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# An Experimental Comparison of Routing Protocols in Multi Hop Ad Hoc Networks

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***Abstract*—This study experimentally compares the performance of three different multi hop ad hoc network routing protocols. Traditional routing protocols have proven inadequate in wireless ad hoc networks, motivating the need for ad hoc specific routing protocols. This study tests link state, distance vector and biologically inspired approaches to routing using OLSR, Babel and BATMAN routing protocols. The importance of OSI layers is also discussed. This study concludes that the routing protocol's overhead is the largest determinant of performance in small multi hop ad hoc networks. The results show that Babel outperforms OLSR and BATMAN routing protocols and that the OSI layer of the routing protocol has little impact on performance.**

## I. Introduction

Routing is one of the most central and important areas in the wireless multi hop ad hoc network architecture. Despite it's importance, and the hundreds of different routing protocols proposed over the past decade, few real world experimental studies have investigated routing. This research study provides an experimental comparison between Optimised Link State Routing (OLSR), Better Approach To Mobile Ad hoc Networking (BATMAN) and Babel. These protocols represent different approaches to routing in multi hop ad hoc networks. OLSR is a link state routing protocol and Babel is an advanced distance vector routing protocol. The BATMAN routing protocol does not fit neatly into pre-existing routing taxonomies. It can be loosely described as a biologically inspired routing protocol.

Before we describe ad hoc routing protocols, we will first discuss the challenges in multi hop ad hoc network protocols. This will explain the inadequacy of traditional routing protocols, such as RIP, OSPF and EIGRP.

### *A. Addressing and Scalability*

Multi hop ad hoc networks are designed to have self-forming and self-healing properties to deal with topology changes. Given the failure of links or nodes, these networks must automatically reform. In traditional wired networks, directly connected interfaces are configured with IP addresses in the same subnet. Hierarchical addressing schemes will not work in multi hop ad hoc networks because; following the failure of one link, a new IP address and network mask would be required to reform a link with a different router. Thus the addressing structure should be flat.

A flat addressing structure provides adaptable self-forming and self-healing properties, however, many of the advantages implicit in hierarchical addressing are lost. Mechanisms that prevent broadcasts are problematic. Address summarization is another feature that is unable to be used by multi hop ad hoc routing protocols.

Flat addressing requires a significantly larger routing table because a separate routing entry will be required for every node. Larger routing tables and changing link conditions may also impose frequent updates and heavier CPU loads.

### *B. Restricted CPU, Bandwidth and Unreliable links*

Multi hop ad hoc nodes will often be low power, low cost embedded machines that must deal with a variety of environmental conditions. Therefore, the CPU power of these devices will be constrained. These devices will also operate using WiFi chips which offer less bandwidth than equivalent wired links. Bandwidth limitations will be exacerbated in dense networks because of media contention.

Traditional routing protocols such as RIP and OSPF update too infrequently to deal with the constant changes that occur in multi hop ad hoc networks [1]. A frequent stream of hellos and topology exchanges is required to track the constantly changing link conditions. Ad hoc routing protocols require significantly lower hello and topology exchange intervals.

Unreliability in wireless networks create numerous other problems. In link-state routing, the Dijkstra algorithm provides 100% loop freedom as long as the link state databases are synchronized. Reliable routing information is critical because desynchronization, which can be caused by lost updates, leads to routing loops. The difficulty in ad hoc networks is that conditions are constantly changing. The shared medium means that, for efficiency reasons, routing information must be unreliably broadcasted. Overheads will therefore be higher in ad hoc routing protocols [2]. Ad hoc routing protocols require mechanisms to reduce these overheads.

### *C. Limited Dissemination*

A popular approach to reduce routing overheads, in both proactive and reactive protocols, is to limit the dissemination of routing information. The origins of limited dissemination techniques were founded in Distance Routing Effect Algorithm for Mobility (DREAM) [3]. DREAM reduces network over-

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heads by updating distant nodes less frequently than nearby nodes.

The application of this concept to link state routing is known as Fish-eye State Routing (FSR) [4]. These techniques have been shown to significantly reduce overheads [5]. The reason that imprecise or slightly inaccurate information can be tolerated is because routing decisions are made on a hop-by-hop basis. This means that if a node is many hops away, a route in the general direction will often suffice.

