Optimizing ODMRP for Underwater Networks

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***Abstract*—Underwater networks have attracted significant attention over the last few years. They can be used in scenarios like environmental monitoring and mine countermeasure but may also be part of modern marine warfare. A prominent example is Anti Submarine Warfare (ASW) with multistatic sonars. These networks may be sparse with potentially long distances between single nodes such that direct communication is not always possible. Furthermore, long propagation delays and shadowzones have a negative impact on the communication channel. A solution to overcome these challenges is to realize a multi-hop network by using ad-hoc routing. A well known protocol from terrestrial networks is the On-Demand Multicast Routing-Protocol (ODMRP). In this paper, we present an optimization for ODMRP, named *Route-Discovery-Suppression*, to improve its performance for the deployment in underwater networks. We evaluate the performance through simulations in different scenarios and show its impact in comparison to other routing protocols.**

I. Introduction

The oceans cover large parts of the earth's surface and have a decisive impact on our global climate. Besides, huge raw material reservoirs (e.g. oil and gas) are expected to reside under the oceans. Nevertheless, our knowledge of the oceans is limited.

Underwater Wireless Networks (UWNs) have the potential to enhance our ability to observe the ocean and to operate inside. The acquirement of controlling Unmanned Underwater Vehicles (UUVs) remotely or transmitting information from Autonomous Underwater Vehicles (AUVs) to base stations enables many novel applications such as *environmental monitoring*, *underwater exploration*, *disaster prevention*, *equipment monitoring*, and *military operations*. Especially the latter greatly benefits from UWNs as they allow to integrate naval units like submarines or AUVs into the network centric approach of today's armies. Furthermore, the efficiency of surveillance and ASW missions can be increased due to faster availability of data and the possibility of deploying sensor data fusion techniques.

In general, UWNs rely on *acoustic communication* since radio waves and optical signals suffer from high attenuation. The acoustic communication channel shows specific characteristics like huge delays, low data rates, and high bit error probabilities. To realize heterogeneous multi-hop communication (cf. Fig. 1) ad-hoc networks present a promising approach. There has been a lot of work in the area of terrestrial ad-hoc networking, but due to the specific characteristics these approaches can not be simply reused. Thus, selected routing protocols need to be adapted and extended for Underwater Acoustic Networks (UANs).

In [2], we have shown that the reactive ODMRP [7], [17] with sophisticated parameter adaptations works well in UANs. In contrast to other multicast routing protocols, ODMRP can be used as an unicast routing protocol as well. Thus, if multiple data sinks are present ODMRP can provide routes using multicast. Otherwise, it simply works as an unicast routing protocol. In this paper, our goal is to further optimize ODMRP for the deployment in UANs.

The rest of the paper is organized as follows: In Section II we present related work including background information on underwater networks and ad-hoc routing. Section III introduces our evaluation architecture. The parametrization of ODMRP for its deployment in UANs, the resulting challenges, and an optimization to improve the performance of ODMRP are described in Section IV. The evaluation (Section V) is followed by our conclusion and outline of future work.

II. Related Work

In this section, we provide a brief overview of the related work on underwater networks and routing protocols.

A. Background: Underwater Networks

UWNs rely on acoustic communication (cf. e.g. [1]). Conventional electromagnetic waves, as used in terrestrial radio networks (e.g. HF, VHF, or WLAN), are not capable in an underwater environment. On the one hand, the attenuation

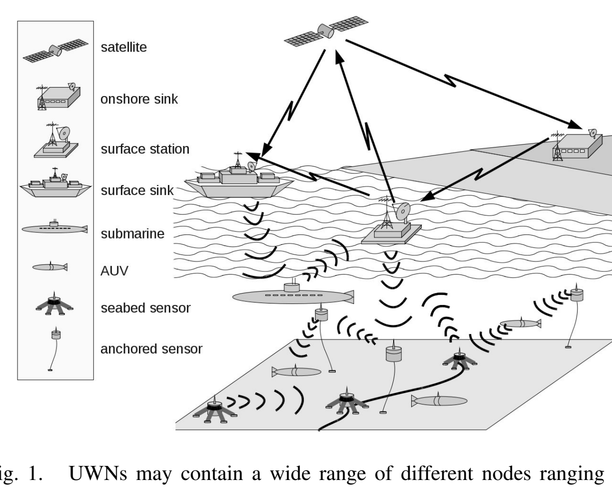

Fig. 1. UWNs may contain a wide range of different nodes ranging from anchored sensors to submarines.

