Performance of Ad Hoc Routing Protocols: Characteristics and Comparison

Sampo Naski
Helsinki University of Technology
Telecommunications Software and Multimedia Laboratory
`snaski@cc.hut.fi`

Abstract

Mobile ad hoc networks are networks without fixed infrastructure. The mobile nodes perform both as a host and a router forwarding packets to other nodes. Because of the nature of ad hoc networks, there are special demands for ad hoc routing protocols. Also the performance is an interesting issue. This document describes some special characteristics of ad hoc routing protocols and their performance measurements. Three major protocols are introduced (DSDV, DSR and AODV). Some relevant studies about ad hoc routing protocols are introduced and their results are compared and analyzed with respect to these three protocols.

KEYWORDS: Ad Hoc Networks, routing protocol, performance, DSDV, DSR, AODV

1 Introduction

A Wireless ad hoc network consists of wireless mobile nodes. Such a network does not have a fixed infrastructure but nodes perform the networking function by acting not only as a host but also as a router forwarding packets to other nodes that may not be within direct wireless transmission range of each other. That is why ad hoc networks are also sometimes called multi-hop wireless ad hoc networks.

Ad Hoc routing has been widely researched over the past years but widely used implementations are yet to come. Several protocols have been developed under the authority of Mobile Ad hoc Networking (MANET) working group. Manet is charter of Internet Engineering Task Force (IETF). Lots of research has also been done about the performance of ad hoc networks under varying scenarios. Different kind of metrics or characteristics may be used to analyze the performance of an ad hoc network.

The special constraints unique to ad hoc networks must be held in mind when conducting the performance analysis. Different kind of approaches and methodology has also been used. Simulations are commonly utilized especially when analyzing the performance of a specific routing protocol. Analytical models have also been developed to be used especially in analysis considering a specific performance issue of ad hoc networks in general.

The purpose of this paper is firstly provide a brief overview of ad hoc routing and different ad hoc routing protocols. Then some characteristics that might be useful for performance analysis of mobile ad hoc networks are presented. After that some of the existing research about the performance of different ad hoc routing protocols are reviewed and their results are then compared with respect to these characteristics.

2 Ad Hoc Network and Performance Characteristics

IETF's MANET group has defined different kind of characteristics that are salient to ad hoc networks. The group also defines some qualitative properties that all ad hoc routing protocols should posses. They can be used to analyze suitability and performance of an ad hoc routing protocol. The MANET working group also specifies some measurements that can be used to evaluate the performance of a routing protocol in a quantitative manner. These are among the most interesting characteristics considering the performance of existing or proposed protocols.

2.1 Characteristics of Ad Hoc Networks

The MANET working group has defined some unique properties of ad hoc networks in RFC 2501 [2]. The properties doesn't directly relate to performance. However they describe the very nature of ad hoc networks and in that sense they formulate the boundary conditions to ad hoc networking. In a manner they impact on performance, since they greatly affect on the design of ad hoc routing protocols.

The following characteristics are defined by the MANET working group in RFC 2501:

1. Dynamic topologies

   The topic refers to the most essential property of an ad hoc network: Nodes can move arbitrarily with respect to other nodes in the network.

2. Bandwidth-constrained

   Nodes in an ad hoc network are mobile. Thus, they are using radio links that have far lower capacity than hardwired links could use. In practice the realized throughput of a wireless network is less than a radio's theoretical maximum transmission rate.

3. Energy constrained operation

Mobile nodes are likely to rely on batteries. That is why the primary design criteria may sometimes be energy conservation.

4. Limited physical security

   In general, radio networks are vulnerable to physical security threats compared to fixed networks. The possibility of eavesdropping, spoofing and DoS attacks is higher. Existing link security techniques can be applied. However, a single point failure in an ad hoc network is not as crucial as in more centralized networks.

2.2 Desirable Properties of Ad Hoc Routing Protocols

The MANET working group also defines some desirable qualitative properties of ad hoc routing protocols in RFC 2501 [2]. They are useful when assessing performance or suitability of an ad hoc routing protocol thus they are worth to mention in the context of this paper.

The following properties are defined in RFC 2501:

1. Distributed operation

   This property is essential to ad hoc networks. It is self-evident that ad hoc networks operate in distributed manner because of their very nature.

2. Loop-freedom

   This property is generally desirable. It refers to avoiding packets spinning around in the network for arbitrary time. Solutions such as TTL values can be used to limit performance effects of the problem. However, a more structured or a sophisticated solution will probably lead to better overall performance.

3. Demand based operation

   Ad hoc routing does not have to assume uniform traffic load in a network but it can adapt to traffic patterns on need basis. This will increase route discovery delay but when implemented intelligently bandwidth and energy resources can be more efficiently utilized.

4. Proactive operation

   This is opposite to demand based operation. If additional delays that occur in demand based operation are unacceptable, proactive approach can be used specially when energy and bandwidth capacities support the use of proactive operation.

