Communication Protocols in Distributed Mobile Autonomous Systems

ADVANCED SEMINAR

Submitted by

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ADVANCED SEMINAR
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Problem description:

The *Fachbereich Neurowissenschaftliche Systemtheorie (NST)* is starting a new large-scale student project that investigates in cooperative behavior of a swarm of autonomously operating flying robots. In such a distributed system, where each individual robot needs to take its own decisions based on locally available sensory input, the robots occasionally still need to communicate with each other to propagate globally relevant messages. Examples of such communication could be the detection of an injured person in a catastrophe/rescue scenario, or the propagation of high-level directions from a human operator into the distributed system.
Such a distributed robotic system cannot rely on existing communication infrastructure such as a WLAN access point, but rather needs to issue point-to-point messages that follow a particular protocol to guarantee delivery - or at least to maximize chances of delivery. Over the past decade several different strategies for such communication schemes have been developed, but mainly for stationary sensory systems. In the new student project, however, the autonomous robots constantly change position, which might turn existing communication links between nodes unusable.

The scope of this Hauptseminar is

- to investigate literature to find existing communication protocols
- to provide an overview of existing techniques
- to evaluate communication protocols for applicability for the new student project

Bibliography:

[1] Diot, C., Dabbous, W., and Crowcroft, J. Multipoint Communication: A Survey of Protocols, Functions, and Mechanisms. IEEE Journal on selected areas in communications, vol. 15, no. 3, April 1997
[2] Akyildiz, I.F., and Wang, X. A survey on wireless mesh networks. IEEE Communications Magazine, vol. 43, no. 9, Sept. 2005

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1 Introduction

1.1 Problem Description

The official problem description and scope of this advanced seminar can be found on page I.

1.2 Existing Circumstances

Due to the low lifting capacity of flying robots only a limited amount of hardware can be mounted on the robots. The small processors limit the computing power and thus the transmission range on each robot. Since the autonomous robots constantly change their position, the topology of the swarm constantly changes and therefore some robots may be out of the transmission range of other robots during certain time periods. The swarm will be used in an indoor environment and thereforel move with a rather slow velocity of about a few meters per minute. The number of flying robots (nodes) will be in the range of up to 30.

1.3 Mobile Ad Hoc Networks versus Wireless Mesh Networks

As mentioned in the official problem description an infrastructure by the means of WLAN access points is not available. This problem can be resolved by using a mobile Ad Hoc Network (MANET). A pure MANET is dynamically established by mobile devices grouped together without any support from an existing infrastructure [1]. One of the main characteristics of MANETs is that they use multi hop communication. Multi hop communication means that there are, in the extreme case, no base stations or access points at all. Instead, the wireless devices forward each other’s traffic and each device is both receiver and transmitter. Another characteristic of MANETs is the dynamic topology. In addition to the previously mentioned MANETs, there also exist Wireless Mesh Networks (WMNs). A WMN is a particular Ad Hoc Network, consisting of two parts: a mesh backbone with several stationary wireless mesh routers (MRs) and mobile mesh clients. The stationary MRs are connected to each other by multi hop wireless links. A few of these MRs may act as Internet gateways (IGWs) to exchange traffic between the WMN and the Internet. The wireless mobile clients could then connect to any MRs to access the Internet via the IGWs in multi hop fashion. Compared to pure MANETs, a WMN has a hierarchical structure and the topology of the wireless backbone is stable [1].

In our given scenario a stationary mesh backbone does not exist, therefore we will only analyze protocols used for MANETs.

1.4 Principal Classification of Routing Protocols

In general, routing can be classified into two categories. First, the network structure can be divided into flat-based routing and hierarchical-based routing. In flat-based routing all nodes are typically assigned equal roles, whereas in hierarchical-based routing, nodes will be assigned different roles in the network. Flat-based routing applies to the robot swarm scenario, since all autonomous robots have an equal function.

Secondly, in terms of data distribution, the protocols can generally be classified in proactive, reactive, location-based and hybrid protocols. Proactive routing uses a routing table that is consistent and up-to-date for each node in the network. This generates a large overhead, but packets are transferred almost immediately. Reactive protocols reduce overhead by never finding paths between nodes that do not need to communicate. A node only tries to find a path to another node when it needs to send data to the other node. Because the routing protocol has to identify a valid route before a packet can be sent, there is a small delay. Location-based routing uses the nodes position (e.g. with GPS) to decide whether to forward a packet or not. This is not applicable to our scenario, because the robots are not aware of their own position. Hybrid protocols combine characteristics of more than one of the above; usually they are both reactive and proactive.

