A Framework for Self-Organized Adaptive Routing in Disaster Scenarios

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***Abstract*—Routing in Mobile Ad hoc Networks (MANETs) remains challenging after years of research because the network conditions can vary significantly depending on the actual application scenario. This effect is even increased if the external conditions are not stable but rather change during the operation of the network as for example in disaster scenarios. In such a case, one single routing approach is usually not able to perform well because it was optimized for one parameter set only. Hybrid routing protocols usually combine two approaches for better adaptability to multiple use cases but still require a careful selection of the protocols in question. In adaptive routing concepts, nodes can choose from multiple protocols and thus adapt to the given network conditions seamlessly. In this paper, we present our adaptive routing framework allowing easy integration of multiple protocols and discuss its advantages over hybrid and traditional routing concepts as well as the application to disaster scenarios.**

***Keywords*—Mobile Ad Hoc Networks; Adaptive Routing; Hybrid Routing; Disaster Scenarios.**

I. Introduction

When a disaster hits a region, fast and efficient rescue operations are essential to save as many lives as possible. This requires an operational communication network ideally for both the first responders and the affected people. But the disaster will also damage the communication infrastructure, resulting in missing coverage or overloaded networks.

Mobile Ad hoc Networks (MANETs) are one promising option to provide communication under these circumstances, as the network is built based on devices at hand. But due to the structure of the network and the node mobility, routing becomes a challenge and remains challenging even after years of research because the network conditions can be quite different depending on the actual circumstances. In disaster scenarios, where after an initial damage to the whole infrastructure more and more first responders arrive to help and parts of the remaining infrastructure get restored, this effect is even increased because the conditions within the network are not stable but rather change during the operation of the network.

In such a case, a single routing protocol is usually not able to perform well under all conditions because routing protocols are typically optimized for one parameter set only. Hybrid routing protocols try to solve this by combining two approaches for better adaptability to multiple use cases. This shows a better performance, if the protocols in question are carefully selected for the envisioned scenarios. If not, the performance might even decrease.

To overcome the need to preselect the employed routing protocols, adaptive routing has been proposed in the literature. When using such approaches, nodes can choose a currently active routing protocol from multiple options and thus adapt to the given network conditions seamlessly as they are enabled to dynamically switch to a better candidate as needed. In this paper, we present our adaptive routing framework Self-organized Routing in heterogeneous MANETs (SEREMA), which allows easy integration of multiple routing protocols, and show its potential for disaster networks. SEREMA was developed during a dissertation project [1].

The paper is organized as follows. In Section II, we will discuss several related adaptive routing approaches that inspired different features of our framework. Afterwards, we introduce the conceptual design of our framework and discuss its components in detail in Section III and show how this framework can provide robust and reliable communication in disaster scenarios. Then, we prove the feasibility of the concept with simulative evaluations in Section IV. Finally, the paper is concluded in Section V where we also present future planned research studies.

II. Related Work

In this section, we present work that has been done in the field of adaptive routing.

Nada et al. [2] proposed a framework that enables the switching between different routing protocols during runtime. This was realized without any modification to the protocols participating in the framework and thus ensuring that new protocols can be integrated later on. However, the approach comes with the drawback that the whole network has to switch to the same (new) routing protocol if the algorithm decides, hence making the system less flexible and unable to handle different conditions in different parts of the network. Moreover, during such a protocol switch the routing tables of all nodes have to be converted to match the required entry structure of the new protocol. Besides that, the decision mechanism of the whole network is deployed to a single node only. This potentially leads to inefficient routing or a complete failure, if this node is not working or gets corrupted.

Another example for this globally switchable routing is the Chameleon Routing Protocol (CML) proposed by Ramrekha et

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al. [3]. This approach is also based on a centralized monitoring agent that controls the choice of the routing protocol used by the whole network. Again, the centralized node introduces an undesired single point of failure into the network. However, the monitoring concept described by the authors is quite interesting in order to identify the optimal switching point. The optimal switching point defines when the benefits of changing to another routing protocol out weight the overhead caused by switching. Ideally, the monitoring to determine this point has to be done in a distributed and cooperative way throughout the network.

