Performance Evaluation of Existing Approaches for Hybrid Ad Hoc Networks across Mobility Models

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Abstract

There is being an on-going effort in the research community to efficiently interconnect Mobile Ad hoc Networks (MANET) to fixed ones like the Internet. Several approaches have been proposed within the MANET working group of the Internet Engineering Task Force (IETF), but there is still no clear evidence about which alternative is best suited for each mobility scenario, and how does mobility affect their performance. In this paper, we answer these questions through a simulation-based performance evaluation across mobility models. Our results show the performance trade-offs of existing proposals and the strong influence that the mobility pattern has on their behavior.

1 Introduction and Motivation

Mobile ad hoc networks consist of a number of mobile nodes which organize themselves in order to communicate one with each other wirelessly. These nodes have routing capabilities which allow them to create multihop paths connecting nodes which are not within radio range. These networks are extremely flexible, self-configurable, and they do not require the deployment of any infrastructure for their operation. However, the idea of facilitating the integration of MANETs and fixed IP networks has gained a lot of momentum within the research community. In such integrated 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 are gateways which can be used by other nodes to seamlessly communicate with hosts in the fixed network.

Within the IETF, several solutions have been proposed to deal with the interconnection of MANETs to the Internet. One of the first proposals by Broch et al. [1] is based on an integration of Mobile IP and MANETs employing a source routing protocol. MIPMANET [2] followed a similar approach based on AODV, but it only works with Mobile IPv4 because it requires foreign agents (FA). In general, these approaches are tightly coupled with specific types of routing protocols, and therefore their applicability gets restricted.

The proposals which are receiving more attention within the IETF and the research community in general are those from Wakikawa et al. [3] and Jelger et al. [4], which define different gateway discovery functions and address allocation schemes. Another interesting proposal is that from Singh et al. [5], which proposes a hybrid gateway discovery procedure which is partially based on the previous schemes.

Many works in the literature have reported the strong impact that mobility has on the performance of MANETs. Thus, mobility will be a central aspect in our evaluations. In particular, we have employed three well-known mobility models (Random Waypoint, Gauss–Markov and Manhattan Grid) that we have used to deeply investigate the inter-relation between the Internet interconnection mechanism and the mobility of the network. An in-depth survey of the Random Waypoint and Gauss–Markov models (and others) can be found in [6], while the Manhattan Grid model is defined in [7].

The main novelty of this paper, is the investigation of the performance of the Internet connectivity solutions which are receiving more attention within the IETF. To the best of our knowledge, such kind of study has not been done before. In the authors' opinion, this paper sheds some light onto the performance implications of the main features of each approach, presenting simulation results which provide valuable information to interworking protocol designers. Moreover, these results can be used to properly tune parameters of a given solution depending on the mobility pattern of the network, what can also be useful for hybrid MANETs deployers.

The remainder of the paper is organized as follows: Section 2 provides a global sight of the most important current interworking mechanisms. The results of the simulations are shown in Section 3. Finally, Section 4 gives some conclusions and draws some future directions.

2 Analysis of Current Proposals

In this section we explore the most significant features of the main MANET interconnection mechanisms nowadays, namely those from Wakikawa et al., Jelger et al. and Singh et al. We refer to these solutions using the surname of their first author from now on. Table 1 summarizes the main features provided by each solution.

2.1 Address Allocation

Nodes requiring global connectivity need a globally routable IP address if we want to avoid other solutions like Network Address Translation (NAT). There are basically two alternatives to the issue of address allocation: they may be assigned by a centralized entity (stateful auto-configuration) or can be generated by the nodes themselves (stateless auto-configuration). The stateful approach is less suitable for ad hoc networks since partitions may occur, although it has also been considered in some works [8]. Both "Wakikawa" and "Jelger" specify a stateless auto-configuration mechanism which is based on network prefixes advertised by gateways. The nodes concatenate an interface identifier to one of those prefixes in order to generate the IP address. Currently, "Singh" does not deal with these issues.

	Wakikawa	**Jelger**	**Singh**
Proactive/Reactive/Hybrid	P/R	P	H
Multiple Prefixes	Yes	Yes	No
Stateless/Stateful	Stateless	Stateless	n/a
DAD	Yes	No	n/a
Routing Header/Default Routing	RH	DR	RH/DR
Restricted Flooding	No	Yes	No
Load Balancing	No	No	Yes
Complete Specification	Yes	Yes	No

Table 1: Summary of features of well-known existing proposals.

