Using Evolving Graphs Foremost Journeys to Evaluate Ad-Hoc Routing Protocols

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Abstract. *The performance evaluation of routing protocols for ad hoc networks is a difficult task. However, a graph theoretic model – the evolving graphs – was recently proposed to help capture the behavior of dynamic networks with fixed-schedule behavior. Our recent experiments showed that evolving graphs have all the potentials to be an effective and powerful tool in the development of routing protocols for dynamic networks. In this paper, we design a new congestion avoidance mechanism and a modified end-to-end delay metric in order to improve the evolving graph based routing protocol proposed previously. We use the NS2 network simulator to compare this new version to the three protocols provided by NS2, namely AODV, DSR and DSDV, and to OLSR, which is included in the experiments for the first time.*

1. Introduction and Motivation

Wireless communication networks have become increasingly popular in the computing industry and are widely available in our every day life. A promising type of these networks is the Mobile Ad hoc NETwork (MANET), which is a collection of mobile devices that are dynamically connected in an arbitrary manner, without the aid of any established infrastructure or centralized administration [Corson and Macker 1999]. These mobile devices with wireless transmitters are called *nodes*. When two nodes want to communicate, they may not be within each other's range, but they may communicate if other nodes between them also participate in the network, acting as routers, forwarding packets to the other end. These are called multi-hop wireless ad hoc networks.

In several environments these nodes are free to move and they may have nonuniform characteristics, driving the emergence of complex ad hoc networks that may have a highly dynamic behavior. Thus, a large number of routing protocols have been developed for MANETs [Akyildiz et al. 2002]. Besides the mobility, such protocols must deal with the typical limitations of these networks, like energy limitations, low processing capacity, low bandwidth, and high error rates [Corson and Macker 1999].

There are different approaches which try to optimize the cost of a routing path, but most of them do not take into account the fact that some networks may have a predictable dynamics. This is the case of some networks such as low earth orbit satellite systems

(LEO), some wireless sensor networks, and periodic or cyclic behavior networks like public transportation.

LEO satellite networks communicate via inter-satellite links among satellites that are in communication range of each other, and the topology behavior is fixed. Hence the trajectories of the satellites are known in advance, and it is possible to exploit this determinism in routing optimization [Ferreira et al. 2002].

Wireless Sensor Networks (WSN) [Akyildiz et al. 2002] are composed of hundreds or even thousands of sensor nodes inter-connected and collaborating with each other to perform a specific task, e.g., detection of fire in forests, mapping of bio-complexity of the environment, vehicle tracking and detection, etc. Due to energy limitations, network nodes can be scheduled to sleep in given periods, in the aim of energy saving. So, in this case, the network topology changes can also be predicted.

The behavior of these networks, henceforth referred to as ***Fixed Schedule Dynamic Networks*** **(FSDNs)** [Ferreira 2004, Bui-Xuan et al. 2003], is such that the topology dynamics at different time intervals can be predicted (see Fig. 1(a)). Therefore, since the classical graph model hardly apply to these networks, recently, *evolving graphs* (EG) [Ferreira 2004, Bui-Xuan et al. 2003] have been proposed as a formal abstraction for dynamic networks, and can be perfectly suited to the case of FSDNs and the construction of least cost routing and other algorithms. The algorithms and insights obtained through this model are theoretically very efficient and intriguing.

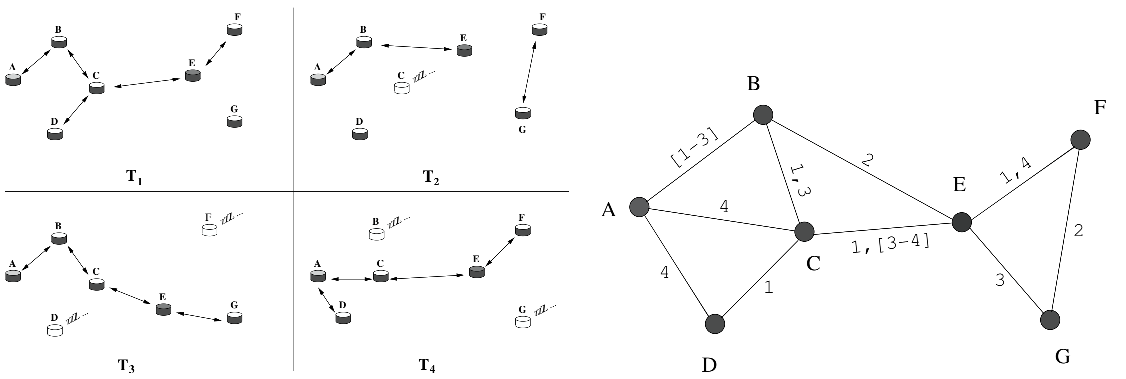
The first implementation and evaluation of an EG routing protocol was done through simulations in [Monteiro et al. 2006] and the results were compared to three other ad-hoc protocols. Extending that work, we have conducted a performance evaluation through extensive simulations using *NS2*. The results are compared to four major ad hoc protocols: DSDV, DSR, AODV and OLSR. In this work we give a more elaborated and detailed behavioral analysis of the congestion on a EG based routing protocol, and a different average end-to-end delay metric is used to measure the performance of the EG protocols over the others. We also include OLSR in the comparison charts and provide much more experimental data.