5. Security

   Because of the vulnerabilities in the physical security mentioned in section 2.1, ad hoc routing protocols are exposed to many kind of attacks. Maintaining link layer security is in practice harder with ad hoc networks than with fixed networks. Sufficient routing protocols security is desirable. Sufficient within this context covers prohibiting disruption or modification of protocol operation.

6. "Sleep" period operation

   Since nodes in ad hoc networks may have energy constraints as explained in section 2.1 or because of some other need, nodes may want to stop sending and/or receiving data for arbitrary time periods. A routing protocol should be able handle such “sleep” periods without overly unfavorable consequences.

7. Unidirectional link support

   Many routing algorithms require bidirectional links to be capable of functioning. Unidirectional links are however more general in radio networks. That is why it’s favorable that an ad hoc routing protocols can handle a situation where two (oppositely directed) unidirectional links form the only bidirectional connection between the nodes. Even though such a situation will probably emerge rarely.

2.3 Characteristics of Performance

There several quantitative metrics that might be used to analyze the performance of a routing protocol. The RFC 2501 [2] defines four measures. Basically they can be used to analyze the performance of any routing protocol.

The following measurements are defined in RFC 2501

1. End-to-end data throughput and delay

   This metric involve analyzing the efficiency of data routing. Statistical measures (e.g. means, variances and distributions) are essential. These are used to analyze the effectiveness of a routing policy as measured of the external perspective (the perspective of other policies that utilize routing).

2. Route acquisition time

   This measures the time required to establish routes. It is an end-to-end measurement. Route acquisition time is concerned especially with on-demand routing approaches.

3. Percentage Out-of-Order Delivery

   This one measures connectionless routing performance. It’s an interesting metric especially from transportation layer’s point of view (e.g. TCP) since Transportation layer prefers mostly in-order delivery.

4. Efficiency

   This refers to internal effectiveness of a routing policy. Thus, to achieve a certain externally evaluated data routing efficiency, two policies may consume different amounts of overhead since their internal efficiencies differ. If control and data traffic use the same transmission channel, then excessive control traffic will probably affect on the internal efficiency of a policy.

When analyzing the performance of ad hoc routing protocols, some parameters of the networking context should be considered carefully. The RFC 2501 [2] defines the following ones:

1. Network size This is simply measured by the number of nodes in a network.

2. Network connectivity

   This refers to the average number of neighbors of a node.

3. Topological rate of change

   The rate of change of network's topology.

4. Link capacity

   The effective speed of a link. Measured with bits per second.

5. Fraction of unidirectional links

   This must be concerned when evaluating, how the number of unidirectional links present in a network effect on protocol's performance.

6. Traffic patterns

   This is concerned when evaluating how well a protocol can adapt to non-uniform or bursty traffic patterns.

7. Mobility

   This is concerned when assessing how relevant temporal or spatial topological correlation is to the performance of a routing protocol.

8. Fraction and frequency of sleeping nodes

   How well a protocol can handle situations where sleeping nodes are present.

3 An Overview of Some Existing Protocols

AD hoc routing protocols can be divided in two major categories. They may be either *table driven (i.e. proactive)* or *on-demand-driven (i.e. reactive)*. In addition to this categorization there are some other generic properties and characteristics for these protocols as explained in section 2.

Protocols using proactive approach maintain consistent routing information from from each node to every other node. The nodes keep routing information up to date by propagating route updates throughout the network. [1]

Protocols using reactive approach are source initiated. It means that when a node needs a route to another node it initiates a *route discovery* process. Thus a route is established only when it is needed. [1]

The following subsections describe shortly three major proposed ad hoc routing protocols. The protocols were chosen mainly because the performance studies reviewed in this paper covers them. They also represent the different categories of ad hoc routing protocols. The first one represented is fully table driven whereas the second one is fully on-demand based. The third one have adopted some of the properties of the both categories.

3.1 Destination Sequence Distance Vector (DSDV)

DSDV [3] [1] is a distance vector routing protocol. It is based on the famous distributed Bellman-Ford routing algorithm. DSDV is a *proactive* routing protocol. It works on hop-by-hop basis meaning that every node maintains a routing table that contains next-hop entry and the number of hops needed for all reachable destinations. DSDV assumes *bidirectional links* and thus does not have *unidirectional link support* (Sec 2.2).

DSDV uses a concept of *sequence numbers* to provide *loop freedom* (Sec 2.2). The sequence number is originated by the destination node. To maintain routing information consistent within a network DSDV requires nodes to *broadcast* periodical route advertisements. In practice updates will happen in every few seconds. The advertisement contains the routing table entries of the advertising node. These entries contain the address of destination, next hop and hop count to that destination and the last known sequence number originated by that destination. When a node receives an advertisement it updates its routing table on this basis. Routes with greater sequence numbers are always preferred. If the sequence numbers are equal, a route with lower hop count is chosen. Note that the receiving node increases the hop counts in the advertisement since the destination needs one hop more to be reached. The receiving node will then subsequently pass this new information forward within its own route advertisement.