Hoebeke et al. [4] proposed a strategy, where every node is able to use its own routing protocol depending on the local scenario. Throughout the whole network, multiple routing mechanisms can be activated at the same time and global decision making is no longer needed. Conceptually, this support for multiple active protocols at the same time is desired. However, all envisioned protocols have to be adapted in order to work with the presented framework. Hence, a plug-and-play solution for newly introduced protocols as well as the interaction with unaware nodes is not possible. This limits the usability of the approach in cases where legacy nodes have to be integrated into the network or a flexible extension of the routing framework is needed.

In the Zone Routing Protocol (ZRP) proposed by Beijar et al. [5], participating nodes have two routing zones, a reactive and a proactive one. Depending on the near-field scenario, a node can adapt the radius of these zones dynamically. However, this only changes the size of the regions in which the two protocols are used. Besides that, it is not possible to change the used protocols during runtime, again limiting the adaptability to changing conditions during the operation of the network. While regions with different protocols and dynamic size adaptation are beneficial, the pre-configuration of the active protocols is not, since these might not suit all scenarios.

Besides these approaches, several recent works show the relevance of adaptive routing. Son et al. [6] present a similar approach with different metrics related to the node mobility. Based on the observed mobility, the routing protocol is switched for the whole network only. To achieve this, the scheme requires extensive control information to synchronize all nodes. This has two drawbacks. First, one single switching decision throughout the network might be suboptimal in some parts and second, the additionally introduced traffic should be avoided.

Kaji and Yoshihiro [7] use adaptive routing to identify alternative paths and thus avoid congestion in the network. To enable fast adaptive switching to different paths, they modify the packet structure and require an additional routing table to store alternative paths. Again, the modifications are problematic for legacy node support.

In the next section, we present our new concept that takes the benefits of the presented approaches while eliminating most of the drawbacks.

III. SEREMA FRAMEWORK

A. Conceptual Design Considerations

In order to allow nodes to dynamically select the best routing protocol according to given network situations, several protocols have to be included into the adaptive routing framework. But there are several things that should be considered when designing such a framework.

The network conditions will not be constant throughout the complete network, especially in disaster networks or any other large-scale MANET covering a sufficiently large geographical region. Therefore, the framework should support the *operation of multiple simultaneously active protocols* in different subzones of the same network and allow the *dynamic switching* of the currently active protocol out of a set of protocols based on monitored metrics. This adaptivity mechanism builds the core functionality of any adaptive routing approach.

The operation of multiple protocols in parallel and the switching poses additional challenges that have to be solved in order to build a robust framework. The first point is related to the lifetime of a system running the adaptive routing framework. In case of disaster scenarios, this is important for the first responder devices that are usually employed for longer periods. At the same time, old devices will be constantly replaced by newer ones. The new devices will benefit from recent advances in both technological and software-related enhancements. This will also include more recent routing protocols outperforming the previous ones. Therefore, the framework should be able to integrate additional routing protocol versions without too much extension effort. Hence, the framework should support *easy integration* of additional protocols.

Besides that, it cannot be ensured that the adaptive framework is deployed on all participating nodes. To enable these nodes to communicate with the remaining network, the framework has to *support legacy nodes*. In a region or zone with legacy nodes, the framework should therefore switch to one standard protocol supported by these nodes. This switching, however, does not require all surrounding nodes with adaptive routing to switch to the same protocol, if they are equipped with a more suitable protocol. In this case, one node can act as a *Border Node* [8] bridging the resulting two zones.

In order to enable the support of legacy nodes, the protocol versions integrated into the framework should be standard compliant as far as possible. This can be achieved if the adaptive routing framework does not require any significant changes of the existing protocols. Therefore, we try to avoid modifications for example of the routing table structure, the control packet structure, or the addition of new packet types. The only exception in our approach are standard compliant extensions that are allowed by the protocol specification.

The limitation of modification raises the question whether the framework introduces its own control messages or is able to benefit from the operation principles of the integrated protocols. Ideally, the normal protocol operations are used as far as possible and only few additional control messages or

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piggy-back extensions to existing control messages should be defined. This is also true for the *routing table structure*. Each protocol comes with its own definition for the routing table it uses and the structure of the corresponding routing entries. An adaptive framework enabling the operation of multiple protocols in parallel has to either define a unified table that is accessed by the forwarding agent or to translate the entries from each table, if multiple tables are used.