Of course, there are other classification possibilities as the above mentioned. The classification can also be divided into more detailed subdivisions. This classification was selected because it is commonly used throughout various papers issuing MANETs. For further reading, a good overview of different routing protocols is given in E. Dutkiewicz et al. “A review of routing protocols for mobile ad hoc networks” [2].

2 Overview of Feasible Routing Protocols

In this chapter different routing protocols which may be applicable to the given scenario are presented. These protocols may not only be suitable for the flying robot swarm scenario, but also have been simulated and evaluated numerous times, which gives us the possibility to compare different results.
The following sections are arranged as follows: First the basic principle of the protocol is introduced, followed by a short general evaluation. A more detailed performance evaluation and comparison, based on simulation results, is then issued in the next chapter, where the focus will be on the applicability to the flying robot swarm scenario. We will start by introducing the reactive Dynamic Source Routing (DSR) and Ad Hoc On-Demand Distance Vector (AODV) protocols, followed by the proactive Optimized Link State Routing (OLSR) and Distance Vector Routing (DSDV) protocols.
It needs to be pointed out that there are also many protocols or derivations of protocols which are proposed and evaluated in only one or two papers. These protocols will not be analyzed because a statistical representative evaluation is not possible, which makes them unsuitable for a literature research. Also, for reasons explained in the following, hybrid protocols will not be evaluated. The most commonly simulated hybrid protocol is the Zone Routing Protocol (ZRP). In their paper "ZRP versus AODV and DSR: A comprehensive study on ZRP performance" [3], Mungara et al. concluded: "Regretfully ZRP was not up to the task and it performed poorly throughout all the simulation sequences, hence putting itself out of competition. In particular it demonstrated a really low packet delivery ratio when compared to DSR and AODV." This conclusion is also reinforced by [4], where simulation results show that ZRP only delivers 40 percent of all packets initiated by the source, whereas AODV and DSR deliver almost 90 percent of all packets. Additionally, in the already mentioned paper of Dutkiewicz et al. [2], it is mentioned that hybrid protocols are more suitable for very large Ad Hoc Networks.
Considering the poor performance of ZRP in MANETs in the range of up to 100 nodes, the hybrid protocols will be neglected in the further progress of this report, as will the location-based protocols (explanation in 1.4). Therefore, we will focus on proactive and reactive routing protocols.

2.1 Dynamic Source Routing (DSR)

The reactive DSR protocol (detailed internet draft: [5]) consists of the two main mechanisms of route discovery and route maintenance. Route discovery is used to find a path from a source to a destination if there is no route known. The route discovery is initiated by sending a "route request" packet to all nodes within transmission range. In case a node receives the "route request" and is the target of route discovery, it will send back a "route reply" with an attached route record. Otherwise it will attach its own address to the route record and broadcast the route request further. After a successful route discovery the source will receive a "route reply" packet with the complete route to the destination. The routes are stored in a route cache. The DSR protocol is able to store multiple routes. To avoid losing packets during route discovery, the data packets are temporarily buffered.

Route maintenance is the mechanism which detects if the topology of the network has changed. If any link on a source route is broken, the source node is notified using a route error (RERR) packet. A broken link is detected if a node which sent a packet to the next node in the route doesn't receive an acknowledgement in return. The source removes any route using this link from its cache. A new route discovery process must be initiated by the source if this route is still needed. The DSR protocol is designed mainly for mobile Ad Hoc Networks of up to about two hundred nodes.

Because the protocol requires each packet to carry the complete route, it will not be very effective in large networks, since the amount of overhead will increase as the network increases. The advantage of DSR is that it can store multiple routes, which is beneficial in a network with rather low mobility since the stored routes will be available longer. Another advantage of DSR is that it does not require any periodic beaconing (or hello message exchanges), therefore nodes can enter sleep mode to conserve their power [2]. This advantage comes with a disadvantage; because there is no periodic beaconing, it can't determine the freshness of routes and hence has no active or timer-based mechanism to expire stale routes.

