Evaluation of Ad Hoc Routing Strategies to Maximize Path Lifetimes

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Abstract—**An important parameter to evaluate the performance of ad hoc routing algorithms is their average route lifetimes. Numerous route breaks require frequent route reestablishments. This certainly limits the performance of routing algorithms and their ability to support QoS applications. The analysis of path lifetimes of different ad hoc routing strategies is a first step towards reasonable optimization of routing algorithms. Our evaluation implies that ad hoc routes with more than five hops are unsuitable for end-to-end data communication as they tend to break prematurely. Further analysis illustrate that multi-path algorithms outperform strategies relying only on the shortest path by at least 50%. Additionally, non-disjoint multi path systems, show better results than their disjoint counterparts do. Their greater flexibility in terms of path selection allows improvements in most variable environments.**
Index Terms— **mobile ad hoc networks, routing strategies, path lifetimes, analysis and evaluation.**

I. Introduction

Ad hoc networks are self configuring wireless networks without any fixed infrastructure. Nodes move independent from each other through the network. Since the maximum radio transmission range of nodes is small, network topologies constantly change. These changes cause frequent route breaks and force sources to reestablish or maintain connections to their distant communication partners.

Numerous ad hoc routing algorithms exist to allow networking under various conditions. They can be separated into two groups: proactive and reactive algorithms [1, 2]. Proactive algorithms always maintain an overview over the network and therewith nodes are able to create instant connections to other nodes. Reactive routing algorithms create routes only on demand and do not try to maintain a network overview. Simulation results depict that reactive algorithms outperform proactive ones, especially for frequently changing network topologies.

Our simulations should give insights of mobile ad hoc networks, therefore we focus on the behavior of reactive algorithms. The average path lifetime (PLT) is the most important parameter for valuable ad hoc routing algorithm design. It heavily influences the number of necessary route requests (RRQ) during data communication between source and destination. Switching to backup routes involves only few nodes and causes only little overhead. A new route request requires all nodes to forward this packet. This in turn affects the possibility of utilizing QoS applications, as frequent RRQs delay packets and prevent timely delivery.

This paper is the continuation of the mathematical evaluations given in [3] and [4]. These papers evaluated single path systems with certain hop numbers but did not show results concerning multi path routing or expected path lengths in certain network environments.

Numerous publications (e.g. [5] and [6]) exist, concerning the selection of most durable paths for QoS ad hoc routing. The authors in [7] show that the shortest path is not always the best choice. It tends to use nodes close to their neighbors transmission range, and therefore shows high probabilities of premature link breaks due to node movements. However, all tried to maximize the lifetime of single path routing algorithms with the help of additional information. None utilized multi-path strategies or described reasonable ad hoc network environments.

The main goal of ad hoc networks is data communication. Therefore, network connectivity [8] is a major characteristic, although it is just a condition for promising ad hoc network setups. Requiring connected networks exceed the necessity of paths between senders and receivers. Guaranteeing connected networks always requires denser node distributions than connections between distant nodes would require. This paper addresses the open questions about necessary node densities and acceptable link error rates for reasonable data communication.

The following evaluation considers the underlying characteristics of routing algorithms in ad hoc networks. It performs an in depth evaluation of different routing strategies and gives some design rules to setup functional ad hoc networks.

The following paper is structured as follows: Section II contains related work, section III describes the utilized simulation model and section IV briefly introduces the simulation environment. A detailed analysis of ad hoc route behaviors follows in section V. The paper sums up with a conclusion in section VI.

II. Related work

The authors in [9] propose an AODV extension to discover multiple node-disjoint routes. AODV [10] uses a route request – route reply mechanism to discover a path between communication partners. Nodes drop additional copies of flooding messages. Therewith intermediate nodes drop messages showing possible backup paths. The new AODV multipath (AODVM) algorithm circumvents this shortcoming. Intermediate forwarding nodes save all received RREQ messages. These messages contain the number of hops back to the source as additional information. The destination generates for each received RREQ a RREP message and returns it to the source, utilizing the path with the fewest hops. Each intermediate node, which receives the RREP message, retrieves the RREQ information with the fewest hops to the source. It forwards the message to the next hop neighbor stated in this particular RREQ and afterwards deletes the information. In case, intermediate nodes do not have any further stored RREQ information, it generates a route discovery error (RDER) as negative acknowledgment and returns it in the direction of the destination. Upon reception of a RDER, intermediate nodes try to forward the message over a different path. After the reception of a RREP message, the source generates a route confirmation message (RRCM) as positive acknowledgement. The protocol prevents non-node-disjoint paths by deleting any utilized link from the nodes RREQ-message tables.