FSR modifies the Time to Live (TTL) in routing messages to update nearby and distant nodes at different intervals. Studies have shown that FSR provides greater optimization in large networks with a large diameter [5]. While FSR can reduce the generation of link state messages, it can lead to suboptimal routes. This trade-off requires consideration [6]. The inclusion of FSR into OLSR [7] is a testament to its effectiveness.

### D. Sequence Numbers

The split horizon rule states that a route should never be re-advertised through the same interface that the route was received. This rule is used to avoid count-to-infinty routing loops in wired networks. In multi hop ad hoc networks, nodes must be able to rebroadcast routing information over the same interface which means that split horizon may not be used. RIP and EIGRP are therefore inapplicable.

In 1994, Perkins et al [8] proposed that routing updates be appended with sequence numbers. With sequence numbers, nodes rehearing the original re-broadcasted route can identify the update freshness. Routers will only trust an update if the sequence number of the route advertisement is newer, indicating a fresher route, or, if the route being re-broadcasted has the same sequence number but a better metric. A node that is receiving a route originally sent through itself can never have a better metric. This mechanism was used in Perkin's [8] seminal Destination Sequenced Distance Vector (DSDV) routing protocol to avoid loops and is now employed in the more modern Babel [2].

### E. Limited and Efficient Dissemination

Traditional link state algorithms such as OSPF are equally inappropriate for routing in ad hoc networks. The OSPF network types that have been designed for existing wired networks, namely; point-to-point, broadcast, non-broadcast multi access, point-to-multi-point and virtual, do not meet the requirements of multi hop ad hoc networks. Although multi hop ad hoc networks are a broadcast based technology, the broadcast network type provided in OSPF is inappropriate. In OSPF broadcast networks, Designated Routers (DRs) are elected for multi-access Ethernet segments. OSPF routers within this network will maintain adjacencies with the DRs. The aim is to reduce OSPF's overhead by reducing the number of adjacencies. The OSPF broadcast network type requires all nodes to be in direct contact, normally known as a full mesh. This cannot translate to multi hop wireless networks because, the underpinning idea in multi hop ad hoc networks is that nodes are beyond direct communication range of other nodes.

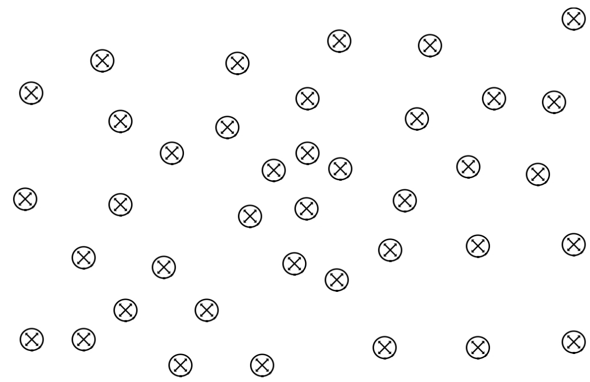

Fig. 1. Routing information must be broadcast to all nodes

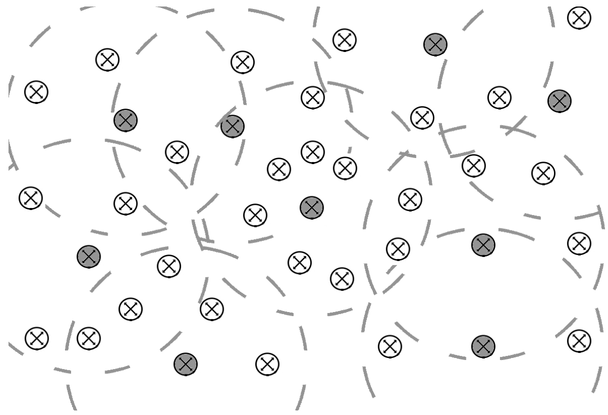

Fig. 2. The election of MPRs allows efficient dissemination

The other OSPF network types; point-to-point and point-to-multipoint, lead to prohibitive amounts of overhead with as few as 20 nodes [9].

The new network type for multi hop wireless networks involves electing or selecting relay nodes that are responsible for flooding link state messages. The technique is better explained diagrammatically. Given the routers shown in Fig 1, an efficient dissemination technique will try to find a set of nodes that can relay topology information to surrounding nodes. In Fig 2, the Grey routers have been elected as MPR nodes to broadcast topology information to the rest of the network. Finding the minimum set that can be chosen as relay nodes is more efficient, however, it is also an NP hard problem [10].