2.2 Ad Hoc On-Demand Distance Vector (AODV)

The Ad hoc On-Demand Distance Vector (detailed internet draft: [6]) is a reactive protocol. AODV uses a similar route discovery procedure as in DSR. The major difference between them is that in AODV the packets only carry the destination address. After route discovery finishes in AODV, each node on a path is only responsible for knowing which neighbor to forward a message to in order to reach the destination. AODV uses sequence numbers maintained at each destination to determine freshness of routing information and to prevent routing loops. In contrast to DSR, the routes are not stored in a cache but in standard routing tables. An important feature of AODV is the use of timer-based states in each node to determine if a routing table entry is up-to-date. A routing table entry expires if not used recently. Neighbors are found by using periodic HELLO messages. In case a node fails to receive HELLO messages from a neighbor which it uses for data forwarding, that link is identified as broken and a link failure indication is sent to its active neighbors. Active neighbors are nodes that were also using the broken link. This way, the link failure message will be propagated back to the source, which can decide whether to stop sending data or to discover a new route. AODV also buffers data packets during route discovery.

AODV will only establish one path between the source and the destination. If that path breaks, the source will have to initiate route discovery to find a different path, which can result in delays during route construction and link failure. According to [7] AODV was one of the first routing protocols created for MANETs, so it is relatively simple yet completely functional. Due to the periodic beaconing AODV may perform better under high mobility and high load conditions. This is because broken links occur more often in highly mobile networks and they can be detected faster with the periodic beaconing mechanism.

2.3 Destination Sequence Distance Vector (DSDV)

The DSDV algorithm (detailed internet draft: [8]) is a proactive routing protocol where each node maintains a routing table that lists all available destinations, the number of hops to reach the destination and the sequence number assigned by the destination node. Each node periodically broadcasts its routing table to its neighbors. This can be done in two ways: full dump or incremental dump. The full dump sends the full routing table to the neighbors whereas the incremental dump only sends those entries which have changed since the last update. The full dumps only are needed in case the network is fast-changing. Similar to AODV, DSDV uses destination sequence number to avoid routing loops and the count-to-infinity problem.

One of the advantages is that it is loop free and also that the complete routing table is known by all nodes. A disadvantage is that DSDV fails to converge for higher rates of mobility, because of the time that is needed for the periodic broadcasts and updates of all nodes. Hence, DSDV protocol can drop packets because a stale routing table entry directed them to be forwarded over a broken link.

2.4 Optimized Link State Routing (OLSR)

OLSR (detailed internet draft: [9]) is a proactive protocol that minimizes the number of rebroadcasting nodes and the size of each control message by using only selected nodes to retransmit control messages. These nodes are called Multipoint Relays (MPR). During each periodical topology update, each node in the network selects a set of neighboring nodes to retransmit its packets. The nodes which are not in the set can still read and process each packet, but they do not retransmit. To select the MPRs, each node periodically broadcasts a list of its one hop neighbors using HELLO messages. From the list of nodes in the HELLO messages, each node selects a subset of one hop neighbors, which cover all of its two hop neighbors (see Figure 1).

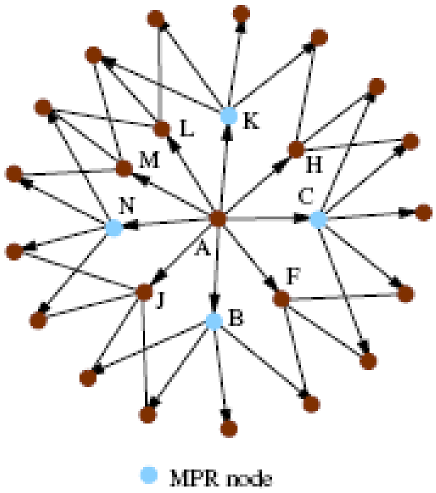


Figure 1: **Multipoint Relays:** Nodes B, C, K and N cover all nodes which are two hops away [2]

In OLSR all nodes with a non-empty MPR selector periodically generate a topological control message (TC-message). The TC-message is sent to all nodes in the network using MPR flooding. Through the TC-message the nodes obtain a partial topological graph. With this graph it is possible to generate short paths from a node to any reachable destination. TC packets are also used to detect broken links.