2.2 Duplicate Address Detection

Once a node has an IP address, it may check whether the address is being used by other node. If that is the case, then the address should be deallocated and the node should try to get another one. This procedure is known as *Duplicate Address Detection* (DAD), and can be performed by asking the whole MANET if an address is already in use. When a node receives one of those messages requesting an IP address which it owns, then it replies to the originator in order to notify the duplication. This easy mechanism is suggested by “Wakikawa”, but it does not work when network partitions and merges occur. Because of this and the little likelihood of address duplication when IPv6 interface identifiers are used, “Jelger” prefers avoiding the DAD procedure.

The main drawback of the DAD mechanism is the control overhead that it introduces in the MANET, specially if the procedure is repeated periodically to avoid address duplications when a partitioned MANET merges.

2.3 Gateway Discovery

The network prefix information is delivered within the messages used by the gateway discovery function. Maybe this is the hottest topic in hybrid MANETs research, since it has been the feature which has received more attention so far. Internet-gateways are responsible for disseminating control messages which advertise their presence in the MANET, and this can be accomplished in several different ways.

“Wakikawa” defines two mechanisms: a reactive and a proactive one. In the reactive version, when a node requires global connectivity it issues a request message which is flooded throughout the MANET. When this request is received by a gateway, then it sends a message which creates reverse routes to the gateway on its way back to the originator. The proactive approach of “Wakikawa” is based on the periodic flooding of gateway advertisement messages, allowing mobile nodes to create routes to the Internet in an unsolicited manner. Of course, this solution heavily increments the gateway discovery overhead because the gateway messages are sent to the whole MANET every now and then.

In order to limit that overhead of proactive gateway discovery, “Jelger” proposes a restricted flooding scheme which is based on the property of *prefix continuity*. A MANET node only forwards the gateway discovery messages which it uses to configure its own IP address. This property guarantees that every node shares the same prefix than its next hop to the gateway, so that the MANET gets divided in as many *subnets* as gateways are present. When “Jelger” is used with a proactive routing protocol, a node creates a default route when it receives a gateway discovery message and uses it to configure its own global address. But if the approach is integrated with a reactive routing protocol, then a node must perform a route discovery to avoid breaking the on-demand operation of the protocol.

Regarding “Singh” approach, it introduces a new scenario where gateways are mobile nodes which are one hop away from a wireless access router. Nodes employ a hybrid gateway discovery scheme, since they can request gateway information or receive it proactively. The first node which becomes a gateway is known as the “default gateway”, and it is responsible for the periodic flooding of gateway messages. Remaining gateways are called “candidate gateways” and they only send gateway information when they receive a request message.

Other research works propose more sophisticated hybrid techniques which proactively send the gateway messages to the nearer nodes, while the furthest ones operate on-demand [9]. Even there are proposals for dynamically changing the coverage of the proactive zone [10].

There is a trade-off between the freshness of the routes and the overhead of the gateway discovery function. The more proactive a solution is, the fresher routes it is going to offer, but it also incurs in a higher overhead. Hybrid schemes make sense because they try to reach a good trade-off.

The controlled flooding scheme of “Jelger” makes this solution more suitable for large ad hoc networks (where many gateways are involved) than the proactive approach of “Wakikawa” and “Singh”. In addition, the latter specification does not manage the situation where several network prefixes are advertised by different access routers. “Wakikawa” does not impose any metric to select the best gateway for a node, although this choice may be performed taking into account the number of hops to the gateway. “Jelger” defines additional criteria like the stability of the IP address and the distance to the gateway.

2.4 Routing Traffic to the Internet

The way traffic is directed to the Internet is also different across approaches. “Wakikawa” prefers using IPv6 routing headers to route data packets to the selected gateways. This introduces more overhead due to the additional header, but it is a flexible solution because nodes may dynamically vary the selected gateway without the need to change their IP address. This helps at maximizing the IP address lifetime. However, “Jelger” relies on *default routing*, i.e., nodes send Internet traffic using their default route and expect the remaining nodes to correctly forward the data packets to the suitable gateway. “Singh” uses both alternatives: default routing is employed when nodes want to route traffic through their “default gateway”, but they can also use routing headers to send packets to a “candidate gateway”.