In the OLSR protocol, this network type is called Multi-Point Relay (MPR). By restricting the nodes responsible for flooding, the number of redundant or identical transmissions is minimised [11]. The details of this process can be found in [12] and [13]. MPRs increase the scalability of link state algorithms, especially in dense environments [5], and are an essential part of the OLSR [12] routing protocol.

### F. Routing Metrics

In multi hop ad hoc networks, the self forming, self healing characteristics mean that variables such as bandwidth and delay cannot be manually entered as they are in OSPF or EIGRP. As a result, designing routing metrics for multi hop ad hoc networks is a difficult endeavour.

Hop count simply favours the path with the least number of hops. The hop count metric is used for simplicity, not performance and the limitations are well known. The traditional problems worsen in multi hop ad hoc networks because paths with fewer hops are likely to be routes between distant, lower data rate links. In many cases this will lead to the utilization of longer distance, lower speed paths. These unintentional cross layer interactions led to performance degradations [14]. Hop count performs poorly in multi hop ad hoc networks [15].

ETX [15] is a reliability metric designed to find paths requiring the fewest transmissions. Although all packets in 802.11 are acknowledged using Automatic Repeat Request (ARQ), retransmissions result in a loss of airtime and hence, bandwidth. ETX calculates the probability of successful transmissions in both directions over a wireless link. To determine these statistics, every node periodically broadcasts a configured number of probes. Receivers calculate the number of probes received; against the number expected. As links are asymmetric, it is important to measure the success rate of probes in both directions. To obtain this information, each node will place its own ETX values in the probes sent. The formula for calculating the ETX of a link is shown in equation 1.

There are well documented problems with ETX [16]. Perhaps the biggest problem is that ETX does not incorporate bandwidth. This may cause ETX to favour fewer slow long distance links over a larger number of high speed links. Despite these problems, ETX is used by numerous routing protocols such as OLSR [13] and Babel [2].

$$ETX_l = \frac{1}{d_f \times d_r} \quad (1)$$

The Expected Transmission Time (ETT) metric [17] improves ETX by adding the ability to measure bandwidth. ETT implementations are limited because they require a standardised way to obtain the data rate from the wireless driver. Until such mechanisms are widespread, ETT implementations will be problematic and suffer from interoperability problems. ETT is a significant improvement over ETX, but, it is difficult to practically implement.

### *G. The Multi Hop Ad Hoc Routing Challenge*

To reiterate the challenges, distance vector routing protocols must solve the count to infinity problem without split horizon. Link state routing protocols must develop a new and much more efficient network/interface type for multi hop ad hoc networks. In addition to these problems, new ad hoc routing protocols must be able to accept a greater number of changes over less reliable links. The routers must operate with less CPU power and comparatively low bandwidth links. A flat addressing structure must also be used. This means that the advantages of heirarchial routing are lost. With flat addressing, every node will require an individual route and thus, routing tables may be large and subject to frequent change. OSPF's areas, IS-IS's levels, administrator configured metrics and address summarization are inappropriate due to the self-forming self-healing requirements of multi hop ad hoc networks [18]. This makes the goal of routing in multi hop ad hoc networks highly challenging.

## II. Routing Protocols

### *A. OLSR*

OLSR [12] was an was an initial attempt at standardizing a proactive link-state routing protocol. OLSR was first implementation by Tonnesen [19] and has been continued by numerous contributors. It is currently the most used ad hoc routing protocol.

The initial OLSR RFC, 3526 [12], used hop count as a metric, however, problems with this metric surfaced in Tonnesen's initial OLSR implementation [19]. Thus, real world implementations have long since broken conformance with this RFC. OLSRv2 [13] uses the ETX [15] metric for routing.

The characteristic feature of OLSR, which differentiated it from competing link state routing protocols, were MPRs. MPRs reduce the number of redundant link state transmissions by electing specific nodes as relays. Selection is performed in a manner such that every OLSR node is a direct neighbour of a MPR. The OLSR protocol also uses FSR techniques which will frequently update nearby nodes and infrequently update distant nodes. FSR reduces the overhead of link state messages in larger networks.

Anecdotal criticisms of OLSR state that a significant amount of MPR redundancy is needed to prevent link state databases from becoming desynchronized and forming routing loops. The additional MPR redundancy increases overheads; reducing performance. These criticisms led others to explore a fundamentally different approach to routing.

