Maximal Source Coverage Adaptive Gateway Discovery for Hybrid Ad Hoc Networks

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Abstract. One of the most important aspects affecting the overall performance of hybrid ad hoc networks is the efficient selection of Internet gateways. We have analytically modeled existing proposals (i.e. adaptive, reactive and hybrid gateway discovery) showing that each of them is only suitable for a particular range of network parameters. We propose a new adaptive gateway discovery scheme based on the dynamic adjustment of the scope of the gateway advertisement packets. We show through simulation that our proposed adaptive gateway discovery scheme based on the maximum source coverage outperforms existing mechanisms over a variety of scenarios and mobility rates.

1 Introduction and Motivation

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 these 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 proactive gateway discovery mechanisms scale badly regarding the number of active sources willing to access the Internet.

There are also other 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 a source based routing protocol, which limits very much the applicability 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, by strongly depending on the scenarios under consideration (e.g. number of sources, number of nodes, degree of the network, etc.) can vary dramatically as the network conditions change. 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 author's 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 approach for hybrid networks which is shown through simulation 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 source coverage. The results of the 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 with three different gateway discovery variants: reactive, proactive and hybrid.

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.

To implement the proactive approach, a new message called GWADV ("Gateway Advertisement") is introduced. 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 send GWADV messages only a few hops away. The sources within that range will behave as in the proactive approach, and those beyond that range will find default routes proactively using the same RREQ_I-based reactive scheme described before.

2.1 Analytical Model

In our model, we assume that the 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 figure 1. Given a node n in the lattice (not in the boundary) 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 equation (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.

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

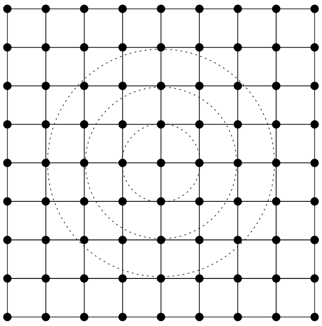

Fig. 1. Rectangular lattice

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 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_INCREMENT=2, TTL_THRESHOLD=7 and NETWORK_DIAMETER=30. Although we think that these values are not appropriate for hybrid networks, we have obeyed the original specification.

Whenever an ad hoc source tries to find a route towards a fixed node it never gets any answer 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 equation (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, plus the number of messages required to send an unicast RREP_I reply from every gateway to the source. Assuming the the gateways are in the borders of the lattice, it is easy to demonstrate that the mean path length is $\sqrt{N} - 1$. Thus, 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 equation (3).

$$\Omega_{r-gw} = N + N_{GW} + N_{GW} \cdot (\sqrt{N} - 1) = N + N_{GW} \cdot \sqrt{N} \tag{3}$$

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 from equation (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 so that every source gets aware that their destination is a fixed node, 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 equation (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 TTLs than $\sqrt{N}-1$, because other gateways will be covering the area beyond that TTL. Then its is easy to derive an expression for the number of nodes which are at t hops, $t \in [0, \sqrt{N}-1]$ from any gateway according to equation (6).

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

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

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 equation (7).

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

If we denote N_c as the number of sources being covered by any gateway when using a TTL of t, then N_c is a random variable obeying a binomial distribution $B \sim (S, P_c(t))$. Thus, the mean number of sources being covered when gateways use a TTL of t can be computed as $E[N_c] = S \cdot P_c(t)$. 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 t 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 equation (8).

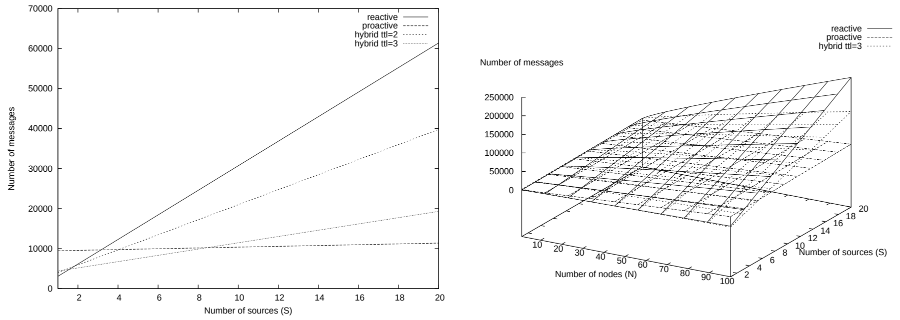
$$\Omega_h = S \cdot \Omega_{FN} + \lambda_{adv} \cdot t \cdot (N_r^{GW}(t) + 1) \cdot N_{GW} + \Omega_{r-gw} \cdot \lambda_{dur} \cdot t \cdot S \cdot (1 - P_c(t)) \tag{8}$$

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 has 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 figure 2(a) and figure 2(b).

Table 1. Values used for the analytical evaluation graphs.

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

As is it also shown in figure 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 figure 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



(a) (b)

Fig. 2. Overhead vs. number of source (a) and vs. number o nodes and number of sources (b)

seems to be unrealistic without adding some degree of adaptability. We describe our proposed hybrid approach in the next section.