2.5 Load Balancing

“Singh” depicts an interesting feature which does not appear in the rest of the proposals: a traffic balancing mechanism. Internet-gateways could advertise a metric of the load which passes across them within the gateway discovery messages. MANET nodes could use this information to take a more intelligent decision than what is taken when only the number of hops to the gateway is considered. Unfortunately, no detailed explanation of this procedure is provided in the current specification.

3 Performance Evaluation

To assess the performance of “Wakikawa” and “Jelger”, we have implemented them within the version 2.27 of the *ns2*[1] network simulator. The gateway selection function uses in both cases the criterion of minimum distance to the gateway, in order to get a fair comparison between the two approaches. “Singh” has not been simulated because the current specification is not complete enough and therefore it has not captured the research community attention yet.

In addition, we have also implemented the OLSR protocol according to the latest IETF specification[2]. We have set up a scenario consisting of 25 mobile nodes using 802.11b at 2 Mb/s with a radio range of 250 m, 2 gateways and 2 nodes in the fixed network. These nodes are placed in a rectangular area of 1200x500m^2. 10 active UDP sources have been simulated, sending out a constant bit rate of 20Kb/s using 512 bytes/packet. The gateways are located in the upper right and lower left corners, so that we can have long enough paths to convey useful information. In addition, we use the two different routing schemes which are being considered for standardization within the IETF: OLSR [11] as a proactive scheme, and AODV [12] as a reactive one. This will help us to determine not only the performance of the proposals, but the type of routing protocols for which they are most suitable under different mobility scenarios. The case of OLSR with a reactive gateway discovery has not been simulated because in OLSR all the routes to every node in the MANET (including the gateways) are already computed proactively. So, there is no need to reactively discover the gateway, because it is already available at every node. In both AODV and OLSR we activated the link layer feedback.

Movement patterns have been generated using the *BonnMotion* [3] tool, creating scenarios with the Random Waypoint, Gauss–Markov and Manhattan Grid mobility models. Random Waypoint is the most widely used mobility model in MANET research because of its simplicity. Nodes select a random speed and destination around the simulation area and move toward that destination. Then they stop for a given pause time and repeat the process. The Gauss–Markov model makes nodes movements to be based on previous ones, so that there are not strong changes of speed and direction. Finally, Manhattan Grid models the simulation area as a city section which is only crossed by vertical and horizontal streets. Nodes are only allowed to move through these streets.

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[1] The Network Simulator, http://www.isi.edu/nsnam/ns/.

[2] Code available at http://ants.dif.um.es/masimum/.

[3] Developed at the University of Bonn, http://web.informatik.uni-bonn.de/IV/Mitarbeiter/dewaal/BonnMotion/.

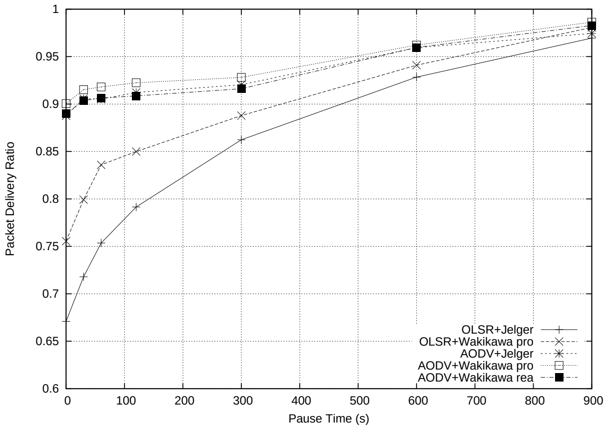


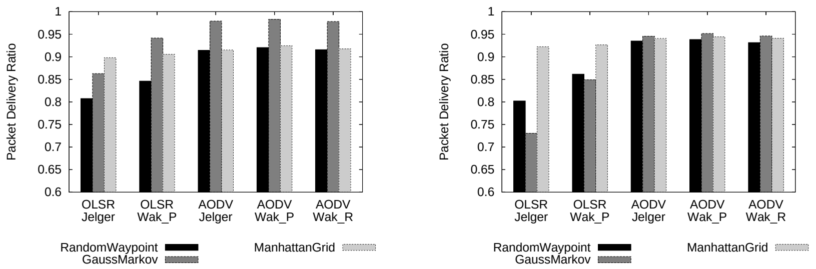
Figure 1: PDR in Random Waypoint model using different pause times (maximum speed = 20 m/s).