Besides that, the framework has to provide a translation mechanism in order to enable seamless communication between the supported protocols. This is needed to exchange routing information between zones using different active protocols, as the format of control messages as well as routing table entries have to be converted into that of the other protocol. For example, the information gathered by one proactive zone should be available in the reactive zone as well. This can be achieved by storing the corresponding routing information in the routing table and use this to respond to corresponding reactive requests. Therefore, the routing information has to be converted or translated from the formats used by the proactive protocol into that of the reactive one and vice versa. To limit the processing overhead introduced by the adaptive routing framework to perform the required translations, the number of the required operations should be minimized.

Finally, the framework has to fulfill multiple performance-related criteria. When employed in a disaster scenario, the framework has to provide *robust* communication and thus reliable packet delivery. For the framework, this requirement results in three crucial design aspects:

- distributed constant *Monitoring* of network conditions,
- distributed *Decision Making*, and
- a high *Decision Quality*.

The first two aspects help to avoid potential single points-of-failure. Besides that, distributed approaches can handle malicious nodes if the surrounding nodes detect apparently contradicting information. A high decision quality is ensured by this because it helps to prevent nodes from switching to a wrong protocol or taking isolated switching decisions. This can be achieved for example by monitoring multiple parameters and integrating them into a weighted scoring function as base for the switching decision.

As mentioned before, the nodes have to monitor the network conditions in their surrounding and take a decision to activate or deactivate specific routing protocols based on the collected data. One of the biggest challenges is the definition of good algorithms realizing such switching decisions.

Based on the points discussed above, the goal of our framework is to provide network-wide adaptive routing which fulfills the following criteria:

- support of an extensible set of routing protocols,
- support of multiple active protocols in different variably-sized zones in parallel,
- support of legacy nodes,
- distributed switching decisions of the active protocol,
- requiring only standard-compliant extensions of the routing protocols, and
- integrating multiple routing tables by building a wrapper component to allow an easy and unified access.

B. Framework Components

Based on the design considerations presented in the previous section, we developed our adaptive routing framework with the following components trying to combine the advantages of previous approaches. In the following, we will introduce the structure of our framework and provide details on how to achieve the mentioned criteria.

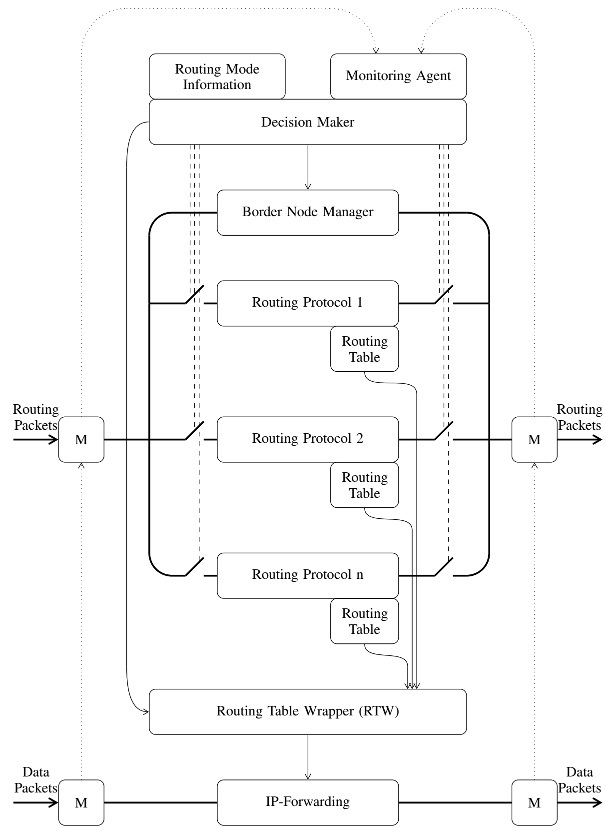

Fig. 1. Architecture of the Adaptive Routing Framework

Our proposed framework has the architecture as shown in Figure 1. The core of the system consists of multiple routing protocols, which can be connected/disconnected from the network via simple switches. Each of the equipped routing protocols can use its own routing table that allows to simply add further protocols without a huge implementation effort or changes to the protocol operation. All of the received and transmitted routing, as well as data packets are monitored locally by probes (M) and all of the gathered information is forwarded to the *Monitoring Agent*. It will calculate relevant statistics on the current traffic, as well as neighboring nodes and provide this information representing the current network situation to the *Decision Maker*. For making a decision about the currently most suitable routing protocol, additional information about the behavior of the protocols is required and provided by the *Routing Mode Information* block. This behavioral information describes the ideal operational parameters of the protocols including the reactions to certain load situations (e.g. increased overhead due to flooding requests). After the *Decision Maker* has used the data from the *Monitoring Agent* and *Routing Mode Information* block to make its protocol decision, it controls the input/output switches of the equipped routing protocols and, therefore, connects/disconnects specific protocols to/from the network. Since the decision is based on the locally observed network conditions at each node including information from its neighbors via received packets, we are able to make a dezentralized decision without requiring additional control traffic.