3 Adaptive Approach Based on Maximal Source Coverage

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 or at least reaching a good trade-off between performance and network overhead.

From the model of the hybrid approach we have learnt 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.

In our approach, the gateways will keep track (using a structure like the one which is shown in 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. This table will be periodically purged so that stale entries do not influence the TTL of the next advertisement.

IP address	TTL	Time learnt
....		

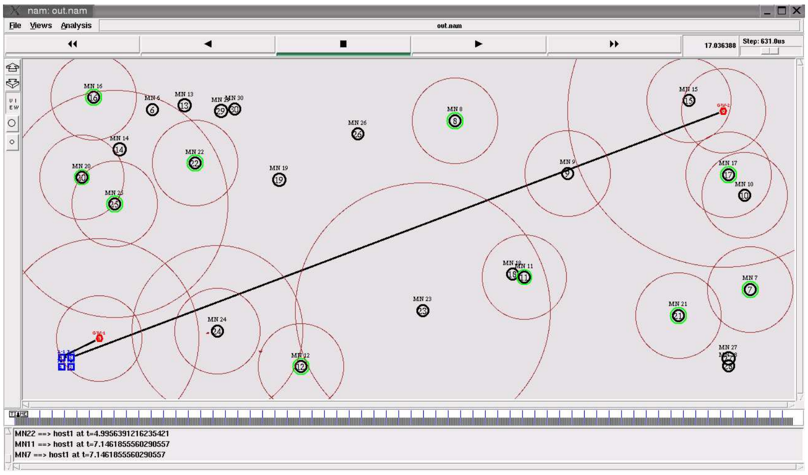
Fig. 3. Table to store source TTL entries

The second part of the problem is which heuristic to use for selecting the TTL of the next advertisement. We propose what we call the "maximum source coverage algorithm". Using this algorithm the gateway will send out the next advertisement with a TTL equal to the maximum number of hops for all its sources. So, our proposed approach uses one of the most proactive heuristics. Other feasible heuristics which behave more reactively are the selection of the TTL to cover only the first source, the TTL which covers a certain number of sources, the TTL which covers a certain percentage of its sources, etc.

The selection of the maximum source coverage is because our main concern is maintaining a high packet delivery ratio as close as possible to the proactive approach at a low overhead. The other heuristics tend to produce in some scenarios less overhead than the selected one, but would achieve a lower packet delivery ratio and would have been less scalable regarding the number of sources. As we show in the next section the proposed approach is able to obtain a similar throughput than the proactive approach while keeping the overhead in the figures of the hybrid and proactive ones.

4 Simulation Results

In order to assess the performance of the proposed scheme, we have performed a series of simulations using 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. An example scenario is shown in figure 4.



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MN22 ==> host1 at t=4.9956391216235421
MN11 ==> host1 at t=7.1461855560290557
MN7 ==> host1 at t=7.1461855560290557
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Fig. 4. Visualization of simulated scenarios

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 a time uniformly distributed between 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).

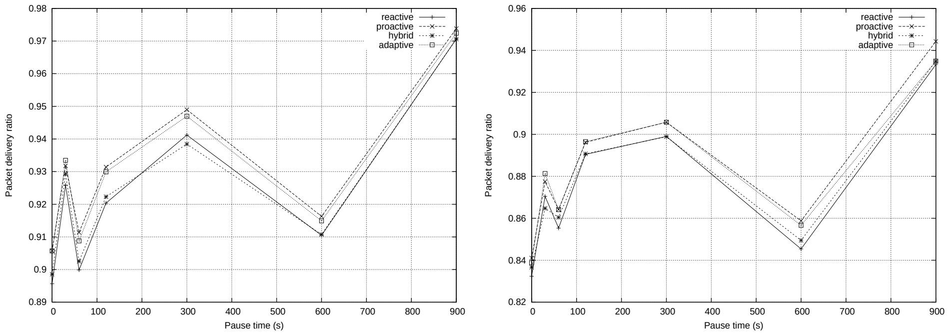
4.1 Performance metrics

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.
- Normalized effectiveness. Defined as the number of packets successfully delivered minus the (weighted) number of control packets required divided by the total number of data packets generated by the sources. This metric gives a value of the overall performance by taking into account not only the packet delivery ratio but the overhead. The maximum value of 1 would only be achieved when all data packets are delivered without any overhead.

4.2 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 differences in overhead are due to the fact that sometimes during the simulation it is required to use higher TTLs than the hybrid approach so that the GWADV messages can reach all the sources.