All simulations have been run during 900 seconds, with speeds randomly chosen between 0 m/s and (5, 10, 15, 20) m/s. Random Waypoint and Manhattan Grid models have employed a mean pause time of 60 seconds, although the former has also been simulated with 0, 30, 60, 120, 300, 600 and 900 seconds of pause time in the case of 20 m/s as maximum speed. The Manhattan Grid scenarios have been divided into 8x3 blocks, what allows MAC layer visibility among nodes which are at opposite streets of a same block.

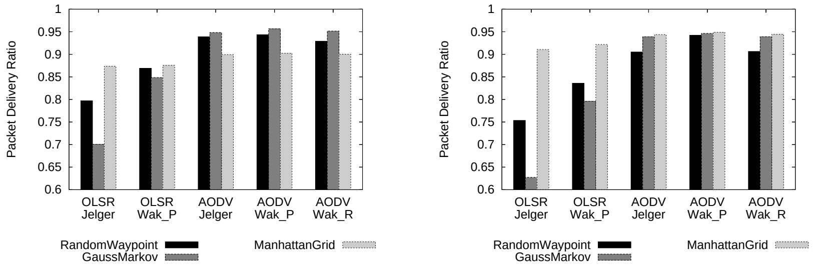
3.1 Packet Delivery Ratio

The PDR is mainly influenced by the routing protocol under consideration, although Internet connectivity mechanisms also have an impact. Similarly to previous simulations of OLSR in the literature, we can see in Fig. 1 that as the mobility increases in the Random Waypoint model, it offers a much lower performance compared to AODV. The reason is that OLSR has a higher convergence time compared to AODV as the link break rate increases. In addition, according to RFC 3626, when link layer feedback informs OLSR about a broken link to a neighbor, the link is marked as “lost” for 6 seconds. During this time packets using this link are dropped in OLSR. This behavior also affects the routes towards Internet gateways, which is the reason why the PDR is so low in OLSR simulations.

In the case of OLSR, “Jelger” performs surprisingly worse than the proactive version of “Wakikawa”. Given that “Jelger” has a lower gateway discovery overhead we expected the results to be the other way around. The reason is that “Jelger” is strongly affected by the mobility of the network. After carefully analyzing the simulations we found out that the selection of next hops and gateways makes the topology created by “Jelger” very fragile to mobility. The problem is that the restrictions imposed by the prefix continuity in “Jelger” concentrates the traffic on a specific set of nodes. In AODV, this problem is not so dramatic because AODV, rather than marking a neighbor as lost, starts finding a new route immediately. So, we can conclude that although prefix continuity has very interesting advantages (as we will see), it has to be carefully designed to avoid



(a) 5 m/s (b) 10 m/s



(c) 15 m/s (d) 20 m/s

Figure 2: PDR obtained from different mobility models for different maximum speeds.

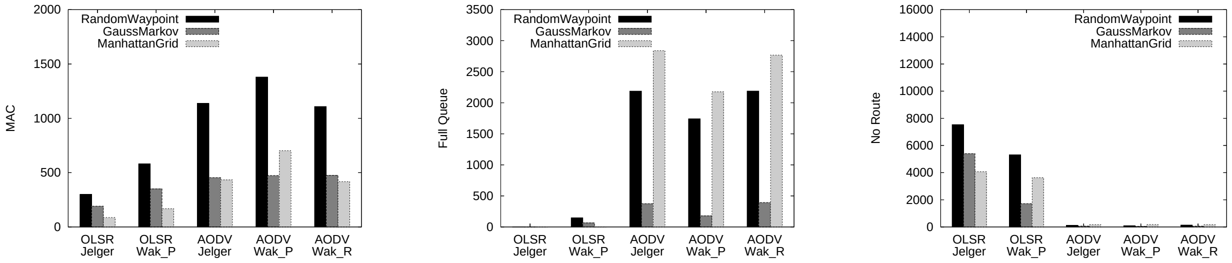
data concentration and provide quick reactions to topological changes.

Regarding AODV, we can see how proactive “Wakikawa” offers a better PDR than the remaining solutions at high speeds. This is due to the proactive dissemination of information, what updates routes to the Internet as soon as they get broken. “Jelger” and reactive “Wakikawa” behave very much the same because the former is designed to create routes on-demand when it is integrated within a reactive routing protocol (although proactive flooding of gateway information is still performed).