The remainder of this paper is organized as follows: In the next section we describe the concept of *evolving graphs*. Section 3 shows the simulation environment and the decisions made in the implementation. Section 4 presents the simulation results and analyses. Finally, we present our conclusions in Section 5.

2. Evolving Graph Model

To capture the deterministic behavior of some fixed scheduled dynamic networks (FSDNs), we use the *evolving graph* (EG) model introduced recently. This theory studied in [Ferreira 2004, Bui-Xuan et al. 2003] aims to represent a formal abstraction of dynamic networks, which formalize a time domain in graphs.

As an example, consider the four snapshots taken at different time intervals of a MANET, as depicted in Fig. 1(a). As one can readily observe, nodes D and G are never connected on a single time interval. Notwithstanding, D can indeed send messages to G, using the *path over time* composed of D, C, E, F, G. Surprisingly, this otherwise trivial fact cannot be directly modeled by usual graphs.



(a) The evolution of a MANET over time.

(b) Evolving graph corresponding to the MANET in the left.

Figure 1. Edges are labeled with corresponding presence time intervals. Observe that $\{E,G,F\}$ is not a valid journey, since the edge $\{G,F\}$ exists only in the past with respect to $\{E,G\}$.

Concisely, an evolving graph is an indexed sequence of τ subgraphs of a given graph, where the subgraph at a given index corresponds to the network connectivity at the time interval indicated by the index number, as shown in Fig. 1(b).

The time domain is further incorporated into the model by restricting *journeys* (i.e., the equivalent of *paths over time*) to never move into edges which only existed in past subgraphs. A journey in an evolving graph is thus a path in the underlying graph whose edge time-labels are in a non-decreasing order. Now, it is easy to see in Fig. 1(b) that D, C, E, F, G is a journey, as mentioned above. Further, note that D, C, E, G is also a journey, with less hops, but delivering the message later (in time interval 3 instead of 2), giving raise to different objective functions that may be optimized.

2.1. Journey Metrics

In the pursue of an optimal journey in FSDN, three metrics have been formalized until now for EG [Bui-Xuan et al. 2003]. They are the *foremost*, *shortest*, and *fastest journey*, which find, respectively, the earliest arrival date, the minimum number of hops, and the minimum delay (time span) route. These three parameters can be individually optimized in polynomial time [Bui-Xuan et al. 2003].

We use in this paper the *Foremost Journey* algorithm, which computes from a source node s the journeys that arrive the earliest as possible on all other nodes. The algorithm to compute such journeys can be seen as an adaptation of *Dijkstra*'s shortest paths algorithm, and is detailed below. The *Foremost Journey* is chosen among other journey metrics because it is the most intuitive.

2.2. Foremost Journey Algorithm

To compute the *Foremost Journey* from s at time t to all other nodes, we use a direct adaptation of *Dijkstra* as detailed in [Bui-Xuan et al. 2003]. The output of the algorithm is a tree with the *Foremost journey* traversal paths from s to all other nodes. The routing protocol originated by this algorithm will be henceforth referred to as $EG_{Foremost}$ and is detailed in Section 3.1

3. Simulation Environment

We have conducted our performance analysis using the *NS2* [NS2 2007] simulator version 2.29, with the mobile extensions by CMU Monarch which provides IEEE 802.11 Medium Access Control (MAC) protocol, and realistic radio and physical layer. The radio model uses characteristics similar to the commercial radio interface, Lucent WaveLAN, modeled as a shared-media radio with a nominal bit rate of 2 MB/s and a nominal propagation range of 250m.

In all simulations, **50 nodes** are randomly placed in a **1500m x 500m** area. The simulation time is **900 seconds**. A number of **10 constant bit rate (CBR) UDP traffic flows**, are chosen between node pairs. The average **traffic rate is 2 packets/sec** with packets with 256 bytes length.

This low data rate is chosen to address a sensor network like environment. The interface queue length at link layer (IFQ) is the default: 50 packets. These values were chosen to be similar as the ones used in [Broch et al. 1998, Perkins et al. 2001]. We do not use TCP for the simulations, as we did not want to investigate TCP particularities, which uses flow control, retransmit features and so on, but rather concentrate on routing protocols behavior.

In these experiments (in contrast with [Monteiro et al. 2006]) we decided to disable the ARP (Address Resolution Protocol) of mobile nodes. In *NS2*, the address resolution is an approximation of the BSD Unix ARP, so the resolution is performed on-demand as packets arrive from the application layer, and the buffer size to each neighbor is only one single packet. When an address resolution is in process, all incoming packet to the same destination will be dropped. This leads to great amount of dropped packets in ARP resolution. Agreeing with the good discussion done in [Carter et al. 2003] by Carter, Yi and Kravets, in which MANET need to have it own ways to do neighbor discovering, the address resolution in our simulations are automatic.