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of high frequency signals prevents the usage in long range scenarios. On the other hand, low frequency signals require very huge antennas. Optical waves (e.g. lasers) are limited to very short distances due to scattering and attenuation from particles in the water. Thus, acoustic communication is the technique most widely used [6], [10].

By commercial off-the-shelf hardware typical transmission ranges around 5 km are obtained [6], [13], [15]. The achievable transmission range depends strongly on the chosen frequency because of the attenuation of the underwater sound channel. Beside the spreading loss, a frequency selective absorption loss occurs with increasing attenuation of high frequency signals. Empirical formulas [14] depending on the salinity, pressure and temperature of the water allow the modeling of the sound speed in different levels of the water column in form of sound speed profile.

Comparable to terrestrial communication, multipath propagation may occur due to reflections on the surface and on the seabed, or due to refraction according to the Snell's law [14]. All these effects may lead to so called shadow- and convergencezones [4], [14]. Shadowzones are areas where the signal cannot spread out or only with an extremely low signal strength. In contrast, convergencezones are areas where the signal overlap due to multipath propagation.

The major challenge of acoustic communication is the slow and varying signal propagation speed of around 1500 m/s which is $2 \cdot 10^5$ times slower than electromagnetic waves. As the distances between nodes may be several kilometers, transmission delays of a few seconds are typical.

Human made noise from oil-rigs or ship engines as well as natural noise induced by animals, wind, or volcanic activities pose another challenge of UANs. Especially on frequently driven ship tracks or in coast regions, a low-frequency wide-spreading noise interfere with communication signals [4]. In Contrast, natural noise is omnipresent and cover a large frequency band from 1 Hz to 100 kHz [14]. Both noise sources are the reason of high bit error rates.

Overall, the characteristics of the underwater acoustic channel are: (1) *high transmission range*, (2) *slow signal propagation*, (3) *high bit error rates*, and (4) *low data rates*.

B. Routing

A mobile multi-hop ad-hoc network is a collection of mobile nodes which are connected in an ad-hoc manner. Each node acts as a potential relay. In order to facilitate a reliable communication, routing protocols are necessary to discover and maintain routes. In the last decade, the research effort on terrestrial mobile ad-hoc networks has induced a wide range of different protocols. These protocols are classified into reactive, proactive, and hybrid protocols.

To the best of our knowledge, there is only one routing approach specific to UANs, the so-called Vector-Based Forwarding (VBF) [16]. Routing decisions in this unicast protocol are based on the geographic positions of nodes and not on the network topology. The protocol is known to scale very well, but has several drawbacks. VBF assumes dense network topologies and requires the distribution of position information. However, the determination of positions underwater is very challenging in practice. Furthermore, we assume UANs to be sparse networks. Moreover, we see a demand for redundancy and especially multiple data-sinks in UANs. Thus, we focus on multicast protocols and do not consider VBF.

In our previous work [2], we have shown that ODMRP which is a well known reactive multicast routing protocol developed for terrestrial networks can be adapted to be deployed in UANs. In ODMRP, a mesh structure between all multicast members is formed using a route establishment prior to any data transmission. The advantage of this mesh structure lies in its robustness. Furthermore, the delay induced by the on demand route establishment is reduced by piggybacking of the first user data during this phase. In this paper, we present an extension of ODMRP specific to UANs.

To evaluate the benefit of this extension, we use Simplified Mulitcast Forwarding (SMF) and simple flooding as benchmarking protocols. SMF with source-based multipoint relay forwarding [8] is a proactive multicast protocol that is widely used in terrestrial networks. Its basic concept is the forwarding of multicast data using an efficient flooding strategy via a selected set of nodes, called relay set. Based on neighborhood information, the relay set is chosen by each node from its direct neighborhood such that all 2-hop neighbors are covered. Simple flooding is the simplest approach to deliver messages to all nodes. Instead of explicitly choosing a route, each node re-broadcasts all messages it receives once. This approach may result in a high overhead and poor performance due to a huge a amount of retransmissions [9]. However, it is used to analyze the benefit of complex routing protocols.