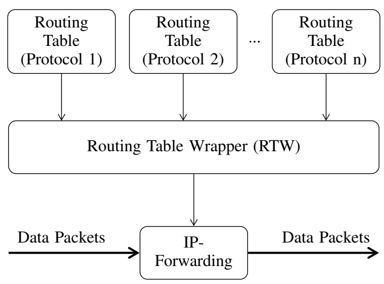

Fig. 2. Routing Table Wrapper

To provide routing information to the forwarding plane, our framework uses a special *Routing Table Wrapper* (c.f. Figure 2) that allows to simply access the information in multiple, different routing tables. With this mechanism, SEREMA is able to use multiple different routing protocols, allowing each protocol to use its own specified routing table. If a route to a specific destination in the network is required, the *Routing Table Wrapper* looks up the destination in all of the equipped routing tables and provides the resulting route to the *IP-Forwarding* module. This mechanism has the big advantage that in the time directly after a routing protocol change, when the new routing protocol has not gathered any new routes yet, the *Routing Table Wrapper* is able to provide the routes from the previously used routing protocol to the *IP-Forwarding*, not interrupting any ongoing data transfers.

If the network uses different routing protocols in different areas at the same time, the *Border Node Manager* (c.f. Figure 1) enables the interconnection of such areas. To achive this, it converts routing information between different protocols and allows to forward routing requests/responses over multiple routing domains. Nodes can freely chose their respective routing protocol in this setup. The interconnection of different routing zones is achieved by Border Nodes, that are able to translate the routing traffic accordingly and thus guarantee the end-to-end consistency of data flows. Any node can act as Border Node, if it detects different routing zones and supports both corresponding routing protocols [8]. Based on this mechanism, we are also able to integrate legacy nodes that support only one protocol as long as a suitable SEREMA node running the required protocol is within range.

The translation also includes a mechanism to enable route discovery across zones with different protocols and possibly different operation principles. This is crucial, if the nodes currently operate with a proactive protocol but are supposed to communicate with nodes in other zones running reactive protocols. In this case, the proactive node has to be enabled to start a reactive-style request. This is achieved by implementing corresponding annotation packets and a passive request mode. All packets needed for this mechanism are designed as standard-compliant packet extensions.

C. Implementation Details

To prove our concept, we implemented an adaptive routing framework that is able to switch between two traditional and well-know routing protocols for our evaluation: Ad hoc On-Demand Distance Vector (AODV) Routing [9] and Optimized Link State Routing Protocol (OLSR) [10].

Core of the implementation is the scoring algorithm employed in the decision maker. It will define which protocol is currently used based on the results of the monitoring agent. Figure 3 shows the implemented scoring algorithm that is used to select the currently active routing protocol.

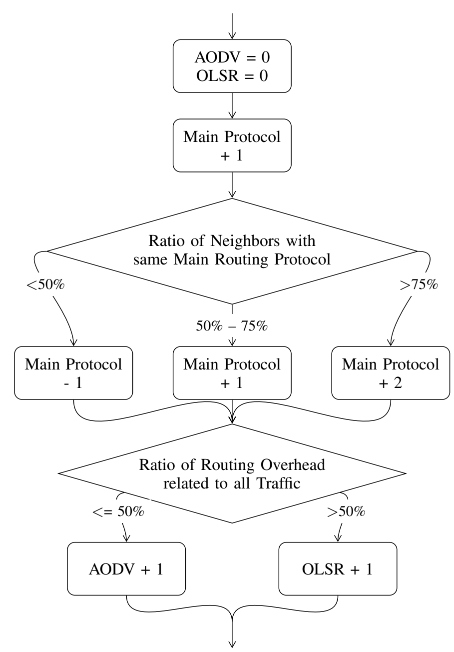

Fig. 3. Scoring Algorithm

To prove the conceptual design of an adaptive switching mechanism, we decided to use simplified criteria to estimate the current conditions in the network that are easy to monitor in simulations. Therefore, the currently implemented algorithm might not take the ideal decisions. However, it is suitable to show the feasibility of our concept in general.