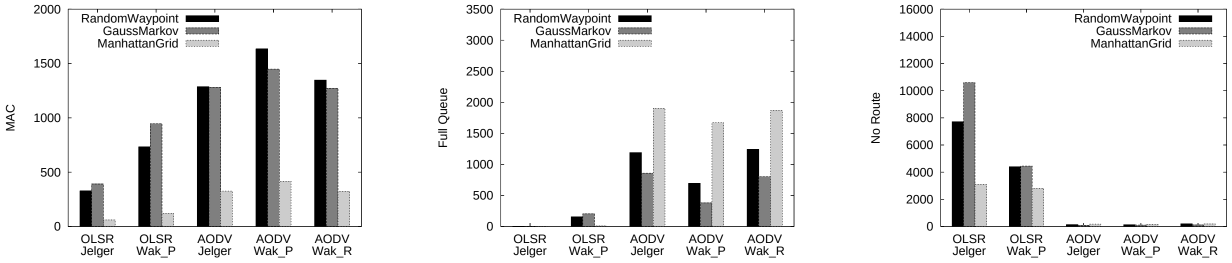
One of our goals is to analyze if the results are congruent across mobility models. Fig. 2 shows a comparison between Random Waypoint, Gauss–Markov and Manhattan Grid mobility models with the above mentioned maximum speeds.

At first sight we can point out an interesting thing: mobility model can heavily influence the resulting PDR, but results seem to be consistent across mobility models. That is, “Jelger” continues offering a lower PDR than “Wakikawa” when they are integrated within an OLSR network, and AODV does not change its PDR very much regardless of the Internet interconnection mechanism and the mobility model used. But in fact, each mobility model influences in a different way every approach showing their strengths and drawbacks. We can better realize this if we make a more in-depth analysis of the causes of packet drops, as we will explain below.

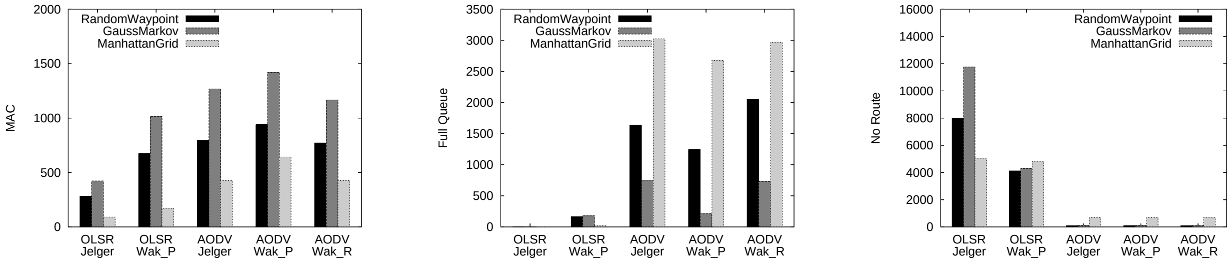
The Gauss–Markov model presents the biggest link break rate of all the simulated mobility



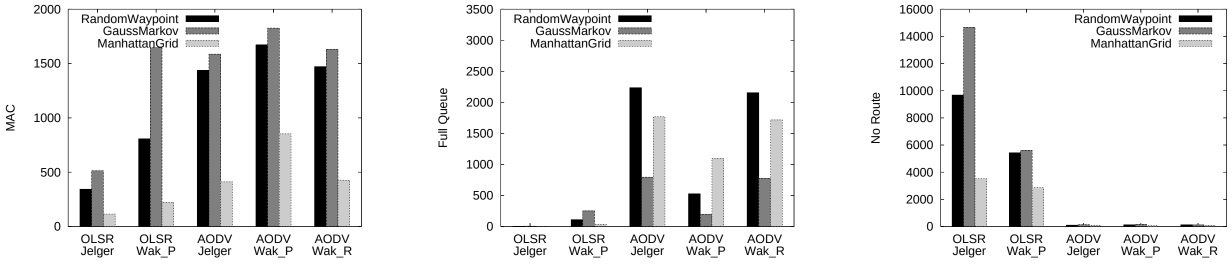
(a) MAC drops (5 m/s) (b) Full Queue drops (5 m/s) (c) No Route drops (5 m/s)



