scenarios under simulation. Each of the gateways is connected to a router and the routers are connected one to each other. Additionally, each router has a fixed node connected to it. All the fixed links have a bandwidth of 10Mb/s, which is enough to accommodate all the traffic coming from the mobile nodes.

Each of the approaches has been evaluated over the same pre-generated set of 840 scenarios with varying movement patterns and traffic loads. Mobile nodes move using a random waypoint model with changing pause times. Nodes start the simulation being static for *pause time* seconds. Then they pick up a random destination inside the simulation area and start moving to the destination at a speed uniformly distributed between 0 and 20 m/s (mean speed = 10m/s). After reaching its destination this behavior is repeated until the end of the simulation. Seven different pause times were used: 0, 30, 60, 120, 300, 600, and 900 seconds. A pause time of 0 seconds corresponds to a continuous motion whereas a pause time of 900 seconds corresponds to a static scenario. For each of these pause times 10 different scenarios where simulated. The results were obtained as the mean values over these 10 runs to guarantee a fair comparison among the alternatives.

Four different traffic loads where tested consisting of 5, 10, 15, and 20 different CBR sources communicating with nodes in the fixed network. Each of these CBR sources start sending data at an uniformly distributed time within the first 10 seconds of the simulation. Each of the sources generates 512 bytes data packets at a rate of 5 packets per second (20Kb/s).

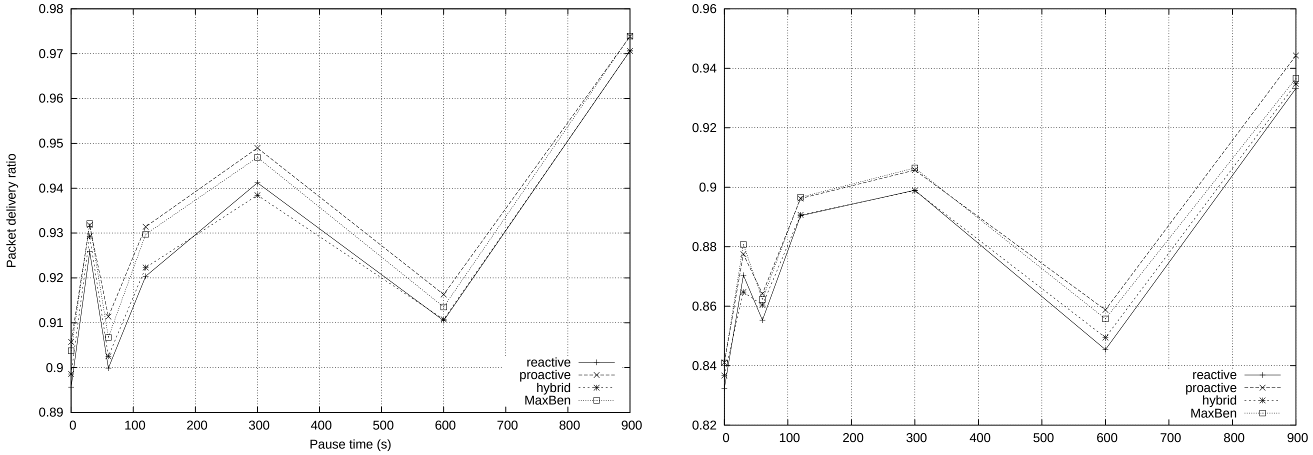
4.2. Performance metrics

To assess the effectiveness of the different gateway discovery mechanisms, we have used the following performance metrics:

- Packet delivery ratio. Defined as the number of data packet successfully delivered over the number of data packets generated by the sources.
- Routing overhead. Defined as the total number of control packets, including gateway discovery, sent out during the simulation time.

4.3. Simulation Results

The simulation results show that our proposed approach is able to offer a packet delivery ratio as higher as the proactive approach at a slightly higher overhead than the reactive and hybrid approaches. This is clearly shown in the case of 10 and 15 sources in figures 5(a) and 5(b) respectively. This high differences in overhead are due to the fact that sometimes during the simulation it is required to use higher TTLs



(a) 10 sources

(b) 15 sources

Figure 5. Packet delivery ratio for different number of sources.

than the hybrid approach so that the GWADV messages can reach all the selected sources.