We divided the mobility models in two separated kind of scenarios, one using the popular *random waypoint* (RWP) model [Perkins et al. 2001], and another proposed in [Monteiro et al. 2006] and even more suitable to the case of sensor networks, called *intermittent model*, and explained below.

In the ***Random Waypoint*** (RWP) mobility model, a mobile node alternately moves to a randomly chosen location, with speed chosen from 1 to 20 m/s according to a normal distribution, and pauses for an uniformly chosen time between 0 and PAUSETIME. The simulation was run with values of PAUSETIME varying from 0 (continuous motion) to 900 seconds (very low mobility in the network). To avoid known problems of the RWP model shown in [Yoon et al. 2003], we are using only non-zero values of minimum speed. The use of this classical scenario, yet with its known limitations, is important to compare the results with other performance studies. The program *setdest* from CMU, bundled in *NS2*, were used to generate these scenarios.

The ***Intermittent Model*** is based on fixed position nodes that remain uninterruptedly turning themselves **on** and **off** (awake and sleep) in given periods (see schema on Fig. 2). Here, the parameters we change are the SLEEPPROB (ranging from 0 to 50%), and the HOLDTIME (ranging from 15s to 180s). In the beginning of simulation each node is awake, and for the entire simulation it has a SLEEPPROB probability to go to sleep (turning itself off). If a node goes to sleep, it remains off for an uniformly randomly chosen HOLDTIME.

Once this time expires, the node is turned on and stays awake for the same amount of slept time. If a node does not go to sleep, it will stay awake for HOLDTIME, calculated the same way of former case. This model aims to capture the behavior of networks with functioning schedules, e.g. wireless sensor networks (see chapter 7 of [Krishnamachari 2005]).

Once this time expires, the node is turned on and stays awake for another period based on HOLDTIME. If a node does not go to sleep (chance of $1 - \text{SLEEPPROB}$), it will stay awake for for HOLDTIMEbefore trying again. It is important to point out that HOLDTIMEis recomputed at each state change. We called this scenario ***Intermittent Model*** and is initially proposed in [Monteiro et al. 2006]. We did not find similar mobility models in the literature. This model aims to capture the behavior of networks with functioning schedules, e.g. wireless sensor networks (see chapter 7 of [Krishnamachari 2005]).

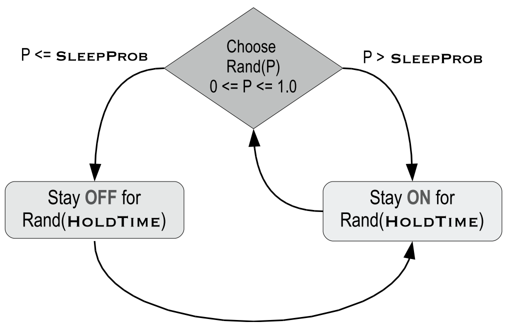

P <= SLEEPPROB
Choose Rand(P) 0 <= P <= 1.0
P > SLEEPPROB
Stay OFF for Rand(HOLDTIME)
Stay ON for Rand(HOLDTIME)

Figure 2. State changes in the Intermittent Mobility Model.

For each evaluated parameter we created 10 random scenarios with different random seeds. Therefore we ran the simulation 110 times for the first model, i.e., 10 times for each value of PAUSETIME: $0, 50, 100, 200, ..., 900$ seconds, and 300 times for the *Intermittent Model*, i.e., 10 times for each combination of SLEEPPROB: $0, 5, 10, ..., 50\%$ and HOLDTIME: $15, 60, 180$ seconds. Note that in the second scenario we change two parameters, and the value of 0% of SLEEPPROB means that no one go to sleep, hence the scenario remains static from the beginning to the end of the simulation, which is relevant as a reference. All five routing protocols (AODV, DSDV, DSR, OLSR, $EG_{Foremost}$) were run on the same 410 scenarios. Thus, identical mobility and traffic scenarios (as they have the same seeds) were used across protocols.

The implementations used to evaluate DSDV, AODV and DSR protocols are the ones provided in the *NS2* package. All of them were implemented by the CMU Monarch group. To the OLSR, we used the implementation by Francisco J. Ros [Ros 2007] (UM-OLSR) version 0.8.8. In all of them, we used the default parameters and constants. AODV implementation, as of *NS2* version 2.29, contains some further optimization code from [Perkins et al. 2001].

Each simulation in *NS2* generates a trace file, containing all communications that have been done between nodes, including the MAC layer. Afterwards this file is analyzed to consolidate the results, shown in section 4.

3.1. Evolving Graph Based Routing Protocol - $EG_{Foremost}$

Mobility in *NS2* is usually represented by a script in Tcl language containing scheduling commands, e.g. *setdest*, *on* or *off*. In general it is saved in a separated file used by the simulation. Therefore, we made a program (*calceg*[*]) that reads a mobility file used by *NS2* and capture the node movements to generate the corresponding EG. This EG is afterwards used as input for the foremost journey *evolving graph* based protocol ($EG_{Foremost}$), as shown in section 2.2. Note that, to calculate the EG, the transmission and reception range of each node must be taken into account, in our case is fixed in exactly 250 meters.