OLSR continuously maintains routes to all destinations in the network; therefore routes to every destination are almost immediately available when data transmission begins [2]. A possible disadvantage of OSLR is that it does not provide buffering of undeliverable data packets as DSR and AODV do. This is based on the assumption that a complete routing table of the network is available and therefore no packets need to be buffered. This applies in scenarios with moderate mobility and higher load conditions. In high mobility scenarios the routing table might not always be updated fast enough. Because there is no buffering, a data packet is either delivered with almost no delay or dropped immediately. As already mentioned above, another advantage of OSLR is that it generates shorter paths as reactive protocols.

3 Comparison of Protocols in Respect of Applicability

The results that are evaluated in this chapter were obtained by simulations. Most commonly used simulators are NS-2, OPNET and Qualnet. The functionality and differences of these simulators are not a topic of this report. Due to the different models, model parameters and simulators the results are sometimes difficult to compare.

3.1 Evaluated Criteria

The different protocols are analyzed with respect to the criteria listed below. The listed criteria are most commonly used in papers that evaluate MANETs because they are important to determine the performance of a protocol.

1) Packet Delivery Ratio
2) End-To-End Delay
3) Overhead
4) Throughput
5) Hop Count/ Path Length
6) Link Error Latency

3.2 Evaluated Papers

The selection of papers used for evaluation is based on different factors. An important aspect is that the simulation parameters are somewhat comparable to the robot swarm scenario, e.g. the number of nodes shouldn't exceed 50. Also, the selected papers should have a mobility model included in their simulation, which applies to the moving robot swarm. Further criteria are the number of simulation results, comprehensive figures, as well as selecting papers that use different simulators and of course papers that evaluate protocols which may be applicable to the given scenario. It is also important that the authors try to link the simulation results to the protocol properties. Papers from large and renowned conferences and proceedings most likely have been reviewed by experts thoroughly. A high citation count can also be a hint that other researchers trusted the obtained results; of course only if the citations acknowledge the work.

In order to obtain a representative evaluation the following five papers were evaluated and compared:

1	Comparative Study of Reactive and Proactive Routing Protocols Performance in Mobile Ad Hoc Networks	[10]
2	Performance Evaluation of Ad Hoc Routing Protocols Using NS2 Simulation	[11]
3	Evaluating Ad Hoc Routing Protocols with Respect to Quality of Service	[12]
4	Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks	[13]
5	Scenario-based Performance Analysis of Routing Protocols for Mobile Ad-hoc Networks	[14]

A quick overview of the different simulation parameters is given below. It is important to note that the different simulations use different simulation parameters. The dimension of specific simulation parameters might be favorable or unfavorable for certain protocol properties.

1	
Simulator	OPNET 11.0
Area	1km x 1km
Simulation Time	1000 sec
Packet Size	--
Packet Rate	--
Number of Nodes	50
Radio Range	--
Velocity	0 – 20 m/s

2	
Simulator	NS2
Area	500m x 500m
Simulation Time	100 sec
Packet Size	512 bytes
Packet Rate	--
Number of Nodes	50
Radio Range	--
Velocity	0 – 20 m/s

3	
Simulator	NS2
Area	1500m X 300m
Simulation Time	300 sec
Packet Size	256 bytes
Packet Rate	1 to 10 packets/sec
Number of Nodes	50
Radio Range	--
Velocity	Max. of 10 m/s then pause for 10 sec

4	
Simulator	NS2
Area	1500m x 300m
Simulation Time	900 sec
Packet Size	512 bytes
Packet Rate	4 packets/sec
Number of Nodes	50
Radio Range	250 m
Velocity	0 – 20 m/s

5	
Simulator	NS2
Area	1000m x 1000m
Simulation Time	250 sec
Packet Size	64 bytes
Packet Rate	5 to 20 packets/sec
Number of Nodes	50
Radio Range	250 m
Velocity	0 – 20 m/s

3.3 Performance Comparison

3.3.1 Packet Delivery Ratio

The Packet Delivery Ratio (PDR) is obtained by dividing the number of packets received by the destination through the number of packets sent by the source. The PDR is evaluated over the number of nodes, the mobility, the pause time and the number of concurrent streams/flows.