When a node detects link failure it marks all routes through that link with hop count of infinity (any number beyond allowed maximum) and broadcasts update information. Since information is considered to be valid only when sequence number is greater, must the node that detected link failure increase it. That is why nodes detecting failures always assign odd sequence numbers to these routes. Original destination originated sequence numbers are again even.

Since frequent route advertisements can generate a lot of control traffic, introduces DSDV two kind of route update packets. The first is known as *full dump* containing all available routing information and may require several *network protocol data units (NPDUs)*. Smaller *incremental* packets are used to distribute only information that has changed since last full dump.

3.2 Dynamic Source Routing (DSR)

DSR [4] is a fully *reactive* routing protocol. It is a source routing protocol meaning that a packet carried in the network contains an ordered list of all nodes through which the packet must be routed. Nodes in a networks using DSR routing are required to maintain so called *Route Cache* where all learned routes to any given node in the network exist.

DSR uses two basic mechanisms that are *Route Discovery* and *Route Maintenance*. Route Discovery is initiated by the source node, say **S**, to obtain a source route to the destination node, say **D**. Route Discovery takes place only when **S** does not already know a route to **D**. The purpose of Route Maintenance is to provide a mechanism, that enables the node **S** to detect if the network topology has changed such that the source route to **D** does not work anymore.

When the node **S** needs to send packets to the node **D**, it obtains a route to **D** by searching its Route Cache of previously learned routes. If no route is found, Route Discovery protocol is initiated by *broadcasting* a ROUTE REQUEST message. Request messages are identified by initiator determined *request id*s. When a node receives a Route Request message, it returns a ROUTE REPLY message to the initiator, if it is the target of the request or a node knowing a valid route to the target. Otherwise if the receiving node has lately seen a request from the same initiator with the same id or if its address is already in the *route record* of the ROUTE REQUEST packet, it discards the packet. Otherwise the receiving node adds it own address to the route record of the request and broadcasts the request forward.

After a successful Route Discovery process, route record of a ROUTE REQUEST contains a complete source route from the initiator to the target. This information is then contained in a ROUTE REPLY message. DSR supports *unidirectional links* (Sec 2.2) since the reply is sent back to the source based on a route in replier's cache or it is piggybacked on a Route Request packet for the initiator.

Route Discovery is initiated when a node needs to discover a route to another node. A *Route Request* packet is broadcasted. When a node receives a Route Request it searches its *route cache* where all routes are stored. If requested route can not be found in the cache, the node broadcasts the packet forward after having added its address to the sequence of hops contained in the header of Route Request packet. The request floods through the network until it reaches the destination node or a node having a valid route to the destination. Then a *Route Reply* packet is unicasted back to the source node by piggybacking or using a route in replier's cache as mentioned earlier.

Route Maintenance requires that each node ensures that forwarded packets are received by the next-hop node. In a case of link breakage a ROUTE ERROR packet is sent back to the source node which removes broken link from its cache. All routes are also truncated at that point.

The DSR specification [4] also specifies a so called *promiscuous mode*. Then nodes are allowed to learn routes by overhearing packets not addressed to them. It means that packets with link level addresses of other nodes are not filtered. Working in a such a mode might however cause unnecessary power consumption. (See section 2.1).

3.3 Ad Hoc On Demand Distance Vector (AODV)

AODV [5] combines some properties of both DSR and DSDV. It uses *route discovery* process to cope with routes *on-demand* basis. The protocol is hence seen as a *reactive* one. However, it adopts DSDV like hop-by-hop routing tables for maintaining routing information.

Hence AODV is a *reactive* protocol, it doesn't need to maintain routes to nodes that are not communicating. AODV handles *route discovery* with *Route Request (RREQ)* messages. RREQ message is *broadcasted* to neighbor nodes. The message floods through the network until wanted destination or a node knowing fresh route is reached. Sequence numbers are used to guarantee *loop freedom* (Sec 2.2) RREQ messages cause bypassed nodes to allocate route table entries for *reverse route*. The destination node *unicasts* a *Route Reply (RREP)* back to the source node. Nodes transmitting a RREP message creates routing table entries for *forward route*.

For *route maintenance* nodes periodically send HELLO messages to neighbor nodes. If a node fails to receive three consecutive HELLO messages from a neighbor, it concludes that link to that specific node is down. A node that detects a broken link sends a *Route Error (RERR)* message to any upstream node. When a node receives a RERR message it will initiate a new source discovery process.

4 Performance of Different Ad Hoc Routing Protocols and Comparison

Within this section some pieces of previously conducted research about the performance of different ad hoc routing protocols are reviewed. The subsection 4.1 overviews the assumptions and models used in these studies and subsection 4.2 then compares their results. Subsection **??** provides some critical analysis about the results.

One must be well aware that the results may not be directly comparable even the used performance metrics are the same, since the conditions of the networking context may be different as pointed out in section 2.1 That is why some analysis about the parameters of the networking context is provided with the comparison. Also the correlation between different simulation models matters when simulations are reviewed.