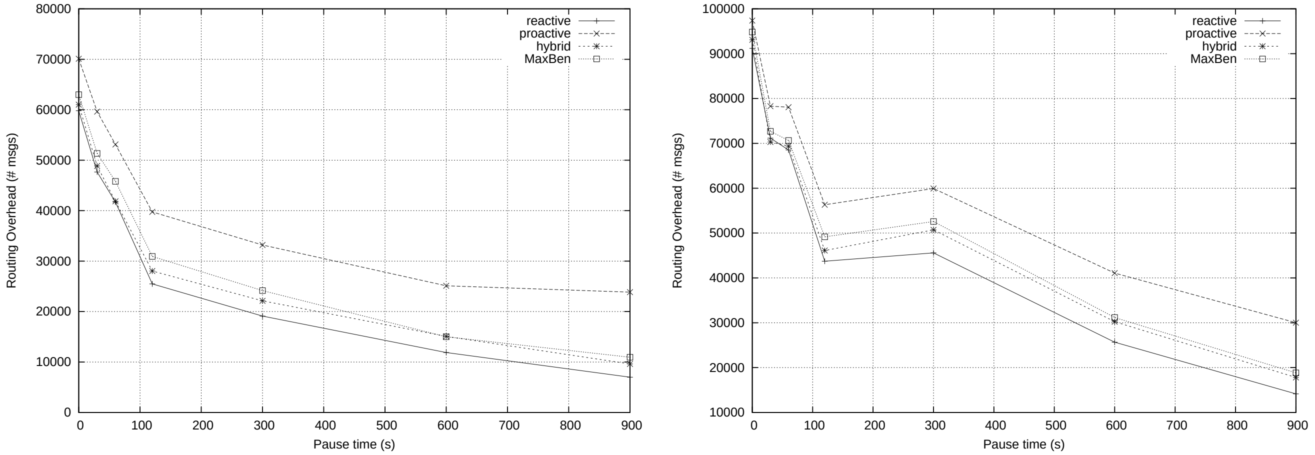
As shown when comparing figures 5(a) and 5(b), the higher the number of sources, the best performs the proposed adaptive scheme compared to the others. In addition, the higher the mobility of the nodes, the best the performance of the adaptive approach. For 10 sources the proposed algorithm is almost obtaining the same packet delivery ratio than the proactive scheme and much better than the hybrid and reactive ones. For 15 sources the proposed approach outperforms all the others. The reason is that with 15 sources the reactive and hybrid approaches require too much overhead due to the need for the sources to reactively discover the gateways. The proactive approach also starts working worse because its high control packet load does not leave enough resources to carry all the data packets generated by the sources. However, the proposed approach by having a lower overhead is able to find a good trade-off between the signaling overhead and the proactivity of the protocol.

Regarding the routing overhead, a similar trend is observed. As it is depicted in figures 6(a) and 6(b), the proposed approach offers a reduction of several thousand of messages in terms of overhead compared to the proactive approach and a little bit more than the reactive and hybrid ones. The differences in overhead are also lesser as the number of sources increase. As explained in our analytical model, this is due to the cost required in the reactive appraoch in which the sources are required to perform a network-wide search of the gateways. It is worth mentioning that the ”maximal benefit coverage” algorithm outperforms all of the other approaches. Key to this is the ability of the maximal benefit algorithm to limit the flooding of GWADV messages only to those sources to which it is cost effective. This is shown in figures 6(a) and 6(b) by a clearly lower overhead of the maximal benefit algorithm compared to the proactive one.

However, the most important result is that, as our analytical model predicted, adaptive approaches can obtain a good trade-off between the efficiency of the protocol in terms of packet delivery ratio and the signaling overhead. As our model also anticipated the performance of the approaches is highly dependent upon the number of sources. In fact, the adaptive approach has shown to be the one which is less affected by the increase of the number of active sources compared to the others. Whereas for 5 sources most of the protocols obtain a high effectiveness, in the rest of the experiments the adaptive approach outperforms the other approaches. In addition, the proposed schemes also tends to be better than the others as the mobility of the nodes increase, which is precisely when the conditions are more demanding. Finally, the maximum benefit algorithm, has been shown to outperform all of the other schemes.

5. Conclusions

We have analytically modeled existing alternatives for gateway discovery in hybrid ad hoc networks. The evaluation has shown that previous approaches do not behave well as the number of sources increase and are not able to offer a good performance in the full range of possible scenarios. We have proposed an adaptive approach being able to dynamically adjust the scope of GWADV messages to obtain the maximal benefit in terms of overhead savings by



(a) 10 sources

(b) 15 sources

Figure 6. Overhead for different number of sources.

avoiding sources to flood the network asking for gateways. We have shown through simulation that the proposed algorithms outperform the approaches proposed so far. In addition, as our model anticipated, we have shown that the proposed approach is more scalable in terms of mobility of the nodes and number of active sources connecting to the Internet than the other approaches.

As a future work we are considering the experimentation with different types of data sources as well as the evaluation of other adaptive coverage algorithms based on heuristic information.

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