Before the simulation begins, the EG of the network is distributed among all nodes. So, each node in the simulation knows exactly what is going to happen in the network topology during the whole simulation. It knows exactly when some other node will be available or not for communication. At first sight, this important assumption may not appear to be realistic. However, there are many practical situations, e.g. those shown in [Akyildiz et al. 2002, Ferreira et al. 2002], in which an EG can be built before the routing phase. Also, when developing or tuning routing protocols or mobility models, the EG can be generated and used as a reference.

3.2. Implementation details

Supposing that all nodes – this can be changed for transmitting nodes only – have the knowledge of the EG, the implementation of the $EG_{Foremost}$ routing algorithm is straightforward.

Let *edge schedules* be a set of time intervals representing the existence of link-connectivity between two nodes. An *edge* exists when two nodes are in the range of each other. The *Evolving Graph* (EG) of a dynamic network can be represented by a list of *edge schedules* for each pair of nodes. Thus, each node has a list of its neighbors at a given time (remember that the EG is calculated from the mobility scenario and a well known transmission range)

When a packet arrives at the routing layer of node u at time t_{now}, the node computes the *foremost journey* from the packet source s to the destination d. Suppose that the journey next hop is the node v at time t_v. If $t_v = t_{now}$, then both nodes are in the range of each other (i.e, there is an edge in *edge schedules* of (u, v) at time t_{now}), and the packet is readily forwarded to v. Otherwise, if $t_v > t_{now}$, the node is not reachable, and node u must schedule the transmission of the packet to the time t_v. This is the earliest feasible edge present in *edge schedules* of (u, v) with time greater than t_{now} and before the simulation's end time.

Using the example in Fig. 1(b), the foremost journey for a message sent at time index 1 from D to G will be D, C, E, F, G. The packet will reach F at the same time index 1, then afterwards F will schedule to send the packet to G at the earliest edge presence in the *edge schedules* of $F - G$. Hence the packet will be sent by F at time index 2.

If two routes have the same time length when computing the *foremost journey*, the one with less number of hops will be chosen for routing, and in the case where they even have the same number of hops, the route with the smaller node ID will be chosen. This way ensure a complete order when choosing nodes (i.e. sorting nodes in the heap).

[*]The EG implementation and related software can be found at http://julian.com.br/mobidyn/software

3.2.1. Estimating the Node Traversal Time

One important input in the EG graph algorithms is the traversal time to be used in the calculation of the least cost journeys. We did several experiments to estimate the average one-hop delay in scenarios with similar network load as the one used in this paper.

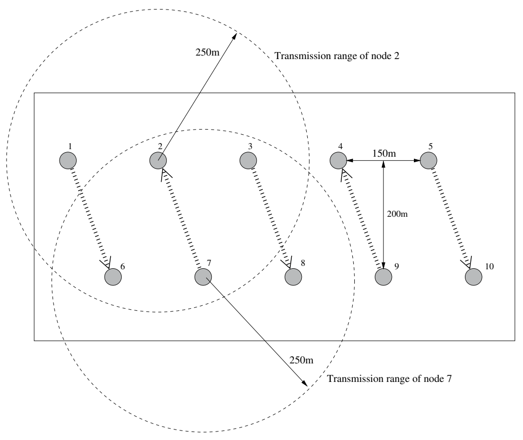


Figure 3. Static scenario to estimate one-hop delay.

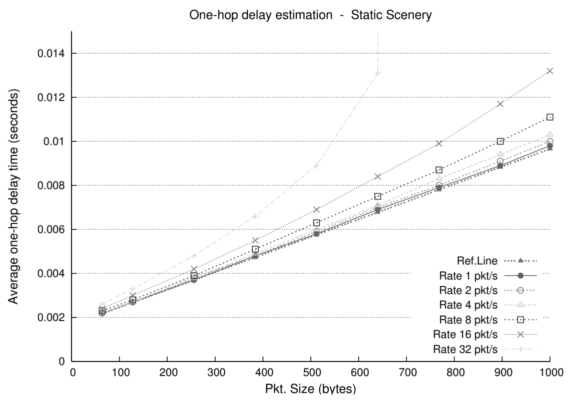


Figure 4. Average one-hop delays time for different traffic rates and packet sizes.

Here, 10 nodes are deployed in one static scenario as shown in Fig. 3. 5 flows are created between nodes and different packet sizes (from 64 to 1000 bytes) and bit rates (from 1 to 32 pkts/s) were simulated. The results (see Fig. 4) showed that the one-hop delay time is almost always linearly dependent of the packet size. So, in all experiments done in this paper, we used a packet size of 256 bytes and a rate of 2 pkt/s, and the average traversal time is estimated in 3.5 ms. The gray dashed line in the bottom is a reference from a 2 node only scenarios (i.e. without collisions).