AODV-non-disjoint multipath (AODV-NDM), utilizes AODV as basis as well. It discovers non-disjoint routes form source to destination. AODV-NDM is an extension of AODVM and utilizes the same messages and follows the same basic ideas. Despite the original AODVM algorithm, nodes do not delete RREQ table entries after usage as outgoing link for RREP messages. Instead, they increase the hop metric for the utilized links and keep them within the table. Subsequent RREP messages favor unused links. However, nodes use previously utilized links, in case yet unoccupied links are not available anymore. The algorithm generates mostly disjoint paths, while reusing some important links. As the source receive all RREP messages, additional error procedures during route setup are not necessary. The destination delays all but the first individual RREP message for some predefined period to prevent inconsistencies within forwarding nodes.

The authors in [11] investigate the impact of different node mobility models on the link and path lifetimes. They run excessive simulations with the network simulator ns-2 under various network conditions. PLTs always have an exponential distribution, independent from the underlying mobility model. Following simulations show the impact of the path length h, the average relative speed v and the radio range R on the average PLT. While R linearly increases the PLT, the reciprocals of h and v are proportional to the PLT. Their simple first order analytical model for PLTs depicts that the distribution-function is $f(x) = \psi \cdot e^{-\psi \cdot x}$ with $\psi = \lambda_0 \cdot h \cdot v / R$ and λ_0 a constant. The assumption is verified with the Kolmogorov Smirnov test. The second analytical model covers the relation between PLTs and network performance. The Pearson correlation test suggests that there is a linear relationship between the reciprocal of the average PLT and the network performance in terms of routing overhead. The same test shows, that the throughput is proportional to the negative reciprocal average PLT. Therewith, the PLT is a good indicator to predict the performance of reactive routing algorithms.

III. Simulation model

Simulations use a simplified real world model. The variable parameters are the number of nodes N, the average number of neighbors n and the maximum node velocity v_{max}. Neighbors are nodes within the maximum transmission range and therewith capable to setup direct node-to-node communication. The radio transmission range R forms a perfect disc around each node. As the parameters n, R and v_{max} depend on each other ($R \sim \sqrt{n} / v_{max}$), the radio range as additional parameter is preventable and therefore is kept constant. The node density δ is calculated with the help of the number of neighbors n and the radio range R

$$\delta = \frac{n+1}{\pi R^2} \quad (1)$$

Hence the initial edge length of the simulation area is

$$a = \sqrt{\frac{N}{\delta}} = R \cdot \sqrt{\pi} \sqrt{\frac{N}{n+1}} \quad (2)$$

As node mobility model, the simulations utilize a simplified random direction (RD) mobility model [12]. A random process assigns all nodes an initial position within the simulation area, and an initial velocity vector. Node $i \in [0..N\text{-}1]$ moves towards direction $\alpha_i \in [0..2\pi]$ with speed v_i. The velocity is uniformly distributed between 0 and v_{max}. Therewith the average node velocity v_{av} is $v_{max}/2$. After the start-up, all nodes immediately start moving towards their direction α_i with their constant velocity v_i. The mobility model does not induce nodes to turn directions or pause between consecutive movements. Only in case nodes approach a border of the simulation area, the movement algorithm reflects them at the perpendicular, in order to keep the overall node density constant throughout the complete simulation. Additionally, nodes never change their velocities.

With the knowledge about the initial positions of all nodes and the radio transmission range R, the simulation calculates all available links between nodes. Hereafter, it randomly chooses source and destination node and calculates all routes between both endpoints. The character and the number of calculated paths depend on the currently utilized model.