4.1 Review of Performance Studies

This section gives an overview of three different studies. The most studies considering performance of some specific protocols are simulations as the ones represented within this section (in contrast to analytical models that mostly seem to cover problems related to the theoretical concept of ad hoc networks in general).

Because of the plentifulness of researches considering performance issues, this paper is supposed to focus on some of the most relevant research work considering specific ad hoc routing protocols. They are frequently referred and some authors of these studies are also authors of ad hoc routing protocol specifications or corresponding documents.

4.1.1 "Performance Comparison of Multi-Hop Ad Hoc Network Routing Protocols"

Broch, Maltz, Johnson, Hu and Jetcheva have analyzed the performance of different ad hoc routing protocols by simulation. They have published the results in a paper titled as "Performance Comparison of Multi-Hop Ad Hoc Network Routing Protocols" [7].

In their simulation research they have used rather realistic model as the basis of their work. The simulation was done with ns2 simulator with some extension done into it. The simulation model include the following extensions:

- Node mobility
- A realistic physical layer modeling that include radio propagation model, supporting propagation delay, capture effects and carrier sense

- Radio network interfaces with varying properties including transmission power, antenna gain and receiver sensitivity
- The IEEE 802.11 Medium Access Control(MAC) protocol.

Since the routing protocols operate on network layer and they use IP addresses, *Address Resolution Protocol (ARP)* was included in the simulation model. The simulation model also includes *packet buffering* up to 50 packets, meaning that each node have a drop-tail fashioned queue of 50 packets at their network interface.

The study covers four protocols: DSDV, TORA, DSR and AODV. (TORA refers to *Temporally-Ordered Routing Algorithm* but it is not covered within this paper) The protocols were implemented according to their specifications at the April 1998. Also some improvements were made to the protocols:

- To avoid synchronization, broadcasts or packets were sent in response to reception of a broadcast were delayed with random delay between 0ms and 10ms.
- To ensure that routing information propagates through the network in time, routing packets were placed at the begin of transmission queue whereas all the other packets were placed at the end of the queue.
- Each protocol used link feedback from the IEEE 802.11 MAC layer for link breakage detection.

The protocol evaluations are based on the simulations with 50 nodes. The nodes move over a rectangular (1500m x 3000m) flat space for 900 seconds. The protocols were challenged with identical loads and environmental conditions to ensure fair comparison. 210 different scenarios with different traffic loads and moving patterns were pre-generated before the actual simulation. The movement model of the simulation is based on a waypoint model. Pause times were also used meaning that a node must stop on a waypoint for the pause time. 7 different pause times were used including 0ms and 900ms (no movement). Two different maximum node movement speeds were also used (1 m/s and 20 m/s).

The communication model was based on *Constant Bit Rate (CBR)* traffic sources. Three different send ratios, three different numbers of CBR sources and two packet sizes (64 and 1024 bytes) were used.

The following metrics were evaluated: *Packet delivery ratio*, *routing overhead* and *path optimality*. The packet delivery refers to the loss ratio of packets. Routing overhead means the total number of routing packets transmitted. Path optimality refers to the difference between the number of hops a packet took to reach its destination and the length of the shortest path that physically existed.

4.1.2 “Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks”

Das, Perkins and Royer have researched the performance of two on-demand ad hoc routing protocols: AODV and DSR. The research is based on simulations as well. The results were published in a paper titled “Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks” [8].

The simulation model has many similarities with the one represented in subsection 4.1.1. The ns2 simulator was used. Realistic physical and link level models were utilized. The support to ns2 simulator for extending the simulation model to include these realistic physical and link layer models was developed by Monarch research group at the Carnegie Mellon University (CMU). IEEE 802.11 MAC layer implementation is included in the model as well.

The radio model uses similar characteristics to commercial radio networks such as Lucent’s WaveLAN with 2Mbps links. The link breakage is detected using feedback from the MAC layer. Each node in the network maintains a send buffer of 64 packets. the buffer is FIFO queue and routing packets have higher priority than data packets. Two different simulations are done: one with 50 nodes and another with 100 nodes.

The traffic model uses CBR sources and one packet size only (512 bytes). Different source and destination pairs and varying send rates were used to generate different kind of load in the network. The mobility model used is the random waypoint model (as in the study reviewed in subsection 4.1.1). Two field configurations are used (1500m x 300m for 50 nodes and 2200m x 600m for 100 nodes). The movement speed is randomly selected between 0-20m/s. Simulations last 900s for 50 nodes and 500s for 100 nodes.

Three key performance metrics were evaluated: *Packet delivery fraction, average end-to-end delay* of data packets and *normalized routing load*. Packet delivery fraction equals to packet delivery ratio in subsection 4.1.1. All delays or latencies caused by any reason are included in the average end-to-end delay metric. Normalized routing load refers to ratio between the number of routing packets “transmitted” and the number of packets “delivered” to the destination. Every hop-wise transmission of a routing packet is considered as one transmission.