III. EVALUATION ARCHITECTURE

As there are no real-world testbeds of significant size available for UANs, we choose simulation as our evaluation method. In this section, we introduce the evaluation architecture, the simulation setup, and the metrics of our performance analysis. We implemented ODMRP in UnderWaterMiracle [3] which is a UAN simulation system based on NS-Miracle [3]. NS-Miracle is an extension of the widely used ns-2 [5] network simulation platform. UnderWaterMiracle models the acoustic underwater channel and supports empirical formulas to approximate the propagation speed, the attenuation, and the ambient noise. On the PHY layer, UnderWaterMiracle offers half-duplex communication and models a common used PSK modulation scheme. On the MAC layer, the simulator features a simple ALOHA protocol which operates without a random back-off mechanism, acknowledgments, and without the retransmission of lost packets.

For our evaluation, we assume all nodes to be placed in a fixed depth of 1 km. According to the sound speed profile used, this leads to a constant propagation speed. We examine two typical transmission distances (2 km and 5 km). The optimal center frequency and a reasonable bandwidth with the 3 dB heuristic of Stojanovic [11] is determined for both distances (see Table I).

TABLE I
CONFIGURATION OF THE ACOUSTIC MODEM: THE NOMINAL DATA RATE RESULTED FROM THE FREQUENCY-BANDWIDTH PAIR AND AN APPROPRIATE JITTER INTERVAL, BOTH DEPENDING ON TRANSMISSION DISTANCE

distance	(km)	2	5
frequency/bandwidth	(kHz)	14.995/17.50	8.519/11.02
jitter interval	(s)	0.4	0.65
nominal data rate	(bit/s)	8751.6	5512.2

Two different scenarios with nodes being arranged in a grid topology are examined in our evaluation. In these scenarios, low propagation speed (1483 m/s) and low data rates are taken into account. We do not consider high error rates due to attenuation and ambient noise by adequately regulating the transmission power. The power is set up sufficiently to achieve a target packet error probability of 0.01 at ranges of 2 km and 5 km, respectively.

On MAC layer we use ALOHA. To avoid synchronization between interfering senders and to mitigate the occurrence of collisions, we deploy a random *jitter* to each packet transmission. According to our evaluation results in [2], we implement a uniformly distributed jitter chosen from intervals of 0.4 s for the 2 km transmission range and 0.65 s for the 5 km transmission range. As traffic, we assume periodic data exchange by a sensor application. This, we model using a constant bit rate agent (with different rates) over UDP based on a lightweight IP (for details see [2]). For all parameterizations, we perform ten replications of each simulation and average the results. The variance is visualized by boxplots or by adding the standard deviation to the figures using error bars.

Since current underwater hardware [13], [15] does not support dynamic packet sizes yet, we deploy a constant packet size in our simulations as well. As in [2], we assume an optimized packet size of 32 byte which is appropriate for UANs and achieves an adequate trade-off between error robustness and energy consumption.

The following three key metrics are used in the performance evaluation of the routing protocols:

- The *packet delivery ratio* (PDR) is considered as an indicator of the reliability of the communication. It is defined as follows:

$$PDR := \frac{\#received\ packets}{\#send\ packets \cdot \#receivers}.$$

- The *overhead factor* reflects the entire communication overhead including packet headers of all involved layers, control packets of routing protocols, redundant transmissions, and lost packets. It is defined as follows:

$$Overhead\ factor := \frac{\sum transmitted\ data}{\sum recv.\ user\ data \cdot \#receivers}.$$

- The averaged *route discovery delay* indicates the duration of the route establish phase of ODMRP.

IV. ODMRP IN UNDERWATER NETWORKS

In this section, we first present our parametrization of ODMRP and discuss the challenge when deploying ODMRP in UANs. Then, we introduce our optimization of ODMRP.