We chose to utilize a score-based mechanism in our algorithm where each protocol can get/lose scoring points depending on the given criteria. This is required because there are several metrics and interactions between them that describe the current conditions in a network. Not all metrics are easy to normalize and afterwards be used in a unified formula which results in a number representing the best protocol.

For example, if we consider the routing overhead on a node related to the data traffic of the node, we get a number between 0 and 100 %. However, if we try to use the number of neighbor nodes for a decision, we do not have a maximum value to use in the formula. Therefore, the scoring algorithm simply adds/removes points to/from a protocol if specific conditions are met. In Figure 3, the notation *Protocol* $\pm$ *1* indicates that either the currently active protocol (main protocol) or the supported variant get an additional scoring point, if the corresponding criteria is fulfilled. Finally, the protocol with the highest score is activated. Depending on the requirements made to the adaptive routing framework, the number of points a protocol gets can be adjusted. In this way the protocol behavior can also simply be adjusted during runtime.

Currently, the algorithm considers three criteria only. These are the network load in terms of an ratio between the overhead introduced by the chosen routing protocol and the actual data traffic, the active protocol, and how many neighboring nodes use the same protocol. The network load in this case is locally observed by each node and relevant metrics are currently not exchanged between neighboring nodes to limit the otherwise introduced signaling overhead. However, the individual decision can propagate through the network, since the protocol selected by neighbors is one criteria. With this subset of criteria, we are able to evaluate our framework in scenarios where the density of nodes varies and should therefore result in adaptive switching decisions.

Future research will be dedicated to the evaluation of more realistic criteria and their corresponding weights in terms of scoring points. This work can be based on previous work on adaptive routing (cf. Lye et al. [11] or Haerri et al. [12]), but should include a thorough evaluation of suitable metrics describing characteristic network situations. Further simulations with our routing framework can help to evaluate the impact of such criteria. Such studies should include the evaluation of routing protocols under the characteristic conditions as well. Besides that, we plan to apply multi criteria decision making principles (e.g., [13]) to enhance our scoring algorithm and thus enable the combination of further relevant criteria. Such approaches allow to consider and optimize multiple criteria even if they have quite different notations. This is based on normalization profiles for each criteria and corresponding weights according to the optimization goals.

D. Application to Disaster Scenarios

Our framework fulfills several points that makes it suitable for disaster communication besides the fact of providing adaptivity. Disaster networks, especially in early stages of any relief mission, are highly heterogeneous and feature intermittent connectivity due to damaged infrastructure or limited communication ranges. At the same time, many users want to communicate either with friends or other affected people, as well as with rescue forces with whatever devices they have available. This adds a high load to the remaining network. In the worst case, this traffic from or to the affected people will however use up valid resources for first responder communication. Therefore, first responders usually provide their own communication network, which is separated from other public communication networks for security reasons.

But affected people can become volunteers, supporting the professional rescuers. In this case, they should have access to the network as well. Besides that, an option to add the devices of affected people for emergency calls is also required, because in this case they are easier to detect and help can be sent faster. Our framework supports both aspects, by allowing legacy nodes to join the network via a suitable *Border Node* acting as gateway. We assume that affected people are equipped with legacy devices, because they most likely did not install any additional software to support our framework just to be prepared for a disaster event.

Using the *Border Nodes* as gateways helps the first responders to become aware of the presence of affected people which might indicate their position and help to rescue them. On the other hand, this gateway can act as traffic shaper to allow the detection of nodes and the placement of emergency calls but limiting other communications to a minimum in order to prevent high traffic by affected people. This could be done by a simple group assignment. Each unauthorized device is assigned to a corresponding group that allows this device to only announce its position and otherwise routes the traffic to the emergency call management. Other destinations are not propagated to these nodes. Once a device has been registered as volunteer, its status changes and it is granted more rights to communicate with further first responders.

With these additional features our framework can ensure reliable and robust communication required during any disaster mission. The core concept here is to provide self-organized adaptivity on the network layer. This ensures the maximum flexibility to various networking conditions, if the selection of any given operation mode is robust.