We assume that the required route setup time is much smaller than the PLT ($t_{route\text{-}setup} \ll t_{PLT}$) and therefore neglect movements during route creation. The simulation is able to calculate three different types of paths: the shortest path (SP), disjoint multipaths (DMP), and non disjoint multipaths (NDMP). Figure 1 depicts an example.

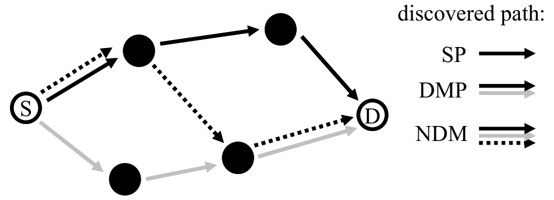

Figure 1: Single path, disjoint multipaths, and non-disjoint multipaths.

The SP represents route request algorithms of reactive ad hoc routing protocols like AODV and DSR [13]. Multipaths strategies consecutively use all available paths, till the last available one break as well. We use the term PLT for SP as well as for multi paths simulations. Within a multi paths group, PLT depicts the failure time of the last available path.

The DMP routing strategy is based on the AODVM protocol. It guarantees link and node disjoint path. Therefore, it has the best reliability against node and link failures. If a permanent error occurs on the primary path, all backup routes are still functional and able to maintain the connection between sender and receiver. The DMP and NDMP paths sets choose the SP as primary path as well. The DMP algorithm iteratively calculates the SP while omitting all already utilized nodes.

The NDMP strategy is based on the AODV-NDM extension. It does not request disjoint nodes and links. The program calculates the primary path (=SP) and increases the weights of all utilized links by a constant value Δw_{nd}. All subsequent paths may reuse important links, but the algorithm favors links with small weights.

DMP and NDMP sets outperform SP in terms of path availability, because they already contain the SP and additional backup routes. Hence, their combined path availabilities are always greater than that of the SP. NDMP sets always contain the requested number of backup paths. In contrast to that, DMP occasionally does not compute all necessary paths, because it is unable to create routes while omitting already utilized nodes.

As all calculations use the exact positions of nodes and all links are available, it always generates the best available paths. In order to allow a more realistic environment, we introduce error prone links. With the threshold th_{link}, a random process decides about link availabilities, and the simulation removes these links from the link list. With a link error probability of 50%, every other link is supposed to have permanent errors.

The modification allows simulations within realistic environments. The computation does not always generate the shortest physical available path and the average number of hops increase.

IV. SIMULATION ENVIRONMENT

The simulator is based on LEDA (Library of Efficient Data Types and Algorithms) [14]. LEDA contains the necessary data types and algorithms, e.g. Dijkstra, to perform the required evaluations easily. Additionally it contains a graphical interface to visualize the different paths within arbitrary network topologies. The optimized implementations of algorithms allow numerous repetitions with varying starting parameters within reasonable periods.

As described, the edge length a of the simulation environment depends on the radio range, the average number of neighbors, and the number of nodes. Therewith the initial simulation area varies for different setups.

As common parameter set we choose N=100 nodes, a radio range R=100m, and a node density n of ten neighbors on average. The maximum node velocity v is 2m/s, the multi-path algorithms try to create up to five paths, and the environment is link error free. The calculation of NDMP paths uses a link weight increment value Δw_{nd} of 0.5 for each utilized paths. If not otherwise stated, all following simulations use this common parameter set.

The evaluation of a parameter set contains at least 10000 independent simulations in order to allow statistically significant results. Additionally, we compute the 95% confidence intervals. However, due to the large number of simulations, the size of the confidence intervals is neglectable, and therefore we refuse to show them within the following graphs.

V. SIMULATIONS

The first simulation compares the path calculation algorithms with respect to different simulation sizes. Figure 2 shows the behavior of PLTs for networks with 50 and 500 nodes. The y-axis depicts the probability, that paths are still alive after a certain amount of time. It is obvious, that small networks only allow short paths and therefore PLTs are greater. It is also evident, that connections with multiple backup routes allow longer lifetimes in comparison to the single path. With 50 nodes within the simulation, 30% of all SP are still alive after 20 seconds, but about 50% of multi-path connections. This turns even worse for 500 nodes networks. The probability of an unbroken SP after the same time is only 5% and 10% for multi-paths systems.