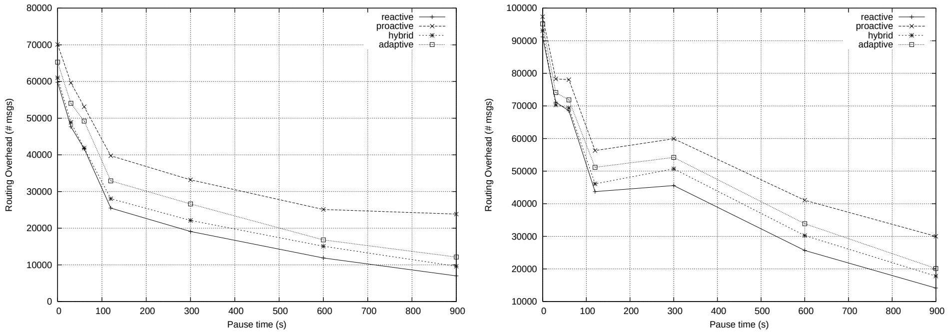


(a) 10 sources (b) 15 sources

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

As shown when comparing figures 5 (a) and 5 (b), the higher the number of sources, the best performs our approach 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 approach 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 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 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 has a lower overhead than 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.



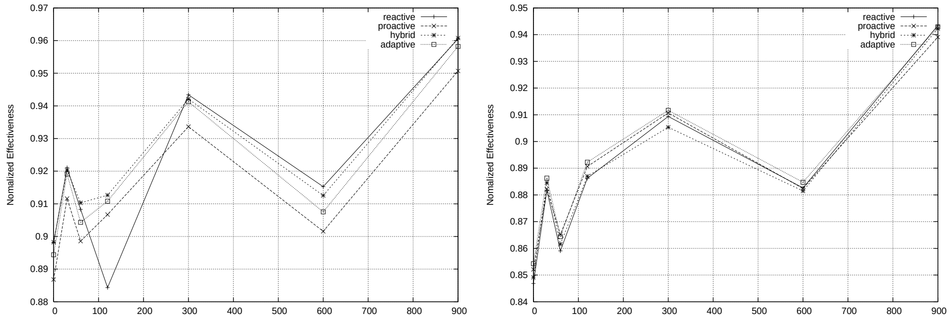
(a) 10 sources

(b) 15 sources

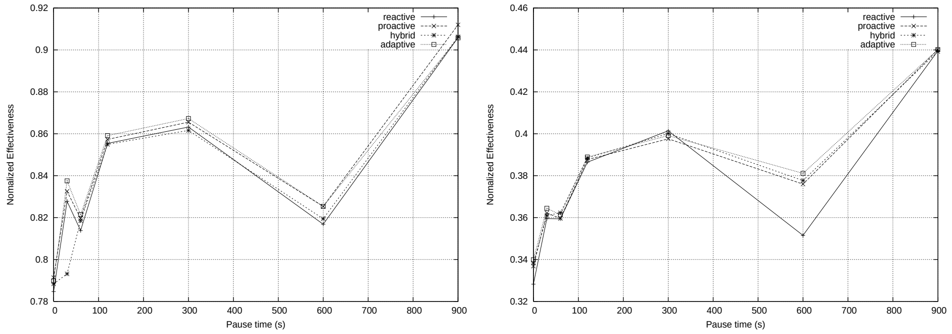
Fig. 6. Overhead for different number of sources sources.

The packet delivery ratio is a good metric to evaluate the performance of the protocol from the outside. That is, what is the performance obtained by the applications. Conversely, the routing overhead is a good internal metric of how much network resources does the protocol need to do its work. So, in order to evaluate the overall performance of the different solutions we need a metric taking into account both internal and external performance. As explained in the previous subsection, the metric that we will use is the normalized effectiveness. Of course, we adjust the weighting factor to give more importance to achieving a good packet delivery ratio, but there is a penalization for not doing it at a low overhead.

In figure 7 we show the normalized effectiveness for different number of sources and different mobility rates. As the mobility of the nodes decrease (higher pause times) the performance of all the approaches improve. The cause is that the number of link breaks decreases and so does the control overhead required to re-establish the routes to to the gateways. It is also worth mentioning that the low performance of all the protocols at a pause time of 600 seconds is due to the fact that the random scenario generator produced several scenarios with very bad connectivity and by no means that performance is related with the mobility of the network.



(a) 5 sources (b) 10 sources



(c) 15 sources (d) 20 sources

Fig. 7. Normalized effectiveness for increasing number of sources.

However, the most important result is that, as our analytical model predicted, an adaptive approach can obtain a good trade-off between the efficiency of the protocol in terms of packet delivery and the signaling overhead. As our model also anticipated the performance of the approaches is highly dependent on the number of sources. In fact, the adaptive approach has shown to be the one which is less affected by the increase of the 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 scheme also tends to be better than the others as the mobility of the nodes increase, which is precisely when the conditions are more demanding.

5 Conclusions and Future Work

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. Furthermore, the proposed model shows hybrid approaches based on limiting the scope of GWADV messages as a good trade-off between performance and overhead. We have proposed an adaptive approach being able to dynamically adjust the scope of GWADV messages to reach the maximal number of active sources. We have shown through simulation that the proposed scheme outperforms 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 kinds of data sources as well as the evaluation of other adaptive coverage algorithms different from the maximal source coverage.

Acknowledgments

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