IV. Simulation and Discussion

In this section, we present simulation results verifing our concept. Simulations were done in the well-known ns-3 [14] in combination with Click [15].

In Figure 4, we show the simulated scenario. We created three subnetworks (routing domains) each with its own active routing protocol. They are connected via Border Nodes translating between the different protocols. In the SEREMA scenario, the first and third routing domain used AODV, while nodes in the second utilized OLSR. Two Border Nodes are used to directly tunnel the reactive control traffic through the OLSR zone [8]. For reason of comparison, we also ran this scenario with AODV and OLSR active on all nodes, respectively.

The simulation was configured to use six data transmissions between areas one and three and in addition one transmission from area one to area two as well as a connection from area two to area three. The rest of the active data transmissions used in the scenarios take place in the proactive routing domain 2.

Each of the simulated routing domains contained 20 nodes with a transmission range of 10 m and a speed of 1-3 m/s. For the movement scenario, we decided to use a Random Waypoint model to not consider special behaviors of specific movement models. The simulated duration of the scenario was 300 s and the results were averaged over ten simulation runs.

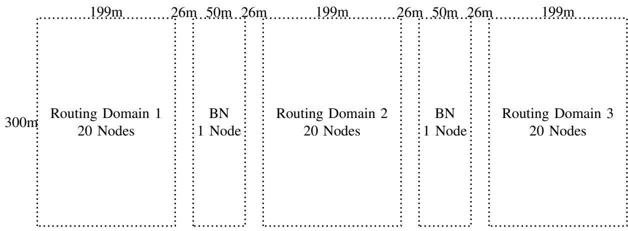

Fig. 4. Simulated Scenario

The first measured parameter is the Packet Delivery Ratio (PDR), showing how successful routes could be established for communication. Figure 5 shows that the gradient of the PDR graph decreases with an increasing number of active data transmissions in the network. This behavior is because in a scenario with a lower number of active data transmissions, the number of received packets increases with the number of sent packets, but if the traffic in the network increases, the percentage of received packets, related to sent packets, decreases. In the simulated scenario, most of the data transmissions take place in routing domain two, which is used by the data transmissions between routing domain one and three for transit. This means that such data packets have to pass a network area with a higher traffic load. Furthermore, it can be seen that in the AODV-only scenario, the PDR is highest, as the reactive routing searches for routes on-demand and therefore delivers the most up-to-date routing information. In this scenario, SEREMA has a higher PDR than OLSR, because of the reactive part of SEREMA which provides better routes than OLSR-only. However, SEREMA cannot reach the performance of AODV in this scenario, because of SEREMA's proactive behavior which produces additional routing traffic in the network.

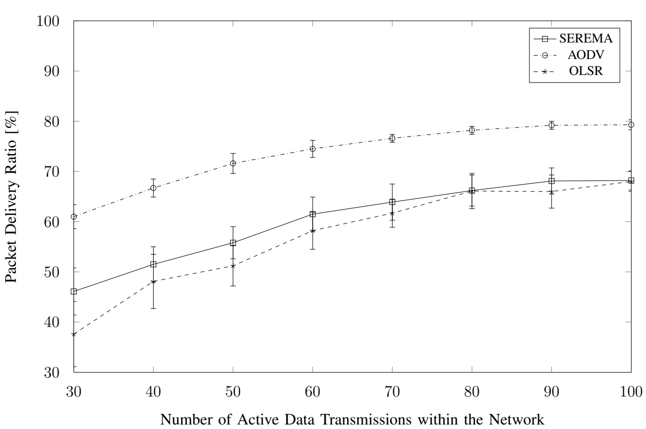

Fig. 5. Comparison between Packet Delivery Ratios

The last parameter we evaluated is the routing overhead related to the overall traffic introduced by the routing protocols as shown in Figure 6. For networks with lower traffic, AODV outperforms OLSR and behaves comparable to SEREMA. However, as soon as the number of active data transmissions in the network increases, AODV generates more routing traffic because of its reactive behavior that emits packets on demand. In this case, the routing overhead ratio of OLSR decreases as the overall traffic in the network increases while the OLSR routing overhead stays more or less constant because of the proactive protocol behavior. SEREMA can outperform both protocols since it benefits from both routing protocols (AODV and OLSR). In routing domain two with a high traffic, it behaves like OLSR and limits the produced routing overhead, while in routing domain one and three which only have a few data transmissions it uses AODV to avoid the periodical static load to the network caused by OLSR. It can be seen that the network benefits from our adaptive routing framework as the routing overhead stays lower, compared to AODV-only as well as OLSR-only networks.