3.3. Other Routing Protocols

A great deal of work has been produced comparing the performance of the three major ad hoc protocols, DSDV, DSR, and AODV [Perkins et al. 2001, Broch et al. 1998]. Consequently, we chose these three, which are available within NS2 package, to perform the assessment of the $EG_{Foremost}$. For the sake of completeness, we included the OLSR protocol in our experiments. Since we are not going to detail these well-known protocols here, we refer the interested reader to the survey in [Lang 2003].

4. Simulation Results

Our results are based in a simulation of an ad hoc network composed by wireless mobile nodes moving around, going to sleep a while, and communicating with each other. As well as mobility models, the results shown here are separated in two parts, one using the RWP mobility model, and another using the *Intermittent Model.* We focused our analysis in four main metrics:

- **Average throughput**: The average number of packets received per amount of time (from the first packet sent to the last packet received).
- **Average end-to-end delay**: The average time between sending and successfully receiving a packet.

- **Ratio of dropped packets by no route (NRTE)**: Fraction of dropped packets by *no available route* per total number of sent packets. In the case of $EG_{Foremost}$, the NRTE is the number of non-existing routes during the simulation.
- **Ratio of dropped packets by Interface Queue overflow (IFQ)**: Fraction of dropped packets by *link queue overflow* per total number of sent packets. This queue is at the link layer, i.e., it is used when the routing layer want to effectively sent a packet to be delivered.

The $EG_{Foremost}$ used in these experiments do not have any protocol overhead (there are no control messages since all nodes already have the EG of the whole network).

4.1. Random Waypoint Mobility Model

As mentioned earlier, in the RWP scenario the parameter we are changing is the PAUSETIME. Low values of PAUSETIME means *high* mobility and high values of PAUSETIME means *low* mobility.

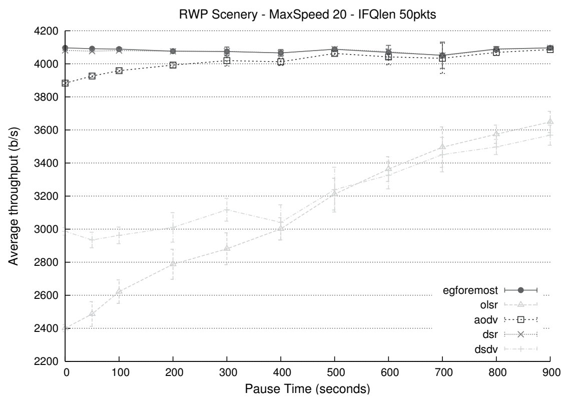


Figure 5. Average throughput as a function of PAUSETIME (mobility).

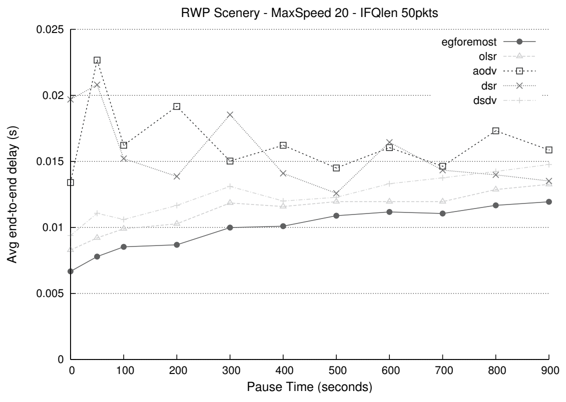


Figure 6. Average end-to-end delay of packets successfully delivered in all protocols.

As shown in Fig. 5, the $EG_{Foremost}$ performance has better values of throughput for all pause times, besides the fact that reactive protocols got very close values in this metric. As suspected, the pro-active (table driven protocols) did not performed well in this first scenario. The periodically updated tables did not get update as fast as needed. They perform better when the mobility decreases. Although the parameters of this mobility model is not so stressing, as we can see, the DSR performed a little better than AODV. Finally, as expected, $EG_{Foremost}$ produced the best results in this metric in all RWP simulations scenarios. The theoretical throughput of the network is $2 * 256 * 8 = 4096$ bits/s and the $EG_{Foremost}$ results are very close to it.

The goal of the foremost journey algorithm is to calculate journeys that reach the destination as soon as possible. But, if we get the absolute values of average end-to-end delay of all packets, the $EG_{Foremost}$ protocol should get high values of delay. Due to the behavior of the EG foremost algorithm, some packets may have to wait for a long time upon an edge exists,

and this time is computed by the end-to-end delay metric. In other words, when using the *Foremost Journey* EG based routing algorithm, the packets could take long in time to reach the destination. However, it is proven in [Bui-Xuan et al. 2003], that using EG the packets will reach the destination as soon as possible if the journey exists in any moment. Indeed, on the other protocols some of this ”late” delivered packets are just being dropped.

Hence, to be fair with the foremost algorithm and better perceive the performance of the $EG_{Foremost}$ protocol, we calculated the average end-to-end delay taking into account only the packets that has been successfully delivered at the destination in all protocols (i.e. the intersection of received packets). The results in the Fig. 6 shows $EG_{Foremost}$ as a lower bound in the end-to-end delay in this scenario. Moreover, almost all packets are delivered. The reactive protocols, AODV and DSR, does not have a smooth curve, due to the induced delays from the route discovering process. The variance of their values is very high too.