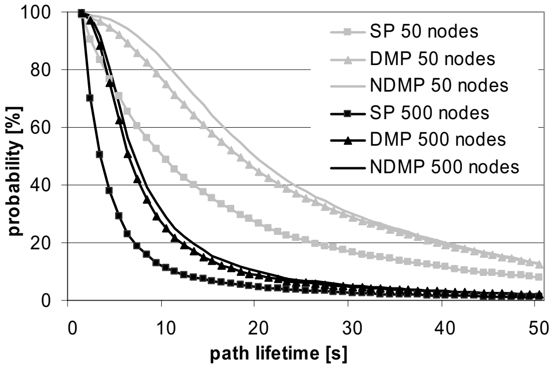

Figure 2: Path lifetimes for 50 and 500 nodes networks and for different path calculations.

The NDMP route selection always outperforms the DMP selection. Figure 3 shows the average path lifetimes.. With ten neighbors on average and 50 node networks, NDMP increases the average connection lifetime by more than 50% compared to SP. With 500 nodes, NDMP allows 80% longer lifetimes than SP. The improvement of NDMP to DMP is always about 8% and independent from the network size. We can state, that multi-paths systems show good results in large networks, where numerous backup routes are available.

As the diameter of a network increases proportional to $\sim \sqrt{N}$, the length of the shortest path raise with the same factor. Consequently, the average path length of DMP and NDMP routes follow the same proportionality. The length of DMP paths is about 15% greater than NDMP routes, independent from the network size. Whereas NDMP require only about 10% more hops than the SP.

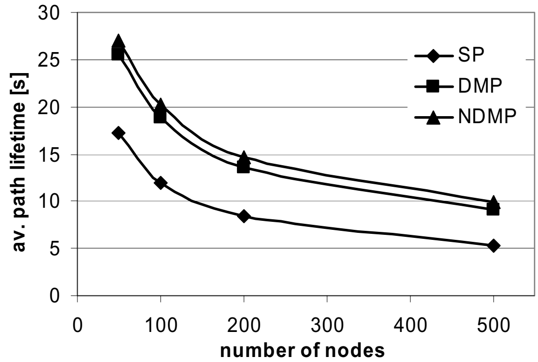

Figure 3: Average path lifetimes as function of simulation sizes.

As described in [4], routes with more hops break earlier than short routes. Figure 4 shows the behavior of the average path length with respect to PLTs. The initial lengths of paths in 500 nodes networks are about three times larger than routes in 50 nodes networks. After 20 seconds, the average path length of unbroken routes is almost equal in both networks. Connections with five or less participating nodes contain unbroken routes, whereas routes with more hops rapidly show errors. The network acts as "low pass filter" for path lengths.

As an approximation, connections with more than 5 hops break within the first 20 seconds (for this parameter set). As consequence, we suggest the usage of a time-to-life (TTL) function within route request packets, in order to limit the maximum route length.

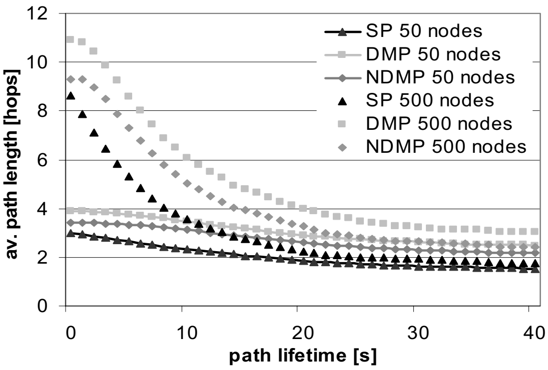

Figure 4: Average path lengths as a function of path lifetimes for 50 and 500 nodes networks.

The average number of neighbors is an important parameter for reasonable ad hoc networking as well. With only five neighbors, 20% of all requested connections are impossible due to partitioned networks. With ten or more neighbors on average, networks are usually fully connected.

With five neighbors, the number of impossible paths raise from 20% without link errors to almost 70% for 50% link error probability. With ten neighbors, the number of impossible paths increases from zero to only 8% with every other link broken. For denser node distributions (more than 20 neighbors on average), the link error probability has no impact on the number of inaccessible destinations.