A. Parametrization and Challenge

As ODMRP is designed for the deployment in radio-based mobile ad-hoc networks, both protocol timers of ODMRP need to be adapted. We set the *route refresh interval* and the *forwarding group timeout interval* to 1000 s and 1500 s (cf. [2]). The first timer defines the period in which an attempt to refresh an established route is performed. The second timer defines the period of time in which each node remains an active part of the forwarding mesh structure corresponding to a specific traffic flow after receiving a request packet. For comparisons with SMF, we adjust the SMF parameters in a similar way. The *neighbor hold time* is set to 1500 s and the *hello interval* is set to 250 s.

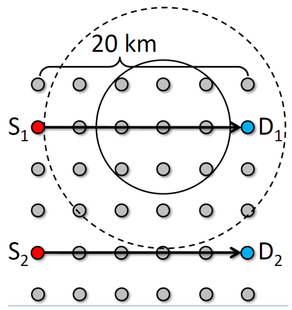
Until a route is established, ODMRP uses simple flooding to disseminate the user data. By doing so, scarce energy is wasted and the probability of collisions increases. Although the delivery of the request packet is likely to be coped by the redundancy of the flooding process, the packet loss during the reply phase is expected to be very high since reply packets are transmitted without redundancy on their path back to the source. Thus, the success probability of the route establishment is significantly diminished.

B. Protocol-specific Optimization

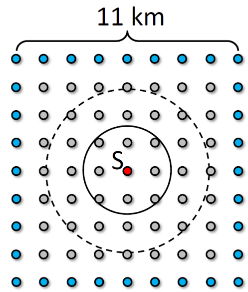
To overcome the challenge described in the previous section, we propose a simple but effective optimization of the original ODMRP which we named *Route-Discovery-Suppression* (RDS). The goal of RDS is twofold. On the one hand, the delivery of the reply packets to the traffic sources is intended to be alleviated. Thus, the route discovery delay is expected to be reduced and valuable energy to be saved. On the other hand, it is intended to save scarce network capabilities to permit the presence of multiple traffic flows.

The basic concept of RDS is to limit the number of parallel route discoveries as long as another discovery is assumed to be in progress. The suppression of additional route discoveries expires as soon as the ongoing discovery finishes or the discovery process fails. To detect this failure, a *discovery timer* is used to approximate the maximum duration which a route discovery phase is expected to last. The timer should be set according to the network size. When the timer expires, the sender can initiate a new discovery.

There are two options of processing the user data which is generated during the suppression phase. The first option is to simply discard this data, whereas the second option buffers the data and forwards it, as soon as the route is established. With regard to the buffering, new questions concerning the *queueing strategy*, the *buffer size*, the packets *residence time*, and the dequeuing process arise. We assume the fast delivery of currently obtained sensor data to be more important in many (sensor) applications than the forwarding of data which may be

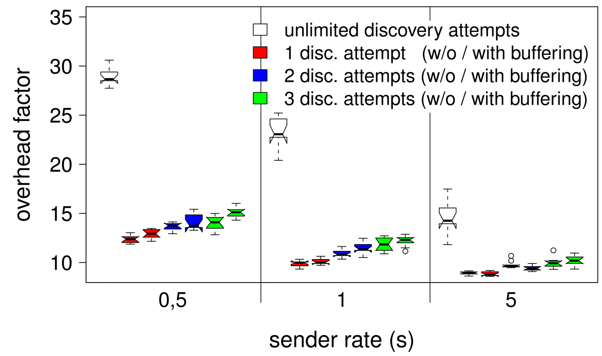


(a) Two traffic flows in a 6×6-nodes-grid topology which are geographically separated, i.e. packet forwardings along the horizontal paths do not interfere each other.

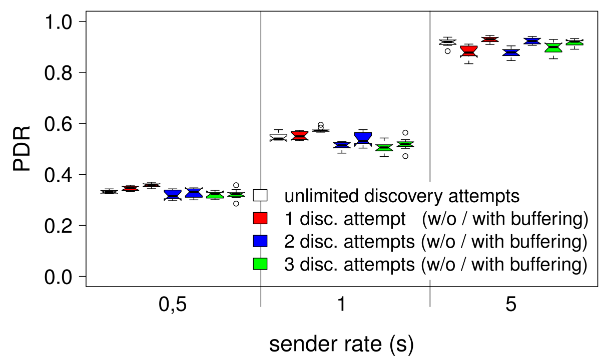


(b) The 9×9-nodes-grid topology with a multicast traffic flow initiated by the central node, addressed to all nodes residing at the boundary of the grid.