### *B. BATMAN*

BATMAN [20], [21] is a new and different approach to routing. In BATMAN, routing tables are built, hence it is a proactive routing protocol, however, routes are acquired in a biologically inspired manner, sharing similarities with AntHocNET [22]. The BATMAN protocol is fundamentally different from classic link state and distance vector routing. It does not try to discover or calculate routing paths, instead it tries to detect which neighbor offers the best path to each originator [21].

In BATMAN, routing information is not communicated directly, instead, each node broadcasts packets called Originator Messages (OGMs) every second. When received by neighbouring nodes, OGMs get re-broadcasted. Route selection for a given destination is based on the node from which the most OGMs have been received for a particular destination. The number of OGMs that can be accepted is limited to a constantly moving window. This window limits the history of OGMs that are allowed to describe a given route.

The scalability of BATMAN counts on packet loss and thus, like other algorithms, OGMs are broadcast as unreliable UDP packets. As nodes continuously broadcast OGMs; without packet loss, these messages would overwhelm the network. The scalability of BATMAN depends on packet loss and thus it is unable to operate in reliable wired networks.

This mechanism also means that OGMs from nearby nodes will be frequently received whereas OGMs from distant nodes will be infrequent. The BATMAN algorithm can also use different TTLs in OGMs to limit dissemination. This function is similar to the limited dissemination FSR concept [4]. As route selection is based on the number of received OGMs, the metric is ultimately a form of reliability and therefore conceptually similar to ETX [15]; the metric used by both OLSR and Babel.

### C. Babel

Babel [2] is a proactive advanced distance vector routing protocol. Babel is newer than OLSR and BATMAN, but interestingly, its design is based on on DSDV [8], the first multi hop ad hoc routing protocol. The use of sequence numbers, to prevent count-to-infinity routing loops, is borrowed from DSDV. Babel also adopts EIGRP's loop avoidance techniques using feasibility conditions [23] to quickly converge on loop free paths. Like OLSR, Babel also uses the ETX [15] metric. Babel updates are transmitted unreliably using IPv6. It has been anecdotally claimed that Babel can outperform competing routing protocols in sparse networks.

## III. Experiment

Our experiment compares OLSR, BATMAN and Babel. Attempts were made to use Ad hoc On demand Distance Vector (AODV) routing, however similar to recent studies [24], implementation problems made this infeasible. Attempts were also made to use the open 802.11s [25] Hybrid Wireless Mesh Protocol (HWMP) routing protocol. Unfortunately, this routing protocol only works with a newer wireless driver known as ath5k. Due to performance problems with this driver, it was necessary to revert to the older MadWiFi driver which ruled out open 802.11s as a consideration.

The BATMAN routing protocol is being developed as both a user-space routing protocol, that operates at the network layer, as well as a kernel-space implementation running at the data link layer. This study experiments with both routing protocols, referring to them as BATMAN L3 and BATMAN L2. Only a couple of real world experimental evaluations of these protocols exist [26], [24]. Further experimental tests are required to ascertain the validity of the conclusions made in these studies.

In the proposed experiment, the wireless nodes were ALIX 500MHz x86 embedded PCs with 256 MB of RAM and Atheros CM9 wireless cards. The platform and routing protocol versions can be found in Table I. All routing protocols were tested with their default configuration.

Comparative tests were performed over four different topologies. The first topology was performed with all nodes in direct communication range of the gateway. This topology was used as a control whereby no routing was occurring.

TABLE I
Platform and routing configuration

| Platform | Version | Routing Protocols | Version |
|---|---|---|---|
| Voyage Linux | 0.6 | OLSR | 0.5.6-rc7 |
| MadWiFi | 0.9.4 | BAT L3 | 0.3 |
| Linux Kernel | 2.6.30-486 -voyage | BAT L2 | 0.2 |
| | | Babel | 0.97 |

The remaining three topologies featured random placements of nodes throughout a building. No specific attempt was made to dictate a particular topology, however, the nodes were placed far enough apart to ensure a multi hopping topology. In the experimental setup, the transmission power was reduced and all wireless nodes were placed in different rooms. This study measured; packet delivery ratios, bandwidth and routing protocol overheads.