(d) MAC drops (10 m/s) (e) Full Queue drops (10 m/s) (f) No Route drops (10 m/s)



(g) MAC drops (15 m/s) (h) Full Queue drops (15 m/s) (i) No Route drops (15 m/s)



(j) MAC drops (20 m/s) (k) Full Queue drops (20 m/s) (l) No Route drops (20 m/s)

Figure 3: Cause of packet drops for different mobility models.

models when the maximum speed is high. However, it provokes very few link losses at low speeds. This can be explained considering how this model works. If a node selects a high speed for a period of time *n*, then it is quite likely that it will pick a high speed again for the period *n+1*. This implies that it is very likely for nodes to be travelling at high speeds, and this makes links to break more often. Similarly, if it chooses a low speed then it is very likely that it will continue travelling at a low speed.

That sheds some light onto the results of Fig. 2, where it is worth pointing out that the PDR dramatically decreases in OLSR as the maximum available speed of the Gauss–Markov model increases. As we previously said, "Jelger" is less strong against frequent topology changes than "Wakikawa", and that is why this behavior of the Gauss–Markov model impacts more on its performance. Fig. 3 clearly outlines this, because the number of drops due to the absence of a suitable route towards the Internet significantly grows at high speeds in Gauss–Markov model. Moreover, the number of packet drops due to the MAC layer not being able to deliver a packet to its destination (because of a link break) also increases. The mobility model has a lower influence in AODV than in OLSR, because the former is able to easily adapt to changing topologies.

On the other hand, Manhattan Grid model does not cause many link breaks because nodes have their mobility very restricted. Instead of that, mobiles tend to form groups, increasing contention at link layer. This is why this model makes the PDR of OLSR and AODV very similar, enhancing results of the former. In addition, the performance of "Jelger" and "Wakikawa" also tend to equal (recall that "Jelger" is very sensitive to those link breaks which this model lacks). This can be easily seen in Fig. 3. There it is shown how Manhattan Grid mobility model fills up interface queues because of MAC layer contention, while it doesn't cause many drops due to link breaks (MAC and No Route drops). As a note, results obtained by this mobility model should depend on the number of blocks used (in this work we have used a fixed configuration though).

In addition, we can ascertain from Fig. 3 that OLSR is not prone to packet drops due to filling up the interface queue. This is obvious since it does not buffer data packets before sending them. Some of these types of drops appear in "Wakikawa" because of its non-controlled flooding, which creates more layer-2 contention than "Jelger". In the case of AODV, queues get full because data packets are buffered when a route is being discovered. But that is not so heavily evidenced in proactive "Wakikawa" because Internet routes are periodically refreshed.

3.2 Gateway Discovery Overhead

Finally, we evaluate the overhead of the gateway discovery function of each of the proposals. As we can see in Fig. 4, AODV simulations result in a higher gateway overhead as the mobility of the network increases in Random Waypoint model. This is due to the increase in the link break rate, which makes ad hoc nodes find a new route to the Internet as soon as their default route is broken. We can clearly see that proactive "Wakikawa" generates the biggest amount of Internet-gateway messages due to its periodic flooding through the whole network. Reactive "Wakikawa" shows the minimum gateway overhead thanks to its reactiveness. "Jelger" sits in between the other two, due to its limited periodical flooding.

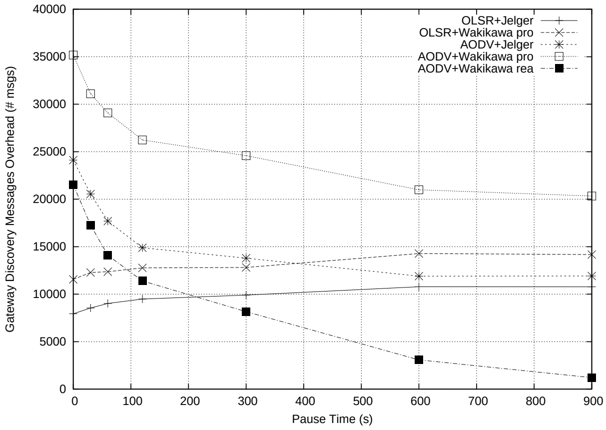


Figure 4: Gateway discovery overhead in the Random Waypoint model using different pause times (maximum speed = 20 m/s).