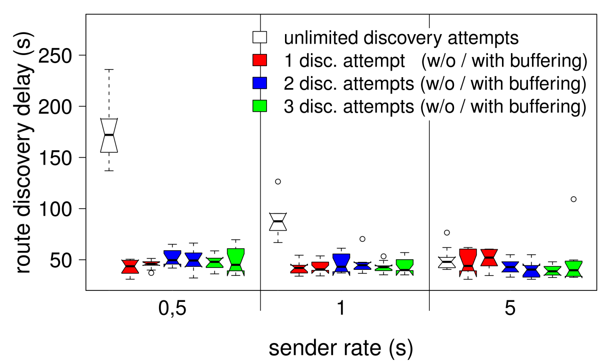
Fig. 2. Two topologies used in our evaluation.



(a) overhead factor



(b) packet delivery ratio



(c) route discovery delay

Fig. 3. The impact of the RDS with different configurations on the overhead factor, the PDR, and the route discovery delay depending on the traffic load given by three different sender rates in the 6×6-nodes-grid scenario. Note that each configuration set (1, 2, and 3 discovery attempts) which is distinguishable by its color is used either without (left boxplot) or with (right boxplot) a buffer mechanism applied.

outdated or obsolete. Therefore, the buffer was implemented as a LIFO queue. Additionally, a residence time of 250 s and a buffer size of 128 packets was chosen. This results in manageable memory requirement, even for resource constrained devices. Once a route is established, the packets residing in the buffer are dequeued. A rapid dequeuing results in bursts and is likely to congest the network. Thus, in order to avoid bursts when dequeuing cached packets, we suggest a temporal separation of one second for each adjacent dequeued packet.

V. Evaluation

In this section, we present the results of our simulative performance evaluation. First, we examine different parameterizations of RDS. Then, the impact of our optimization is evaluated.

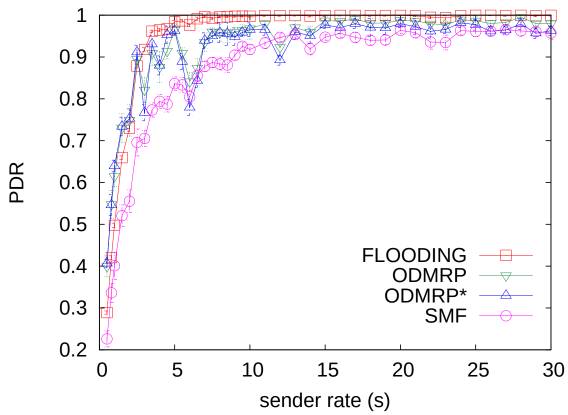
A. Parametrization of RDS

As the limitation to only one route discovery per node might be too restrictive, we evaluate two and three parallel *discovery attempts* as well. In addition, we evaluate the effect of buffering versus discarding user data, while no route is established. We compare all parameterizations to a basic ODMRP.

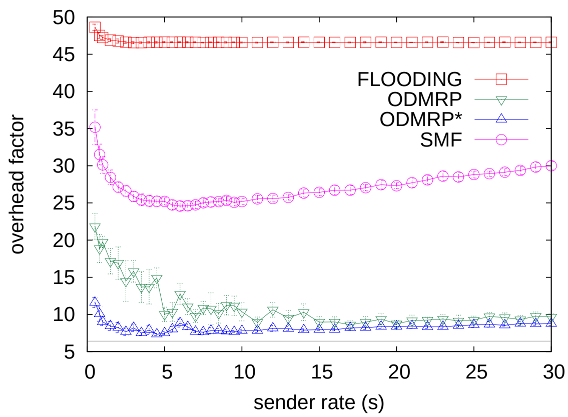
We consider a scenario (outlined in Fig. 2(a)) with 36 nodes in a 20 km^2 grid topology and a transmission range of 5 km. Two parallel traffic flows (S_1 to D_1 and S_2 to D_2) are simulated with the duration of 3600 s. Since our optimization aims to improve the deployment of ODMRP in networks with busy capabilities, we examine two sender rates (0.5 s and 1 s) which are known to lead to congestion and very high traffic load, respectively [2]. In addition, we examine the sender rate of 5 s which yields a medium congestion. The traffic in this topology may be routed along non-interfering paths. Thus, if both sources can establish their routes successfully, it is likely that no competition between the flows occurs during the forwarding process until the routes need to be refreshed.