4.1.3 “Scenario-based Performance Analysis of Routing Protocols for Mobile Ad-hoc Networks”

Johansson, Larsson, Hedman, Mielczarek and Degermark have also conducted some serious research about ad hoc routing performance. They studied three different routing protocols: DSDV, DSR and AODV. The results were published under a title: “Scenario-based Performance Analysis of Routing Protocols for Mobile Ad-hoc Networks” [9].

Their work is also based on simulations. Simulation environment had again lots of similarities with ones presented in subsections 4.1.1 and 4.1.2. However they decided to do two kind of simulations: ones for random scenarios and others for three different realistic scenarios.

The simulation environment was again ns2 simulator with the ad hoc networking extensions provided by the Monarch research group of the Carnegie Mellon University. This extension set is the same one that was used in the study presented in subsection 4.1.2. Also 2Mbps radio links are expected in their research.

The random scenarios used a field of 1000m x 1000m with

50 nodes. 64 byte packet size was utilized and seven node mobility values were used (maximal node velocity varying between 0-20m/s). CBR sources were also used. Two sets of simulations were run. Simulations lasted for 250s. At the first round the mobility was varying and load was held constant. At the second phase both the mobility and load patterns were varied. Two main metrics, delay and throughput, were measured. Overhead imposed by routing protocols were also evaluated.

The realistic scenarios are: Conference (low mobility), Event Coverage (fairly high mobility) and Disaster Area (slow nodes modeling humans and fast nodes modeling vehicles).

The Conference scenario consists of 50 nodes in a 150m x 90m field. 2 nodes are acting as CBR sources and 6 as receivers. The area is divided in three zones: the speaker zone, the audience zone and the entrance zone. To be realistic, the scenario assumes that low pow-power indoor equipment (with significantly low transmission ranges of 25m) is used and thus obstacles (walls) were added in the radio propagation model. Only 10 percent of nodes are moving at the same time and the traffic is concentrated to the speaker.

Event coverage scenario has 1500m x 900m sized field. there are 2 CBR sources and 45 receivers. All 50 nodes are moving around. At any given time 50 percent of nodes are moving. The movement speed can be at maximum 1m/s as in the previous scenario also.

The disaster scenario has also a field of 1500m x 900m. The scene has three group of 50 nodes. The groups (subnets) can only communicate through two fast back and forth moving nodes (vehicles). These two nodes move at maximum speed of 20m/s in contrast to the rest that can move around within its group at the maximum speed of 1m/s. There are 38 CBR sources and 87 receivers.

4.2 Comparison

The results of the studies reviewed in section 4.1 are presented and compared within this section. With the comparison, some analysis considering different kind of characteristics that have an affect on the results, is provided. Also one must carefully look at the metrics that the different studies have used to validate the comparison. However since the direct comparison of accurate values of different simulation results is rather confusing, the big picture of the performance of different protocols is tried to be brought up here. The comparison is done with respect to the same protocols represented in section 3.

There are also three figures (fig. 1, fig. 2 and fig. 3), one figure for each protocol. The figures are supposed to give a very simplistic view of the results of the three studies. Three metrics (*routing overhead, end-to-end delay and packet delivery fraction*) are included in the figures. The values representing the results are High (H), Mediocre(M), Low(L) an N/A (The corresponding metric isn't measured in the study). They are rough estimations that are not based on any actual boundary values. They show on a given protocol how high a metric's value is compared to other protocols within the same study. The figures are meant just to help the reader handle the facts that are brought up within the following subsections. It must be emphasized, that they are not exact results, but they are just to help figure out how the performance of an protocol behaves compared to other protocols and studies when mobility and traffic load are set low or high.

4.2.1 DSDV

Broch, Maltz, Johnson, Hu and Jetcheva [7] (subsection 4.1.1) found in their simulation that the packet delivery ratio starts to fall drastically when mobility increases (pause times less than 300s). That is quite an expected result since DSDV has difficulties to maintain fresh routing information when nodes are moving fast (route update interval was set to 15s). Practically all discarded packets were dropped because a stale routing table entry forwarded packets over a broken link. DSDV maintains only one route per destination, thus in case of broken link no alternative route can be found. The routing overhead was found to stay stable (around 45000 packets) regardless of mobility rate. This can be explained by the proactive nature of the protocol. The path optimality for DSDV was found to be really good.

Johansson, Larsson, Hedman, Mielczarek and Degermark [9] (subsection 4.1.3) got similar kind of results with their random scenarios. When mobility was varying DSDV started to suffer poor throughput and greater packet loss with higher mobility. The delay was good on low traffic loads even the mobility was high. When the traffic load started to increase, delays increased too, even though with higher mobility values the delays were quite close to each other. The routing overhead was again found to be stable - DSDV does not react to increased mobility because of its proactive nature (constant route update intervals).

The findings in these studies were quite similar (See figure 1). DSDV has low delays when mobility stays low. With increased mobility delays starts to grow and throughput decrease. The bottle neck of DSDV seems to be vastly decreasing packet delivery ratio when mobility gets high. However Johansson et al. [9] found in their conference scenario that packet delivery ratio can be significantly low (75,6 percent) even though mobility and the number of moving nodes are low. That can be explained with breakage of long lived routes. That might indicate that ad hoc routing protocols should be able to adapt quickly to changes in the network topology even with low mobility.