Simulations of [10] vary the number of nodes from 25 to 100 in an area of 1km x 1km. The results show that the PDR of all examined protocols (AODV, DSR, OLSR) remains almost constant (+/- 5%) for an increasing number of nodes. The velocity (in m/s) is varied from 0 m/s to 20 m/s. In case of a fixed nodes network, DSR, AODV and OLSR perform very well with a PDR of almost 100%. For DSR and OLSR the PDR remains constant at about 100% for speeds up to 5 m/s whereas for AODV the PDR decreases from 100% to 80%. [12] obtains slightly different results; for their mobility model AODV and DSR achieve a PDR of about 95% and OLSR is slightly lower with a PDR of 90%. Papers [11] and [13] examine the PDR versus different pause times (0s – 100s/900s) for moving nodes. Using pause times is another way to simulate the mobility. The pause time is the time, in which a node remains at a fixed position before moving to the next position; therefore short pause times denote a high mobility and long pause times denote low mobility. The PDR of AODV and DSR varies between 90% and 100% (for 10/20 sources) over the different pause times, whereas die PDR of DSDV reaches 70% for short pause times. Both papers run their simulations with 50 nodes and in both simulations the PDR decreases visibly when using more than 20 sources. Simulation results of [12] show that the PDR of DSR, OLSR and AODV remains constant for up to 5 packets per second. But in their scenario DSR and AODV perform slightly better than OLSR. When considering the PDR over the number of sources, [10] shows that for DSR the PDR decreases if more than 40% of the nodes act as sources at the same time. On the other hand, the PDR of OLSR isn’t affected by an increasing number of sources. The average PDR of DSR, AODV and OLSR for the different simulation scenarios is in between 80% and 100%. The PDR of DSDV reached values as low as 50%. For higher traffic the PDR of DSR drops visibly, whereas the PDR of OLSR and AODV only decreases slightly for higher traffic [10].

In the robot swarm scenario, where speeds are definitely below 5 m/s and there are rather short pause times in which a flying robot remains at a constant position, protocols AODV, DSR and OLSR perform well with packet delivery ratios of 80% to 100%, depending on the paper and simulation parameters. According to the surveyed papers, to obtain a high PDR for AODV and DSR, not more than 40% of the nodes should act as sources at the same time and the sent packets per second shouldn't exceed 5. DSDV shows poor results for the PDR as soon as the mobility increases.

3.3.2 End-To-End Delay

The end-to-end delay is the time between transmitting a packet from the source and receiving it at its destination. Delays appear due to route discovery, queuing, propagation and transfer time.

In [10] the number of nodes is varied from 25 to 100. They observe that proactive routing protocols (DSDV, OLSR) have the lowest end-to-end delays (max. of 0.1 sec) and there is only a very small increase with an increasing number of nodes. This of course is due to the always up-to-date routing tables. DSR has a slightly higher end-to-end delay than AODV in scenarios with high traffic and mobility; this is because the destination replies to every RREQ (Route Request) it receives, whereas in AODV every destination replies to the first RREQ. When investigating the end-to-end delay over transmitted packets per second, [12] shows that there is only a large increase in the end-to-end delay of AODV, DSR and OLSR when sending more than 6 packets/s. This result is reinforced by [14] where the delay of AODV, DSR and DSDV increases to over 0.1 s when sending more than 5 packets/s. According to [10] the end-to-end delay of OLSR isn't affected by an increasing speed of the nodes and for AODV and DSR there only is a significant increase for velocities over 10 m/s. [14] obtains similar results; the delay for AODV, DSR and DSDV increases for higher velocities but remains below 0.1 s even for 20 m/s. Simulation results concerning the number of sources show, that if more than 40% of the nodes act as sources the end-to-end delay for DSR and AODV increases largely, but for OLSR it remains consistent. For pause times between 10 and 20 seconds, [11] shows that the delay for DSR increases significantly whereas the delays for AODV and DSDV are very low and vary only slightly for different pause times. As already mentioned in the previous section this could be due to the fact that DSR needs more time to determine a stale route. In all simulation scenarios the end-to-end delay is not higher than 0.1 s for moderate conditions; only for a large number of sources or very high traffic the delays increase to a maximum of 0.4 s. Overall OSLR and DSDV have the lowest delay, followed by AODV and finally DSR with a slightly higher delay on average.