An average of only three neighbors already turns 70% of all destinations inaccessible. In case of coincidental link errors, the network is not functional anymore. As expected, networks with sparser node distributions than five neighbors per node are unsuitable for reasonable ad hoc networking. With high node densities, the possibility of undisturbed communication between adjacent nodes decreases rapidly. Nodes block each others transmissions and the overall performance of the network decrease again. Ten neighbors seem to be a good trade off between both contrary requirements.

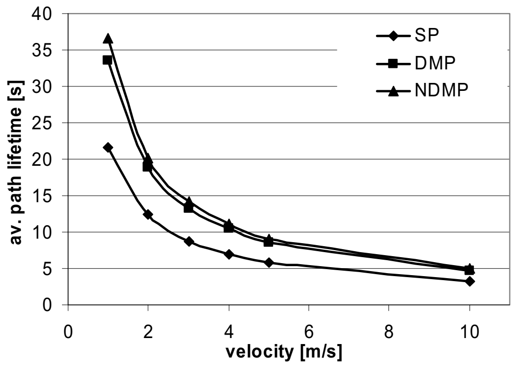

Figure 5: Average path lifetimes with respect to maximum node velocities.

As Figure 5 depicts, the average path lifetime decrease with increasing maximum node velocities. As the time of movement for a certain distance decrease with ~1/*v*, the average path lifetime also decrease with the same proportion (see [4] for more details). For low mobility networks, the probabilities that backup routes still exist, when primary routes break is higher, that within highly dynamic environments. Therefore, the benefit of backup routes is greater in low mobility cases. In this case, the usage of NDMP improves the path lifetime by 80%. Within highly dynamic environments, the improvement drops to 50%. The benefit of NDMP in comparison to DMP is about 8%, again more favoring low mobility scenarios.

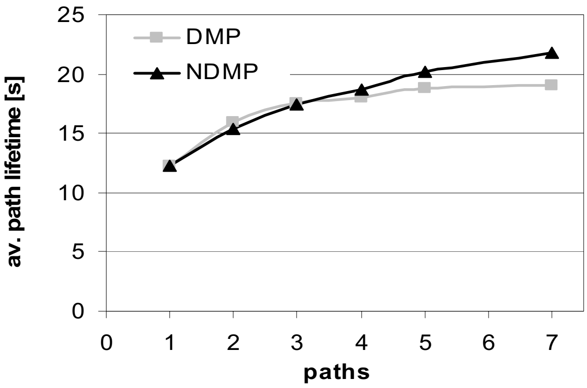

Figure 6: Average path lifetimes as a function of number of simultaneous paths.

Following, we focus on the benefit of multiple backup routes. DMP is able to setup a single backup route with few hops only in case the node density is greater than ten neighbors. With lower node densities, NDMP shows superior results. Figure 6 illustrates that with three routes, DMP and NDMP lifetimes are equivalent. If more routes are favored, NDMP is preferable, because DMP is unable to create routes with short path lengths or even does not find enough disjoint backup routes at all. For densities of only five neighbors, DMP finds two routes. Only for 20 or more neighbors, it is able to calculate five disjoint paths. Consequently, the NDMP algorithm is more flexible and allows the creation of numerous backup routes. Figure 6 again illustrates this behavior. All backup routes improve the average PLTs of NDMP. However the improvement rate decreases with increasing numbers of backup routes.

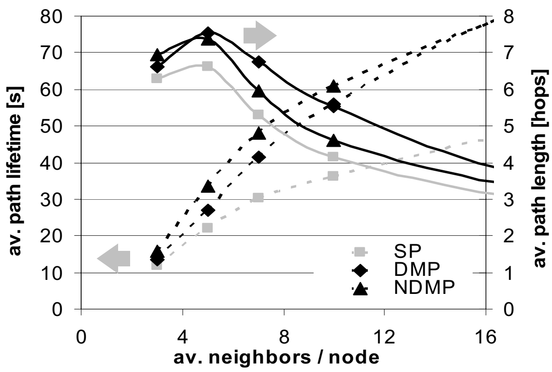

Figure 7: Path lifetimes and path length as a function of node densities.