4.2. Intermittent Mobility Model

The intermittent mobility scenarios are more realistic in the sense of FSDN networks, on which the nodes have fixed position and their on/off dynamics can be more easily predicted.

In the next results we change the values of SLEEPPROB from 0 to 50%. High probability to sleep means that the network has a low connectivity, i.e., a large quantity of nodes are disconnected from each other because many of them are in sleep state.

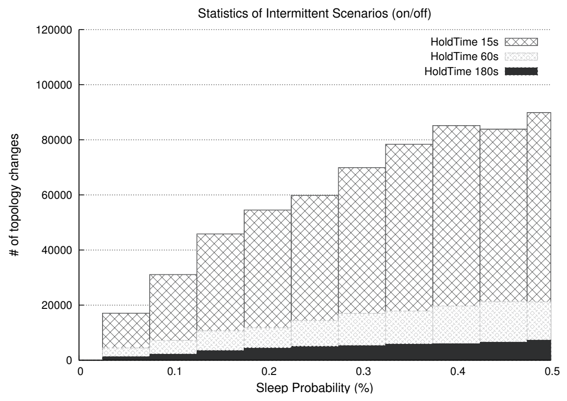
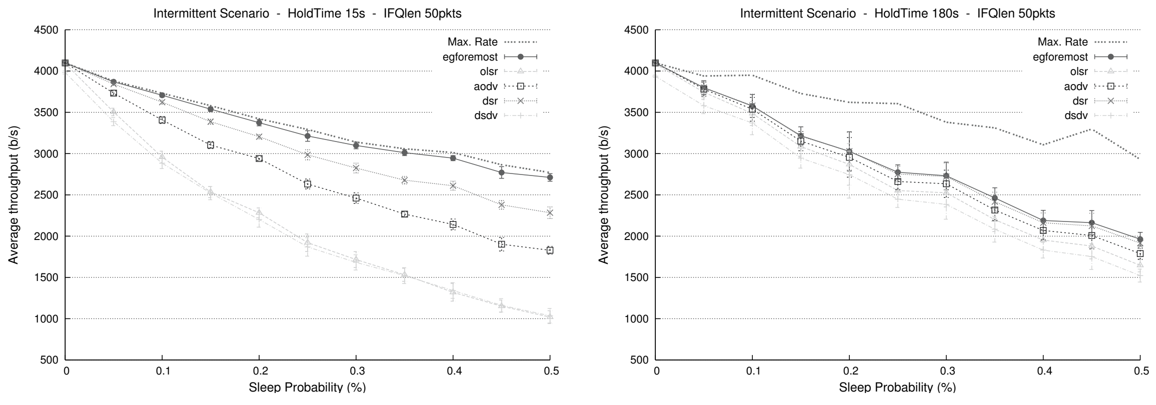


Figure 7. Number of changes in the network topology in the Intermittent Model scenario for different values of SLEEPPROB.

The values of HOLDTIME means dynamism, i.e., how often the connections among nodes changes, low values of HOLDTIME means high dynamics and vice versa. Fig. 7 is an analysis of the Intermittent Model scenarios and illustrates that behavior. In the low connectivity scenarios (50% of SLEEPPROB) the number of topology changes for an HOLDTIME of 15s is 12 times the number of the ones with HOLDTIME 180s.

As we will see in the following results, this model harness some characteristics of mobility that are not captured with the former RWP model.

In Fig. 8, we show again that $EG_{Foremost}$ has better values of throughput. The gray line above all is the rate of generated traffic flows, this means it is the maximum expected value of throughput. The rate value is not constant due to the transmitting nodes

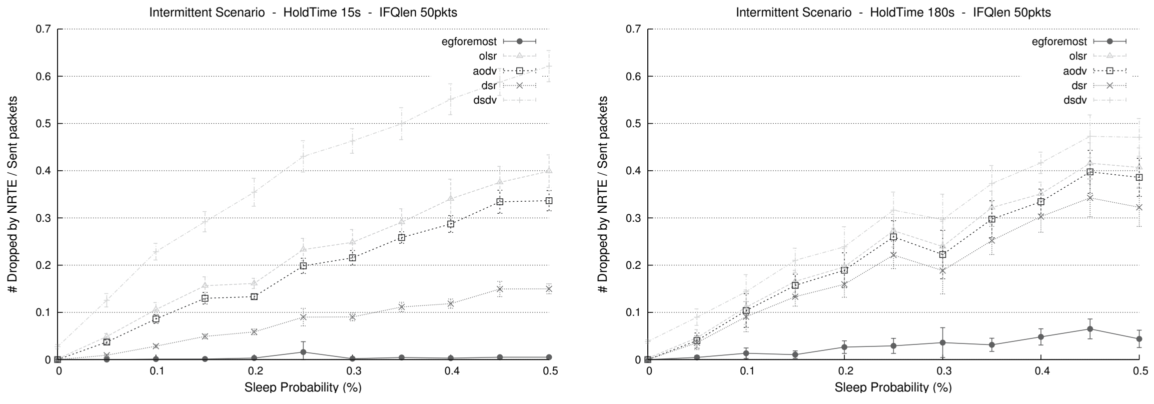


(a) HOLDTIME 15s (b) HOLDTIME 180s

Figure 8. Average throughput as a function of SLEEPPROB (connectivity).

that can also go to sleep, and, when they are off, they do not generate traffic. In Fig. 8(a) the values of the flow rate vary from 4096 b/s to 2728 b/s, an decrease of 33.4% of generated packets in the network.