In our scenario the flying robots act autonomously based on locally available sensory input and only need to communicate with each other occasionally. This means pause times in the range of up to about 500ms are acceptable. According to the various simulation results, all analyzed protocols are within this range for simulation parameters that fit to the flying robot scenario. In general, proactive protocols have shorter delays than reactive protocols.

3.3.3 Routing Overhead/ Routing load

The overhead can be defined as the number of packets and total number of bytes generated during the simulation. Analyzing the overhead is important to determine whether a protocol will function in low-bandwidth scenarios, also the routing overhead relates to how much node battery power is consumed.

In [10] the overhead in bps (bytes per second) is analyzed. Simulation results show that DSR and AODV have an overhead of similar magnitude (range 10 - 30 Kbps for their applied simulation parameters). As a proactive routing protocol OLSR has a far higher overhead (range 1 – 4 Mbps). The overhead of all protocols increases with a higher number of nodes because more nodes generate more control messages. If the number of nodes is below 50, the overhead only increases slowly; if the number of nodes exceeds 50, the overhead, especially of AODV, increases rapidly. The overhead of OLSR isn't affected by a rising number of sources (proactive protocol), whereas AODV and DSR have an increasing overhead (reactive protocols). This is because more routes to more destinations need to be found. In [12] the overhead in packets per second is simulated over the sent agent packets/s. For up to 5 agent packet/s, the packet overhead remains almost constant. When sending more than 5 packets the overhead of AODV increases drastically, whereas the overhead of OSLR and DSR only increases slightly. AODV usually has a higher packet overhead than DSR, due to the periodic HELLO messages it broadcasts. Paper [12] also simulates the overhead in bps versus agent packets/s. Their results show the lowest overhead for DSR, followed by AODV. OLSR achieves the highest overhead, but only by a magnitude of three higher than AODV and DSR. The different results of [10] and [12] could be due to the use of different simulators, but according to the routing properties the routing overhead of proactive protocols should exceed the overhead of a reactive protocol by far, since it needs to maintain consistent routing tables of the complete network. When analyzing the behavior of the packet overhead versus different pause times (in [11]), it can be seen that the overhead increases for pause times up to 10 seconds but decreases again for pause times longer than 10 seconds. This is because the old routes need to be replaced by new routes more often. Overall the overhead of reactive protocols increases for higher mobility since more routes need to be updated more often. In paper [13] (packet size 512 bytes) AODV has a higher overhead than DSR, whereas in [14] (packet size 64 bytes) the overhead of DSR is higher. This leads to the conclusion that the overhead of DSR and AODV is very dependent on the selected parameters. They also analyze DSDV which reaches the highest overhead in their simulation, as it is a proactive protocol.

For nodes in the range of 50 the routing overhead only increases slightly for all protocols. For velocities below 5 m/s the overhead of all analyzed protocols remains stable, but when applying higher traffic the overhead increases constantly. The overhead of proactive routing protocols is higher than the overhead of reactive routing protocols. AODV tends to have a higher packet overhead because of the periodic beaconing and DSR tends to have a higher byte overhead in larger networks, since it stores the complete routes. Of course the overhead increases for higher traffic as well.

3.3.4 Throughput

The throughput is the measurement of traffic passing through the network in a unit of time. The goal is to achieve a high throughput.

From the selected papers only [10] and [14] provide a detailed analysis of the throughput. Simulations of [10] show, that under light traffic, DSR performance is comparable to OLSR, but its throughput saturates at around 75 Kbps. AODV performs better because its throughput saturates later at 125 Kbps. The throughput of OLSR continues to increase in a linear manner even for higher network loads. Also, the throughput of the three protocols increases with the number of sources. Only DSR saturates for more than 10 sources, whereas for the other two protocols the throughput continues to increase. An increasing number of nodes have no effect on the throughput. Paper [14] compares the throughput of AODV, DSR and DSDV versus mobility. For zero mobility the throughput of all protocols is in the range of 2.5 Kbps. Keep in mind that the absolute numbers of the different simulations (throughput in Kbps) cannot be compared with each other due to different simulation parameters. For higher mobility, the throughput of DSDV decreases significantly to 1.5 Kbps. The throughput of DSR and AODV is almost the same and only decreases slightly to 2.4 Kbps for high mobility. Also the throughput increases when sending more packets per second.