Figure 7 shows the PLTs as well as the average path length with respect to the node density. The dashed lines depict the average PLTs whereas the solid lines show the paths lengths.

As described, with few neighbors, path setup is complicated, and even the NDMP algorithm is unable to create the necessary number of non-disjoint backup routes. Therefore, NDMP improves the average path length only by 30% with respect to the belonging SP. The improvement between NDMP and DMP is 17%. With five to seven neighbors, NDMP increase the average duration of routes most (≈ 20% to DMP and 60% to SP).

With further increasing node densities, networks allow numerous and short disjoint multi paths and the benefit of non-disjoint paths are neglectable. Therefore, with more than 20 neighbors on average, DMP path calculation outperforms the NDMP algorithm with respect to the average PLT.

With only three neighbors, the sparse node distribution limits the paths length. The network is often disconnected, and therewith favors connections with few hops. Consequently, the average paths lengths decrease with further decreasing node densities. The average path length is seven with five neighbors and path lengths of NDMP are smaller than those from DMP calculation are. With more neighbors, the probability of disconnected networks is almost zero and the average paths lengths decrease rapidly.

NDMP benefit most from node densities between five and ten neighbors. The additional PLT in comparison to DMP is maximized for networks with five neighbors. Whereas ten neighbors enables the algorithm to setup numerous additional paths with almost optimal path lengths. Within sparser networks, the SP is the most useful path calculation algorithm. In contrast to that, the DMP is the optimal path calculation algorithm in crowded networks.

With increasing link error probabilities, the path lengths of NDMP increase faster than the length of DMP paths. This is unexpected, as the inflexible DMP algorithm should calculate much longer backup routes within error prone scenarios than the NDMP algorithm. The DMP algorithm often does not even find a single backup route. This in turn reduces the average path length of DMP as its primary path is always the optimal/shortest path. However, this does not benefit the PLT. In contrast to DMP, the NDMP algorithm finds multiple backup routes, which certainly are longer than the primary path and increase the average path length. Without errors, NDMP connections have 20% shorter paths than DMP, whereas this advantage drops to only 8% with every other link broken.

For low link error probabilities (up to 20%), the PLTs do not degrade significantly. Only with even higher error rates, all PLTs shorten. SP routes are not as affected form these errors as the routes form the multi-path algorithms.

Especially the DMP lifetimes degrade with numerous link errors. While NDMP outperforms DMP by 8% for error free scenarios, it shows 16% improved PLTs within highly error prone scenarios. With fewer available links, the more flexible NDMP algorithm is able to create a sufficient number of backup paths with reasonable hop lengths. DMP must use long path or even does not find backup routes and therewith its PLTs degrade faster with increasing link error probabilities.

VI. Conclusion

In this paper, we evaluated the performance of single path as well as multipath ad hoc routing algorithms. The focus is especially on the lifetimes of routes, their lengths, and the network conditions for optimal results.

For all analyzed simulation setups and with assumed transmission ranges of 100m, PLTs are usually much smaller than 100 seconds. Paths with many hops break even more premature. As only short paths allow reasonable PLTs, we propose the usage of TTL extensions, in order to limit the maximum path length. This certainly limits the usability of ad hoc networks. However, avoiding TTL increase the combined routing overhead while it does not increase network performance.

Only within very dense networks, DMP outperforms NDMP, as numerous disjoint paths exist. In all other cases, NDMP shows better results, due to its greater flexibility. It improves results with respect to PLTs and average path length. Especially the reduced average path lengths also decrease the energy consumption for data packet transmissions. It also copes better with error prone networks, as it is able to reuse certain important links, rather than preventing these links, as DMP demands.

DMP shows best results with five consecutive paths, whereas NDMP slightly increases the PLTs with each new path. However, as open question remains the cost of path diversity? It requires an increased effort to setup multiple paths and the switching to backup routes also include the possibility, that the new route is already broken. This relationship requires further investigation.

The currently utilized three routing algorithms are based on the Dijkstra algorithm. As outlook for further investigation, we plan to implement a route request and flooding based algorithm in order to analyze its ability to generate valuable multipaths.

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