4.2.2 DSR

J. Broch et al. [7] (subsection 4.1.1) found out that DSR has quite stable packet delivery ratio with low and high mobility values. Actually it has the lowest packet loss ratio of all the three protocols covered in the study. They found also that packet delivery ratio does not also seem to response moderate changes in traffic load patterns. The routing overhead seems to increase drastically when the mobility increases and vanishes when nodes does not move at all. That is an obvious result since DSR relays on on-demand routing packets only. In addition to the fact that the maximum routing overhead in the study was significantly lower (less than 35000) than the constant 45000 of DSDV. DSR manages the path optimality also well as DSDV did.

Perkins et al. [8] (subsection 4.1.2) pointed out in their study that the packet delivery fraction stays quite stable regardless of the mobility ratios especially with lower traffic loads. When loads were increased fractions started to slightly increase. Mobility also has greater affect on delivery fractions with higher loads. Higher mobility means less improving behavior of the delivery fraction. They also found an interesting detail about the end-to-end delays. On high traffic loads delays seem to increase significantly with low mobility. This can be explained with network congestion at some parts of the network since DSR has no mechanism for load balancing. The normalized routing load of DSR seems to be quite good and it stays quite stable with respect to node mobility even on high traffic loads.

Johansson et al. [9] (subsection 4.1.3) found the delays in their random scenarios to to be bit higher than Perkins et al. [8] did in their 50 node simulation with similar traffic loads. The gap between the results can be explained by differences in mobility patterns. The general behavior however seems to be similar with lower loads. Johnasson et al. did not experiment with very high loads as Perkins et al. did. They found out also that the delays grow with higher loads. They discovered that throughput responses very moderately to mobility even on high traffic loads. They also found out that routing overhead increases as mobility gets higher but the maximum overhead still stays less than the overhead of DSDV. On the other hand the throughput of DSDV is better with very low mobility and low traffic load.

All three studies have similar kind of results, even though actual values have differences because of different kind simulation parameters (See figure 2) The most important parameters as the network size and mobility and traffic patterns are quite similar. Perkins et al. [8] also experimented with higher traffic and brought up some interesting facts about end-to-end delays. DSR also seems to perform better with respect to packet delivery ratio and throughput than DSDV especially with higher mobility. The routing overhead also seems to be lower with DSR than DSDV even with higher mobility at least in moderate sized networks. However the throughput of DSDV can be better with low loads and with very small mobility.

4.2.3 AODV

J.Broch et al. [7] discovered that the overall performance of AODV is quite similar with the other on-demand protocol: DSR. The packet delivery ratio seems to stay quite stable regardless of mobility, even though it is a bit worse with high mobility rates compared to DSR. Routing overhead acts as is did in the case of DSR. However with high mobility ratios it is drastically greater (over 160000 packet) than overheads of DSDV (maximum at 35000) or DSR (stable 45000). With lower mobility the overhead difference between ADOV and DSR gets smaller. The path optimality is worse compared to DSDV or DSR according to the study. On the other hand, the path optimality of AODV depends on mobility: with low mobility it is far closer to the optimum than with high mobility ratios.

Perkins et al. [8] found also that the behavior of AODV performance follows quite similar pattern as a function of mobility rate than the performance of DSR. The packet delivery is a bit worse with AODV than with DSR on low traffic loads. On higher loads AODV has better packet delivery ratio. The same kind of correlation on end-to-end delays can be found between AODV and DSR. With higher loads AODV has lower delays than DSR. The 100 node simulation also showed that difference in delays between DSR and AODV is emphasized when amount of nodes increases. When traffic load is low DSR outperforms, but when traffic load increase AODV has far lower delays. However the normalized routing load of DSR seems to stay better than the routing load of AODV even with greater amounts of nodes, with high and low mobility and traffic patterns.

Johansson et al. [9] pointed out that throughput of AODV behaves like the throughput of DSR (See figure 3). It responses moderately to varying mobility and gives the best throughput compared to DSR or DSDV except in the case of low traffic loads and mobility when DSDV seem to outperform. The study also points out that the overhead of AODV is worse of the three protocols with high mobility rates. When mobility ratio decrease the overhead of AODV is becomes better than the overhead of DSDV even though DSR still outperforms.

As an on-demand protocol, the performance of AODV has many similarities to the performance of DSR. Both DSR and AODV seem to have generally better packet delivery ratio than DSDV that react heavily to changes in mobility ratios The throughput and delays of DSDV are generally better than corresponding metrics of AODV and DSR when mobility rate is significantly low. With higher mobility ratios the two on-demand protocols are generally better. DSR seems to perform better with low traffic loads and fewer nodes in a network than AODV. However when the stress in a network is increased by increasing the number of nodes and traffic load, AODV has better performance than DSR. The routing overhead seem to be an exception: on high mobility AODV performs worse than DSDV or DSR even when the stress in a network is increased.