Observing the results, in the case of high dynamics (HOLDTIME 15s), the throughput of $EG_{Foremost}$ is almost the highest possible in all connectivity scenarios (the throughput curve is very close to the flow rate). On the other hand, in the case of low dynamics, the values of throughput for EG decreases, with the others protocols, as the connectivity decreases (from 0 to 50% SLEEPPROB).



(a) HOLDTIME 15s (b) HOLDTIME 180s

Figure 9. Drop packets by NRTE ratio as a function of SLEEPPROB (connectivity).

This $EG_{Foremost}$ loose of performance (37% less if compared to the rate of flow) is not related to the number of inexistent routes. As shown in the graph of Fig. 9, the number of packet dropped by NRTE is very low (an average of 3.3% on the low connectivity scenario). The values of dropped packets by no available route (NRTE) means that there are no available path from the moment of generation to the end of simulation.

So, the explanation of this throughput decrease on low connectivity scenarios is not due to inexistent routes, but to another reasons explained ahead:

4.2.1. Bottlenecks and Congestion

The intrinsic behavior of $EG_{Foremost}$ to schedule packets to be sent when some node awakes arises the problem of *bottlenecks*, on which a large quantity of packets are scheduled to be sent in the same moment, and the link interface queue (IFQ) does not hold that incoming traffic (the default value in *NS2* is 50 pkts). Furthermore, the EG algorithm do not have any mechanism to load balance the flows, so, many flows with different sources could potentially pass through the same path in the middle of the journey, even when some other ones are available at the same cost (i.e. arriving at the same time).

The simulation done using the *random waypoint model* does not suffer from this effect, due to the high mobility of the system, the *bottlenecks* do not exist at all. This characteristic appeared in the low connectivity and low dynamics scenarios of the *Intermittent Model*, on which the nodes in the evolving graph remain disconnected for long time periods, and a large quantity of packets are being scheduled to the moment when these nodes wake-up.

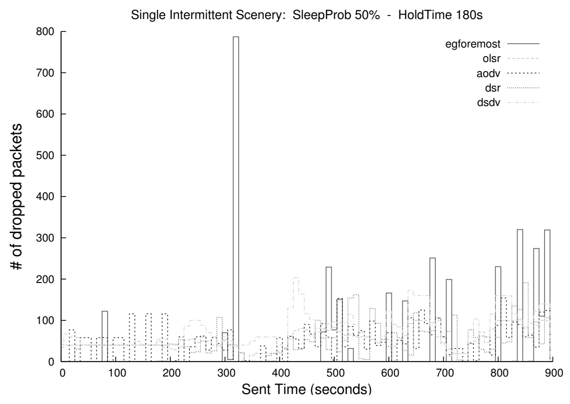


Figure 10. Number of dropped packets over time for one single Intermittent Scenario (SLEEPPROB 50% and HOLDTIME 180s).

The histogram at Fig. 10 contains the number of dropped packets over time on one single simulation, in this case, is one scenario with SLEEPPROB of 50% and HOLDTIME of 180s. It shows that the packets are dropped in the $EG_{Foremost}$ in a burst, and again, due to few specific nodes that goes to sleep for a long a time and when they wake-up, a large quantity of packets are waiting to be sent, overflowing the queues and then dropping packets.

In Fig. 11 we see the high values of dropped packets by IFQ overflow on a low connectivity scenario (35% of packets are dropped by IFQ). These high values negatively affect the throughput of $EG_{Foremost}$ as already shown in Fig. 8(b). We tried 3 different approaches to minimize this dropping problem (see Table 1):

1. **Jitter**: Add an enforced jitter (uniformly random value from 0 to 0.5s) at sent time to each packet;
2. **SmartJitter**: Add a fixed size jitter only when some connection is congested, the size of this jitter is the same as the average edge traversal time;
3. **Increase the IFQ length**: Raise buffer size of the interface queue from 50 to 500 pkts.