For velocities below 5 m/s the throughput of DSR, OSLR and AODV remains constant. Increasing the number of sources increases the throughput. However, as mentioned in the previous sections, increasing the number of sources to more than 20 in a 50 node network has a negative effect on DSR and AODV concerning the PDR, delay and overhead. OLSR is able to maintain a good PDR even for high traffic and a high number of sources, but at the cost of a very high overhead.
The throughput of DSDV decreases for a higher mobility, which is not beneficial for the applied scenario.

3.3.5 Hop Count/ Path Length

The hop count is the number of nodes that a packet needs to pass until it reaches its destination. It is also referred to as the path length.

Paper [12] analyses the path length over the packets which are sent per second. In their simulation scenario, AODV has the most hops on average (2.5), followed by DSR (2.2), while OLSR has the least hops on average (1.9). Also there is a small decrease of hops for more packets per second. Proactive routing protocols like OLSR have a complete routing table of the network and hence can locate shorter paths. On contrary, reactive protocols such as DSR and AODV can’t guarantee the shortest path because of their lack of complete topological information.

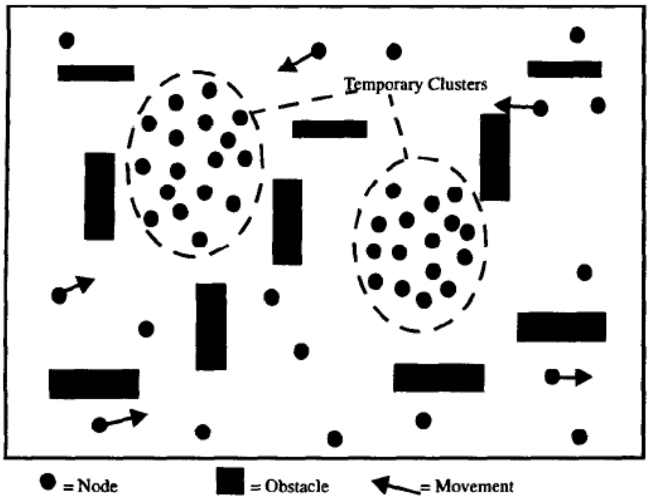
A shorter path should result in a higher throughput. But the average hop count of OLSR in a simulated network of 50 nodes isn’t significantly higher than the average hop count of DSR and AODV. Therefore considering the hop count may be negligible for the rather small node network in the flying robot swarm scenario.

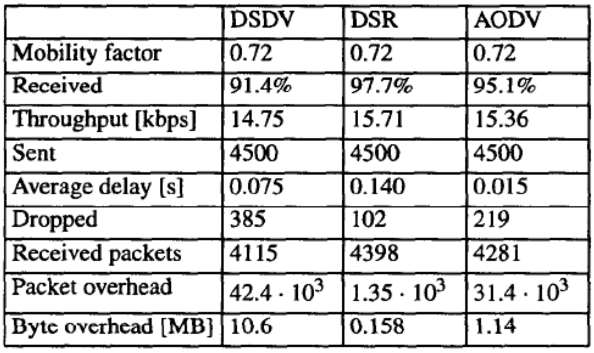
3.3.6 Link Error Latency with/without Link Layer Feedback

The link error latency is the time it takes to detect a broken link to a neighbor. During this period, a node will forward packets on the broken link. The link error latency is mainly evaluated in the already mentioned paper from John Novatnack et al. “Evaluating Ad hoc Routing Protocols With Respect to Quality of Service” [12]. They state that OLSR, AODV and DSR can be used with or without a link layer feedback.
Without a link error detection mechanism, the link error latency is in the range of several seconds (e.g. in [12], 6 s for OLSR and 4.5 s for AODV, DSR isn’t evaluated without link layer feedback). With link layer feedback, the link error latency is 0 s for all protocols. The different internet drafts of DSR, AODV and OLSR provide mechanisms for link layer feedback. According to [12], OLSR is often studied without link layer feedback, but it is usually used for AODV and DSR.