4.3 Critical Analysis about the Results

The results of the three different studies were quite similar after all. That was not necessarily surprising. The simulation environments and models were quite close to each other. Some of the results are also somewhat predictable because of proactive/reactive nature of a protocol. It is quite self-evident that, for example, DSDV's routing overhead does not react on changes in mobility in the way that AODV's or DSR's overhead do.

All the three studies based their simulations on moderate sized networks (about 50 nodes varied mobility and traffic load ratios). That is one reason why the results are quite similar. On the other hand there were some expectations. Perkins et al. [8] experimented also with 100 node networks and higher traffic loads. In this case, the differences (section 4.2.3) between AODV's and DSR's behavior on high and low loads became clearly visible. That indicates that there would be need to research different sized networks. On the other hand the overall performance of all protocols seem to fall when the number of nodes or the traffic load is increased heavily. That indicates that the concept of ad hoc routing suits only quite small networks with sufficient number of static nodes. The realistic scenarios based simulations that Johansson et al. [9] did, support also this hypothesis. The conference scenario (sections 4.1.3, 4.2.1) showed, that even in a small network, table driven approach may suffer from significant packet loss. The disaster scenario (4.1.3) gives even stronger evidence that ad hoc routing will not necessarily work on larger networks especially when there are certain bottlenecks present (e.g. moving vehicles). The work of Johansson et al. also shows that it might be more useful to study special scenarios with network nodes, that have specific functions, rather than doing simulations with bulk nodes moving randomly around a flat square.

One might also ask why just these three protocols were evaluated in this paper especially when MANET charter lists DSR, AODV and Optimized Link State Routing (OLSR) -protocol. The main reason to this was that suitable performance studies to be reviewed in this paper dealt with these protocols. It should also be noted that all the papers are at least few years old. That emphasizes the need foe further performance research of ad hoc routing performance.

5 Conclusions

At the first place this paper explained some special characteristics that an ad hoc network and routing protocols acting in it have. Then some characteristics of routing protocols were introduced. Some properties of the networking environment, that must be considered when analyzing performance, were also brought up. After that three major ad hoc routing protocols were represented.

The actual work consisted of representing and comparing some researches about the ad routing performance. Three studies were reviewed and their results were compared. The comparison was done with respect to three major protocols: DSDV, DSR and AODV. The studies compared were based on simulations.

Comparison of accurate simulation parameters seemed to be rather fruitless and the aim was to found out how the performance of the protocols generally act when different characteristics are varying. Generally on-demand protocols (DSR and AODV) seemed to perform better than DSDV. Especially when mobility increases. Even with lower mobility and with few moving nodes, DSDV may suffer from quite a big packet loss as pointed out in subsection 4.2.1. That brought up the idea that ad hoc protocols should be able to response quickly on changes in the network topology.

DSR seems to perform better than AODV on less “stressful” situations. However, when stress increases AODV has generally better performance.

After all the simulation results of the different studies were quite similar. On the other hand, the special scenarios and simulation runs with larger networks pointed out that the performance of ad hoc routing protocols may decrease rapidly especially if there are some bottlenecks in the network. It was also concluded that any protocol does not scale up without problems. After all, it comes clearly out that no protocol is better than other with respect to every metric on different situations. That is fundamentally because of the very nature of the ad hoc network.

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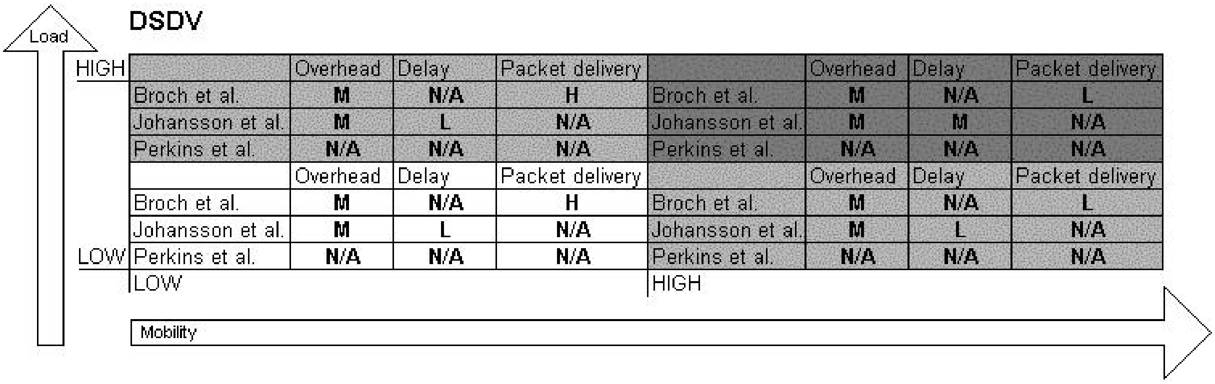
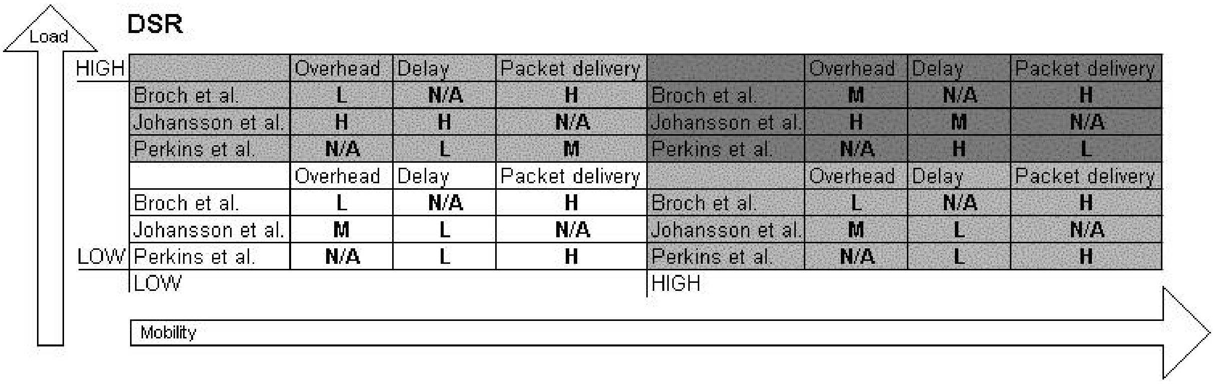