To measure packet delivery ratios, a simple ruby program was created to send ICMP messages from the gateway to all nodes. The program was written such that only one ICMP was present in the network at any one time. This ensured that the losses measured did not include congestion based losses. These tests were based on the success of 10,000 ICMP messages and were performed many times for each routing protocol in each of the four topologies.

We also performed bandwidth tests. One gateway node was connected to a dedicated server running the lighthttpd web server. Wireless nodes were simultaneously issued instructions to download a large 158MB file from the lighthttpd server. The downloads were timed. The elapsed time between when the download command was issued and the final node completed the file transfer was recorded. These tests were performed multiple times for each routing protocol in each topology and the results were averaged.

This study also captured routing protocol overheads. The nodes were not powerful enough to capture the traffic traversing their interfaces when routing thousands of packets per-second. This made the determination of the exact routing overhead difficult. To measure routing protocol overheads All wireless nodes were placed within range of an external capturing device. Wireshark was used to capture packets over 60 second intervals. An aspect of this test which requires consideration is that the overheads of routing protocols may have been different in topologies where the nodes were not all within transmission range of one another.

## IV. Results and Discussion

From a qualitative perspective, all routing protocols were equally reliable and rarely suffered from TCP dropouts. Packet delivery ratios for the three routing protocols were also consistent. Results varied for the different topologies however all packet delivery ratios were between 99.6% and 99.98%. These results differ from other experimental studies which found significantly lower packet delivery ratios [26], [24].

The results of the bandwidth tests, shown in Fig 3, reveal that the Babel routing protocol provided better throughputs than OLSR, BATMAN L3 or BATMAN L2. Fig 3 also shows that BATMAN L2 outperformed BATMAN L3 and OLSR in three of the four topologies, however, the performance differences are too small for definitive conclusions. One peer reviewed study [24] concurs that Babel offers greater throughput than both BATMAN and OLSR. This study also found that OLSR performed poorly, however, I believe that this result may have been caused by a bug in the version of OLSR used.

Another study [26] comparing OLSR and BATMAN found that BATMANs throughput was approximately 15% better than OLSR. We question the validity of this result based on their selection of network variables. By default, OLSR has a hello interval of 2 seconds and a topology exchange interval of 5 seconds. Comparatively, BATMAN transmits an entirely different message known as an OGM every 1 second. In this study, Johnson et al [26] claims that for fairness reasons, OLSR's hello and topology exchange intervals should be the same as BATMAN's OGM intervals of 1 second. This is unfair because BATMAN and OLSR are completely different protocols. BATMAN's OGMs are minuscule because they carry very little routing information and are required to be sent more often than OLSR hellos and topology exchanges. We believe that routing protocols should be compared with their default hello and topology exchange intervals.

In our study, which used the default routing parameters, Babel consistently outperformed other protocols. We questioned whether this was due to a better selection of routes, or lower overheads. Recall that topology 1, was designed as a control and all nodes were within direct range of the gateway. A curious artefact in the results is seen in topology 1. In this topology, no actual routing decisions were being made. As no routing decisions were being made in topology 1, throughput differences were likely a result of protocol overheads.

The overhead of the routing traffic, in bytes, is shown in Table II. This shows that under default settings, OLSR transfers the greatest number of bytes of routing protocol overhead. Comparatively, Babel produces a minuscule overhead, however, the number of bytes transferred is not a exact measure. Due to the fixed overheads of IFS (Inter Frame Spacing), DCF (Distributed Coordination Function), preambles and trailers; updates are more efficiently transferred in fewer large packets rather than multiple small packets.

Table II shows the number of routing packets transmitted per minute. It is evident that BATMAN transmits the largest number of routing packets/frames. Recall that BATMAN detects routes by frequently broadcasting small OGMs. This describes why BATMAN transmits the largest number of routing messages. It also explains why the average packet size is so small because BATMANs OGMs do not carry data describing routes. Babel and OLSR routing messages are comparatively larger because they carry routing information.