We reduced the ODMRP timer values (cf. Section IV-A) to one-fifth to emphasize the effect of route refreshing. Due to the propagation speed and the averaged jitter the route discovery phase takes about 30 s in this scenario if the shortest path is used and no collisions occurs. Thus, we set the *discovery timer* to 60 s. This is assumed to be a sufficient value to finish a discovery even in a congested network.

The simulation results averaged over both traffic flows are shown in Fig. 3. As can be seen in Fig. 3(a) all parameterizations of ODMRP with RDS do significantly reduce the overhead of the data delivery compared to the original



(a) packet delivery ratio



(b) overhead factor

Fig. 4. The averaged packet delivery ratio and the overhead factor in the 6×6-nodes-grid, as a function of the senders transmission rate, averaged over two traffic flows. The arrangement of nodes allows each one to communicate with its eight single-hop neighbors using low loss packet transmissions.

ODMRP (unlimited discovery attempts) – the higher the traffic load the better the results. Moreover, it can be seen that the increase of parallel route discoveries attempts results in a linear rising overhead factor. Additionally, a slight decline of the PDR (see Fig. 3(b)) and only marginal changes of the route discovery delay (see Fig. 3(c)) can be observed. Thus, allowing parallel discovery attempts is not advantageous. However, we note that in this scenario, collisions are the major reason of packet loss. Nevertheless, we believe that in more realistic scenarios with high bit errors occurring, the resulting packet loss has to be faced with other techniques such as *packet cloning* [12] instead of increasing the number of parallel discoveries. RDS lowers the route discovery delay especially for higher loads. Although the delay is not lowered for a sender rate of 5 s, there is a significant overhead reduction.

Regarding the buffering of user data, Fig. 3(b) shows that only if enough network capability is available, a slight improvement of the PDR is seen. In contrast, in congested networks the dequeued packets yield more collisions. They interfere with subsequent packets whose delivery might be more important.

In summary, RDS achieves significant improvements in busy networks. Furthermore, it does not impair the performance of ODMRP in congestion free networks. Moreover, our evaluation confirms the sufficiency of the limitation to only one route discovery per node.

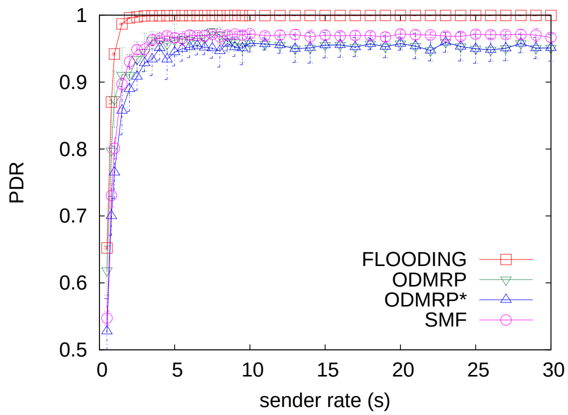
B. Impact of RDS

To show the impact of ODMRP with RDS, we compare it with the original ODMRP, the proactive SMF protocol, and simple flooding. We create the same scenario as in the previous section, but using protocol specific timer allocations noted in Section IV-A and varying the sender rate from 0 s to 30 s. Based on the results from the previous section, we (1) restrict RDS to one discovery attempt in progress, (2) do not buffer packets, and (3) choose a discovery timer of 60 s. Since in the proactive approach of SMF each node necessitates a certain time to establish its local topology awareness and furthermore, data delivery is unavailable during that period, we admit an initialization period of 1250 s to SMF. Again, we average the simulation results over both traffic flows.