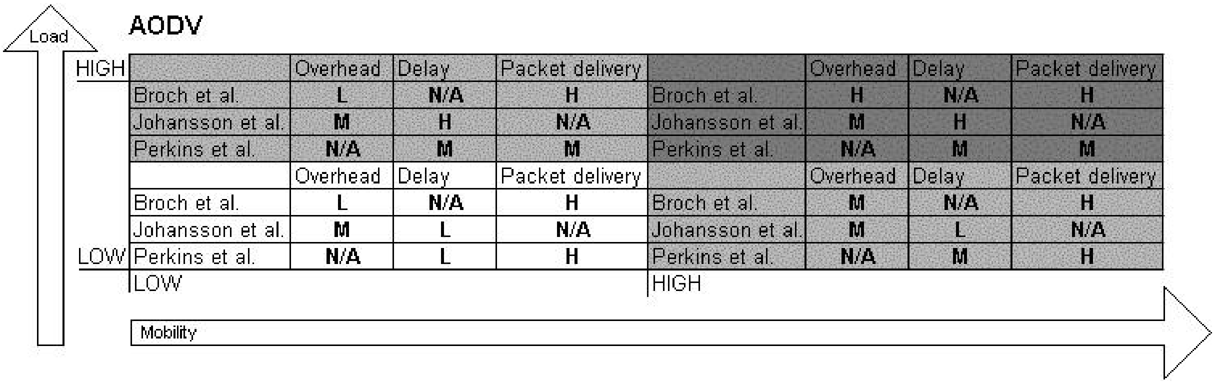
	Overhead	Delay	Packet delivery		Overhead	Delay	Packet delivery
Broch et al.	M	N/A	H	Broch et al.	M	N/A	L
Johansson et al.	M	L	N/A	Johansson et al.	M	M	N/A
Perkins et al.	N/A	N/A	N/A	Perkins et al.	N/A	N/A	N/A
	Overhead	Delay	Packet delivery		Overhead	Delay	Packet delivery
Broch et al.	M	N/A	H	Broch et al.	M	N/A	L
Johansson et al.	M	L	N/A	Johansson et al.	M	L	N/A
Perkins et al.	N/A	N/A	N/A	Perkins et al.	N/A	N/A	N/A

Figure 1: An overview of DSDV performance according to the different studies



	Overhead	Delay	Packet delivery		Overhead	Delay	Packet delivery
Broch et al.	L	N/A	H	Broch et al.	M	N/A	H
Johansson et al.	H	H	N/A	Johansson et al.	H	M	N/A
Perkins et al.	N/A	L	M	Perkins et al.	N/A	H	L
	Overhead	Delay	Packet delivery		Overhead	Delay	Packet delivery
Broch et al.	L	N/A	H	Broch et al.	L	N/A	H
Johansson et al.	M	L	N/A	Johansson et al.	M	L	N/A
Perkins et al.	N/A	L	H	Perkins et al.	N/A	L	H

Figure 2: An overview of DSR performance according to the different studies



	Overhead	Delay	Packet delivery		Overhead	Delay	Packet delivery
Broch et al.	L	N/A	H	Broch et al.	H	N/A	H
Johansson et al.	M	H	N/A	Johansson et al.	M	H	N/A
Perkins et al.	N/A	M	M	Perkins et al.	N/A	M	M
	Overhead	Delay	Packet delivery		Overhead	Delay	Packet delivery
Broch et al.	L	N/A	H	Broch et al.	M	N/A	H
Johansson et al.	M	L	N/A	Johansson et al.	M	L	N/A
Perkins et al.	N/A	L	H	Perkins et al.	N/A	M	H

Figure 3: An overview of AODV performance according to the different studies