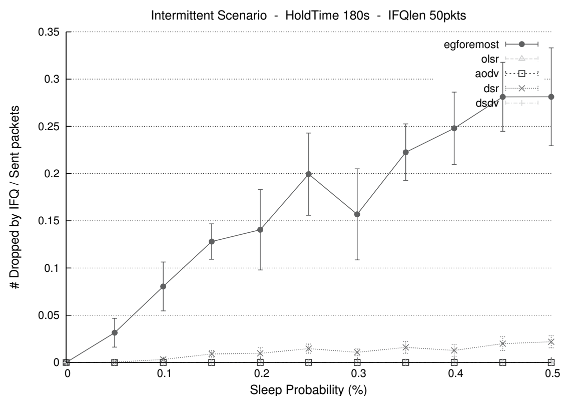


Figure 11. Number of dropped pkts by IFQ on HOLDTIME 180s

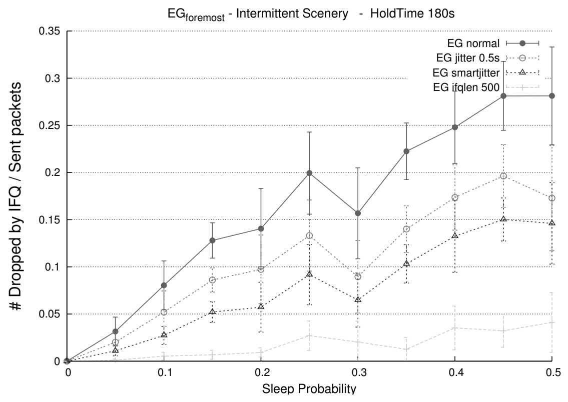


Figure 12. Different approaches to minimize the drop by IFQ rate (enforced jitter, smart jitter and raise de ifqlen to 500pkts).

Table 1. Scheduling schemas used to minimize the bottlenecks (Fig. 12).

Packet	IFQlen 500	Jitter 0.5s	SmartJitter
p_1	t	t + rnd(0.5)	t
p_2	t	t + rnd(0.5)	t
…	t	t + rnd(0.5)	t
p_{50}	t	t + rnd(0.5)	t
p_{51}	t	t + rnd(0.5)	$t + \delta$
p_{52}	t	t + rnd(0.5)	$t + 2 * \delta$
p_n	t	t + rnd(0.5)	$t + (n - IFQlen) * \delta$

The results of the experiments with these 3 approaches can be seen in Fig.12. *EG normal* is the reference curve, as seen in Fig. 11. The first approach is the enforced random chosen jitter from 0 to half second (0.5s) when sending each packet at each node. In the average, the number of dropped packets decreased 30%. One trade-off with this approach is the high values of end-to-end delay, due to the extra time added at each scheduled packet.

The second one, the SmartJitter, is an improvement of the former. Here, when the queues (one for each pair of neighbors) are not full, the nodes can send packets to other nodes without any jitter on sent time. However, when some node fulls the IFQueue, then a fixed size jitter is added to each subsequent packet to be sent. The calculation of the SmartJitter time at node u sending a packet to v at time t_v is shown in the following schema:

```
**if** $npkts[t_v] \leq IFQlen$ **then**
    $smartjitter = 0$
**else**
    $smartjitter = \delta * (npkts[t_v] - IFQlen)$
**end if**
$t_v = t_v + smartjitter$
$npkts[t_v] = nPkts[t_v] + 1$
```

Where $npkts[t_v]$ is the number of packets already scheduled to use the edge from u to v at time t_v. $IFQlen$ is the interface queue length, and δ is the average traversal time of one-hop transmission. We used the value 3.5 ms in all simulations, and it was estimated from the average value of one-hop transmission with packet size 256 bytes. The value of the traversal time is linearly dependent of the size of the packet. This value was obtained through simulations using similar network load and is briefly discussed in section 3.2.1.

With the SmartJitter, the number of dropped packets decreased 47% compared to original $EG_{Foremost}$.Although, the best solution so far is to increase the default length of the IFQ from 50 to 500 packets. With this last approach, the values of dropped packets decreased 91%. Indeed, the SmartJitter is a good solution, in practical situations, when the size of IFQ buffer could not be changed.

5. Conclusion

Our main contribution in this paper is to address some questions stemming from the first implementation of an EG routing protocol [Monteiro et al. 2006], and to reinforce that EG theory can be used as a benchmark tool to the development of other ad-hoc protocols.

For instance, a congestion problem may happen when a highly loaded node remains unavailable for long time, causing a huge overhead when it comes back, and packets are dropped due to packet collision and queue overflows. The use of high values of enforced jitter time when sending packets can minimize the drop rate, but is not feasible in regular protocols. We introduced the *SmartJitter* as an option to minimize the congestion and achieved good results. The development of a good EG adaptive algorithm could possibly manage that problem, identifying such congested nodes to find out alternative routing paths. However there are no theoretical results on flows over EGs, which remains an interesting open problem.

It should be noted that the high values of average end-to-end delay is an inherent characteristic of the communication network dynamics. In the case of EG based protocols, on which the *foremost journey* metric is studied, the end-to-end delay is in any case the minimum arrival date for a packet. If large delays are not acceptable, then one policy could be to drop packets that are aged in the network, or – even better – use a *fastest journey* approach instead of the *foremost journey* as done here.

Future work includes implementation of other EG based protocols with different metrics, like *shortest path* and *fastest journey*. A natural extension to this work is related to the deviations in the predicted network dynamics, on which the actual EG used by the nodes is not accurate anymore. This engenders the utilization of a model with stochastically predictable behavior to better address such variations.

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