As it was expected, the gateway discovery overhead for Internet connectivity mechanisms combined with OLSR remains almost unaffected by network mobility. This is due to the fact that Internet connectivity messages are periodically sent out by OLSR without reaction to link breaks. So, its gateway control overhead is not heavily affected by mobility. Fig. 4 shows that “Jelger” always maintains a lower overhead than proactive “Wakikawa” due to the restriction of forwarding imposed by prefix continuity. The difference remains almost constant independently of the mobility of the network.

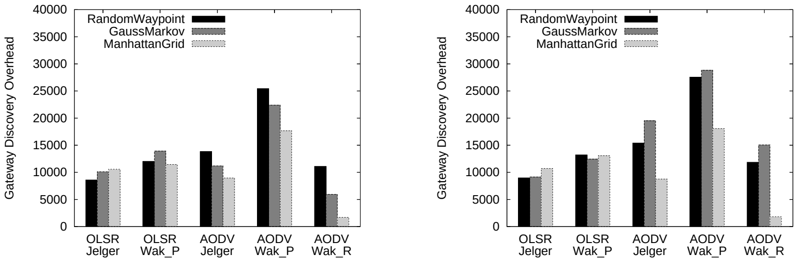
The number of messages due to the gateway discovery function in OLSR simulations does not vary very much regardless of the mobility model used (Fig. 5). The mobility model does not seem to significantly impact the overhead offered by all these approaches, except in the case of the Manhattan Grid model which tends to equal the results of “Jelger” and “Wakikawa” when they are integrated within OLSR . This is due to the higher contention caused by this mobility model, which reduces the number of control messages which can be sent in “Wakikawa”.

The gateway discovery overhead of AODV gets very much affected by the influence of the mobility model, but as it happened with the PDR, it remains consistent across mobility models. The Manhattan Grid model offers the minimum amount of link breaks, and therefore there is a low overhead in all AODV solutions. The Gauss–Markov model causes little overhead at low speeds (few link breaks) but a lot of overhead at higher speeds (many link breaks). The Random Waypoint mobility model sits in between the others.

4 Conclusions, Discussion and Future Work

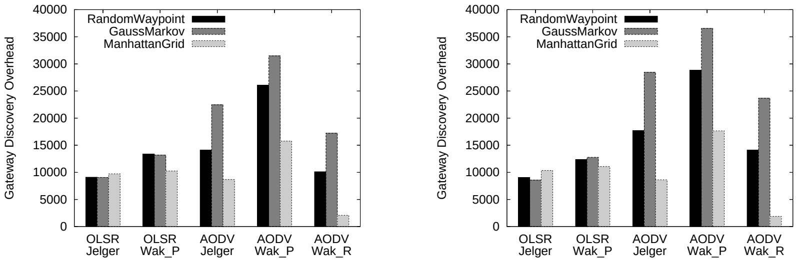
In this paper we have conducted a simulation-based study of the current approaches for interconnecting MANETs and fixed networks. This study has evaluated their performance, and it has shown how different mobility models influence in a different way the behavior of each solution.

Our results show that depending on the scenario we want to model, every solution has its strong



(a) 5 m/s

(b) 10 m/s



(c) 15 m/s

(d) 20 m/s

Figure 5: Gateway discovery overhead obtained from different mobility models for different maximum speeds.

and weak points. Hence, “Jelger” suits better for mobility patterns where few link breaks occur, like the Gauss–Markov (at low speeds) and Manhattan Grid mobility models. In those cases it offers a good PDR with a reduced gateway discovery overhead. However, we have seen that although prefix continuity offers an interesting mechanism of limited flooding, it has to be carefully designed in order to avoid routes which are fragile to changing topologies. On the other hand, reactive and proactive versions of “Wakikawa” are more suitable for high mobility scenarios. Random Waypoint and Gauss–Markov (at high speeds) mobility models generate a big number of link breaks, but “Wakikawa” solution is able to perform quite well under these circumstances. Nevertheless, it is also clear that proactive gateway discovery needs a constrained flooding mechanism to avoid the huge amount of overhead associated with the discovery of gateways.

In our opinion, this result opens up the need for new adaptive schemes being able to adapt to the mobility of the network. In addition to adaptive gateway discovery and auto-configuration, there are other areas in which we plan to focus our future work. These include among others improved DAD (Duplicate Address Detection) mechanisms, efficient support of DNS, discovery of application and network services, network authentication and integrated security mechanisms.

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