4 Simulations for Realistic Scenarios

In the work of Johansson, Larsson, Hedman and Mielczarek [14], three “realistic” MANET scenarios are simulated. The goal is to create scenarios which are not as artificial as the standard simulation models. The scenario they call “Event Coverage” (Figure 2) is somewhat comparable to our flying robot exploration scenario. The scenario has different obstacles, as well as 50 highly mobile people which change their position frequently. 50% of all people are always in movement with a velocity of 1 m/s. There are several clusters with about 10 people. There are 9 constant bit rate sources and 45 receivers. The packet rate is set to 4 packets/s and the packet size is 512 bytes. Goal of the scenario is to simulate the fast topology changes in MANETs.
The simulation results show a surprisingly high PDR for DSDV; in many simulations the PDR of DSDV already decreases visibly in low mobility scenarios. As expected the overhead of DSDV is very high. Both DSR and AODV show a very high PDR and an almost equal throughput. The delays are well within the range of what is acceptable for an autonomous acting swarm. As a result of the periodic beaconing, the packet overhead of AODV is much higher than the one of DSR and because the network is rather small, DSR also achieves a smaller byte overhead. The average delay of all simulated protocols is well within the range of what is acceptable in an autonomously moving swarm.





	DSDV	DSR	AODV
Mobility factor	0.72	0.72	0.72
Received	91.4%	97.7%	95.1%
Throughput [kbps]	14.75	15.71	15.36
Sent	4500	4500	4500
Average delay [s]	0.075	0.140	0.015
Dropped	385	102	219
Received packets	4115	4398	4281
Packet overhead	$42.4 \cdot 10^3$	$1.35 \cdot 10^3$	$31.4 \cdot 10^3$
Byte overhead [MB]	10.6	0.158	1.14

Figure 2: Event scenario and simulation results [14]

5 Discussion

Because of the different simulators and simulation parameters it is often difficult to compare the results of simulations. Nevertheless, it is possible to observe common trends throughout the different simulations and also determine which protocols are suitable for the flying robot swarm scenario.

DSDV shows a decreasing PDR and throughput in networks with increasing mobility. As a proactive protocol, it also has the disadvantage of a rather high overhead. Taken into account the existing circumstances of the given scenario, DSDV cannot be recommended.

Overall, OLSR, DSR and AODV are applicable to the flying robot scenario. They show a good performance for simulation parameters which apply to the robot swarm (moderate mobility, limited number of nodes). Each of the three protocols has different assets and drawbacks. As reactive protocols, DSR and AODV focus on the needed connectivity and only find paths when necessary. This limits the overhead, especially in networks in the range of about 30 nodes. Since the swarm consists of autonomously flying robots, the communication between the nodes is not continuous. This may be more suitable for reactive protocols. Because DSR does not use periodic beaconing it has a limited packet overhead, but as it stores the complete route to the destination, it has an increasing byte overhead for an increasing network. AODV on the other hand applies periodic beaconing and therefore tends to have a higher packet overhead, but because each node only has to know where to forward its packet to, it usually has a lower byte overhead. The periodic beaconing is of advantage in highly mobile networks, where links break more often. Due to these reasons, DSR performs better in less “stressful” scenarios, where the number of nodes, the traffic and mobility are moderate. AODV outperforms DSR for highly mobile and larger networks. One of the common disadvantages of reactive protocols is the delay time due to route exploration. But for an autonomously flying swarm a delay below 500 ms is acceptable and this time isn’t exceeded in the different simulations. According to the analyzed papers, the throughput of AODV and DSR saturates for more than 30 nodes or networks with many sources and high traffic. A common trend throughout various performance evaluations is to limit the sent packets per second to below 5 and to limit the sources to under 40% to obtain a good throughput and PDR for AODV and DSR. Of course one also has to consider the packet size; 64 bytes, 256 bytes and 512 bytes are used throughout the different evaluations.

If these proposed limitations need to be exceeded, the alternative would be OLSR. Although OLSR is a proactive protocol it still performs well in mobile scenarios. According to [10] the throughput of OLSR saturates later even for many sources and high loads. It also has a smaller delay and shorter paths than reactive protocols. But all of these advantages come with the cost of very high overhead.

There is no “ideal” protocol which outperforms all the others. For example if you take the packet delivery ratio; in one simulation DSR may perform slightly better than AODV and OLSR, whereas in another simulation one of the other protocols may perform marginally better. Before selecting a certain protocol, a first step would be to think of criteria as packet size, packets/s and the number of sources. One can then analyze which of the selected, feasible protocols performs best for the given parameters.

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