The approximate percentage of channel time consumed by routing updates is calculated using equation 2. This calculation includes IFS, DCF, preambles, trailers and the size of the packet, divided by the baseline bit-rate. The baseline bit rate is used for all broadcast UDP and TCP segments. Once this value is derived, it can be multiplied by the number of times

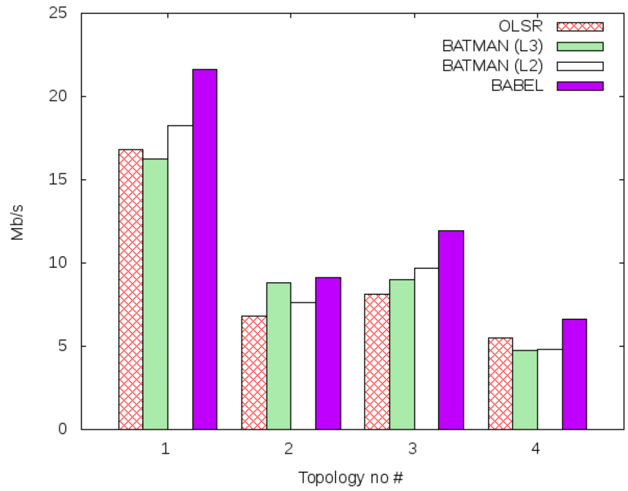


Fig. 3. Achieved bandwidth

TABLE II
ROUTING PROTOCOL OVERHEAD STATISTICS

| | OLSR | BAT L2 | BAT L3 | Babel |
|---|---|---|---|---|
| Bytes/sec | 10816 | 3795 | 3952 | 447 |
| Packets/min | 1761 | 3926 | 3017 | 125 |
| Avg packet size | 368.6 | 58 | 78.6 | 214.8 |
| % Time used by RP | 8.4 | 3.3 | 3.3 | 0.35 |

the routing protocol transmits these packets per second. An approximation of the channel time used by these routing updates is shown in Table II. We believe this to be the most accurate measure of the real cost of routing overheads. These results concur with the results of a previous study that suggest OLSR has a higher network overhead than BATMAN [26], however, I believe that the conclusions drawn by Johnson et al [26] are overstated and exaggerated due to their choice of network variables.

$$\frac{AvgPacketSize(inbits)}{1048576} + DIFS + (preamble + trailer) \tag{2}$$

## V. ADDRESSING AND OSI LAYERS DISCUSSION

Routing was traditionally envisaged to occur at the OSI network layer and will therefore be used with any link layer technology. However, an advantage of routing at the data link layer is that any network layer protocol may operate over the top. When using a data link layer routing protocol, IPv4, IPv6 and DHCP will be able to operate above the routing protocol and provide convenient addressing mechanisms.

OSPF, BATMAN and Babel have been implemented and tested as network layer routing protocols. Recently, attempts have been made to create data link layer protocols such as 802.11s and L2 BATMAN. There is considerable debate as to whether routing is better performed at the network layer or data link layer with the IETF and IEEE both working on independent routing protocols. Either scheme will violate the layering principle. A flat IP addressing scheme will break the usual hierarchical addressing that occurs at the network layer. Equally, routing at the data link layer is fundamentally wrong because the data link layer will be performing routing; which is a network layer function. Regardless of the layer chosen, traditional layering principles will be distorted.

Upon inspection of the BATMAN L2 and BATMAN L3 results, the only major performance difference between data link layer routing and network layer routing is the packet size. Data link layer routing protocols will not require a network layer IPv4/IPv6 header and may therefore be smaller. This argument is of minimal consequence because the routing protocol is a far bigger determinant of overheads. To illustrate this point, Babel, which uses a large IPv6 header, increasing the packet size of every routing message by 40 bytes, has lower overheads than BATMAN L2 which operates without a IP header. We conclude that the layer has few performance benefits or drawbacks and that the decision to use one or the other should be architectural.

## VI. Conclusion

This research compares routing protocols, however, more specifically, it investigates the cause of performance loss or gain in multi hop ad hoc networks. We have confirmed the findings of the only other peer reviewed experimental study [24] that tested Babel. The conclusion is that in small wireless networks, Babel offers higher throughputs. The results confirm that the overhead of OLSR is higher than BATMAN [26], [24], but contradict other studies that claim large throughput differences between OLSR and BATMAN [26], [24]. The results of this study suggest that the performance of OLSR and BATMAN is similar.

A separate conclusion is that, in small multi hop ad hoc networks, the overhead of the routing protocol has the largest impact on throughput. In the future, similar tests should be run in larger experimental set-ups. Statistics on CPU load and convergence time could also be interesting. This study concludes that Babel provides higher throughputs in small networks but it is untested in larger networks. These findings should provide the impetus for further experimentation.

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