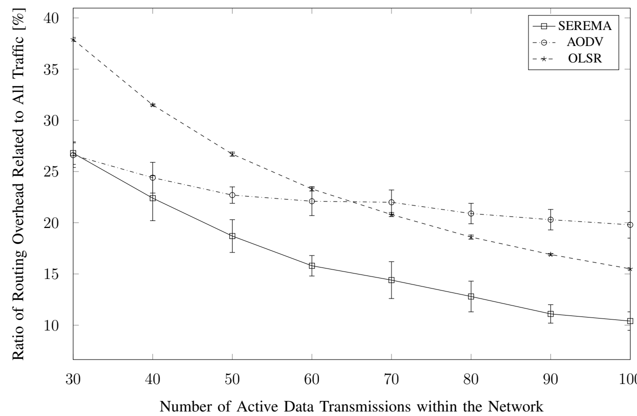

Fig. 6. Comparison between the Routing Overhead

Finally, we evaluated the switching performance of our scoring algorithm (cf. Figure 3). To do that, the resulting decision was evaluated analytically for both protocols. Tables I and II present the corresponding switching matrices. The criteria used are the overhead ratio between routing traffic and data traffic and the neighbor ratio indicating which subset of all neighboring nodes runs the same protocol (cf. Section III-C). In both tables '1' denotes the decision to switch the protocol and '0' to keep the current protocol.

It should be noted that the number of neighboring nodes running the same routing protocol is a ratio here and does not reflect the node density in the network. This commonly used metric for the utilization of reactive or proactive routing schemes will be considered in future versions of our algorithm.

Based on the two metrics currently considered, both tables show that our approach is able to switch the routing protocol under given network conditions. Here, the switching is in general done when few neighboring nodes run the same protocol and depending on the current overhead introduced by the routing protocol, AODV is favored for low overhead cases and OLSR for cases with higher overhead.

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TABLE I
SWITCHING DECISION UNDER OLSR

Neighbor Ratio	Overhead Ratio									
	10	20	30	40	50	60	70	80	90	100
0	1	1	1	1	0	0	0	0	0	0
10	1	1	1	1	0	0	0	0	0	0
20	1	1	1	1	0	0	0	0	0	0
30	1	1	1	1	0	0	0	0	0	0
40	1	1	1	1	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0

TABLE II
SWITCHING DECISION UNDER AODV

Neighbor Ratio	Overhead Ratio									
	10	20	30	40	50	60	70	80	90	100
0	0	0	0	0	1	1	1	1	1	1
10	0	0	0	0	1	1	1	1	1	1
20	0	0	0	0	1	1	1	1	1	1
30	0	0	0	0	1	1	1	1	1	1
40	0	0	0	0	1	1	1	1	1	1
50	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0

If a node detects that it should act as border node, this decision matrix is obsolete as both protocols have to be active in this case.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented our adaptive routing framework SEREMA and discussed relevant design choices required for a common solution in highly dynamic scenarios. Our framework is able to fulfill the resulting requirements by providing distributed decision making and support of legacy nodes.

The framework was implemented and evaluated using ns-3 and click. Simulations showed that adaptive routing in MANETs is an interesting solution if conditions are not constant network wide. Even though we use simplistic scoring criteria, our solution is able to outperform single routing protocols with respect to the analyzed metrics. To overcome the reduced PDR in comparison to pure OLSR, further research is required to identify both the ideal switching point and the relevant metrics.

Future work will therefore include a thorough evaluation of further more realistic metrics and criteria that are characteristic for given network conditions, as well as the impact of these parameters on different routing protocols in order to enhance the performance of our adaptive routing framework. We also plan to incorporate further relevant routing protocols into our framework to enhance the adaptivity to additional conditions and exploit the combination of adaptive routing and Delay Tolerant Networks (DTNs) principles in an hybrid DTN-MANET scenario. Finally, the adaptive approach could be combined with address resolution and service discovery mechanisms as presented by Finke et al. [16]. Such combination of different approaches could provide benefits in terms of lower delay for name resolutions and robustness to node failures.

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