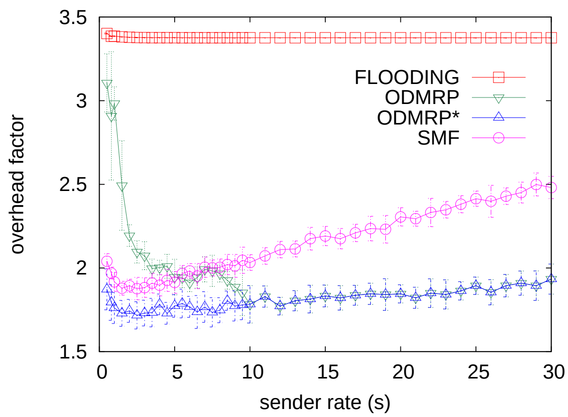
Fig. 4 shows the results. The enhanced version of ODMRP is labeled as ODMRP*. As can be seen in Fig. 4(a), the discarding of user data in ODMRP* during route discoveries only causes a slight decrease of the PDR. Furthermore, ODMRP and accordingly ODMRP* yield a more reliable PDR than SMF at almost all sender rates. Both versions of ODMRP cannot compete with simple flooding whose massive redundancy achieves a high reliability if it is allowed by the sender rate. However, this redundancy results in an excessive overhead (Fig. 4(b)) which is about seven times higher than the theoretical minimum visualized by the horizontal line in Figure 4(b). SMF reduces the excessive overhead of simple flooding, but shows a significantly higher overhead than ODMRP due to its proactive approach. ODMRP clearly outperforms simple flooding and SMF concerning the overhead due to its scoped flooding. Moreover, ODMRP* significantly improves the original ODMRP. The higher the load, the better the impact, as already evaluated in the previous section.

As a second scenario, we consider a sensor network where control messages are sent by a centrally placed authority to the members of a specific multicast group. Again, we use a simulation time of 3600 s and construct a grid topology. This time, we position 81 nodes in a grid covering 11 km^2 and select the central node to initiate a constant bit rate multicast traffic flow addressed to each node which resides on the boundary (see Fig. 2(b)). We reduce the transmission power as well as the frequency, the bandwidth, and the jitter (cf. Table I) to a reasonable setting for a 2 km transmission.

The results of the simulation in the second scenario (Fig. 5) confirm our results from the previous scenario. Furthermore, it can be seen that ODMRP with RDS yields a larger overhead gain in congested networks including a larger number of nodes (see Fig. 5(b)). However, a slightly lower reliability must be tolerated, compared to the original ODMRP (cf. Fig. 5(a)). Compared to the previous scenario, a better SMF performance



(a) packet delivery ratio



(b) overhead factor

Fig. 5. The averaged packet delivery ratio and the overhead factor in the 9×9-nodes-grid multicast scenario, as a function of the senders transmission rate, averaged over all traffic flows. The arrangement of nodes allows each node to communicate with its eight single-hop neighbors using low loss packet transmissions.

has to be admitted in this one due to the traffic profile which requires a network wide data dissemination. In busy networks, SMF outperforms the original ODMRP concerning the overhead factor. Regarding the PDR both protocols are comparable. RDS yields a slightly higher packet loss probability, but amortizes this by a high reduction of the resulting overhead.

VI. Conclusion and Future Work

In this paper, we focused on routing in UANs and presented an optimization of the reactive ODMRP to deal with the slow propagation speed and high error probabilities of acoustic communication. The Route-Discovery-Suppression (RDS) does prevent every node from flooding a second route discovery, while another discovery is already taking place. We parametrized RDS and showed its impact by comparing its performance to SMF and simple flooding. The evaluation showed that ODMRP with RDS outperforms all other protocols. It significantly reduces the overhead and, thus, saves limited energy resources and scarce network capabilities.

In our future work, we plan to continue our evaluation in dynamic scenarios and to take higher bit error rates into account. In detail, we plan to consider drifting of buoys, mobile devices, and the impact of variances of the depth depending sound speed, as well as a more accurate channel error model. Our goal is to provide further optimizations of ODMRP.

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