Geocast Routing of Symbolically Addressed Messages in Wireless Mesh Networks

Frank Dürr, Harald Weinschrott, Kurt Rothermel

Institute of Parallel and Distributed Systems (IPVS), Universität Stuttgart
Universitätsstraße 38, 70569 Stuttgart, Germany
{duerr,weinschrott,rothermel}@ipvs.uni-stuttgart.de

***Abstract*—Geocast protocols can be used to send messages to all receivers in a geographic target area. In this paper we present geocast routing algorithms for Wireless Mesh Networks that are tailored to symbolic addressing using symbolic location names like floor or room numbers. Since in particular indoors no geometric information is available, our algorithms use symbolic location models to derive directional information for routing. Moreover, we show how to integrate geometric and symbolic geographic routing algorithms into a hybrid routing approach which is applicable to larger areas consisting of symbolically and geometrically defined locations.**

I. INTRODUCTION

The geocast communication paradigm allows for sending messages to all receivers in a geographic target area. Geocast protocols for forwarding geographically addressed messages have been implemented for different system models such as infrastructure-based systems like the Internet [1]–[3] or mobile ad hoc networks [4] made up of mobile devices. In this paper, we focus on geocast protocols implemented on top of a new class of systems, namely *Wireless Mesh Networks (WMN)*. WMNs share similarities with both infrastructure-based systems and ad hoc systems. On the one hand, an infrastructure of fixed WMN routers is used as a multi-hop routing infrastructure. On the other hand, mobile devices can be integrated into the WMN not only as clients but also routers similar to the nodes of a MANET to extend the WMN to areas without fixed routers. Because of the lack of a costly wired infrastructure, WMN have emerged as a cost-efficient means to install medium-scale local area networks. For instance, a WMN could be used to provide wireless network connectivity within a building or even a whole city.

We envision to utilize WMNs together with a suitable geocast protocol to implement a location-based information system for distributing location-based notifications and ad hoc querying of location-based information. For instance, the visitors of a conference could be notified about the departure of a shuttle bus by sending a message to all persons at the conference location. Or an on-demand meeting detection could be realized in an ad-hoc manner without a dedicated server infrastructure by sending a query to all devices (laptops, smart phones, sensor nodes, etc.) in the room via geocast to determine the noise level or number of persons in the room.

To realize such a service efficiently, WMNs have to be extended to support location-based addressing and routing. We argue that in particular the addressing of locations by *symbolic names* like building and room numbers has to be supported instead of relying on geometric addressing using for instance polygons. On the one hand, such symbolic addresses are very intuitive to use by the human user. On the other hand, geometric location and position information is often not available indoors since common positioning systems like GPS do not operate there. Here, symbolic positioning systems like RFID-based systems are often the only means for positioning. Moreover, the creation of a complex geometric model is very cumbersum compared to symbolic models, which are based on simple topological relations such as inclusion and connectivity between locations [5]. Since we focus on such indoor scenarios, we argue that geographic routing should be based on symbolic addresses rather than geometric coordinates.

In this paper we present a geocast routing algorithm for forwarding symbolically addressed messages in WMNs. The basic idea of the approach is to use a symbolic location model that is detailed enough to determine directional information for message forwarding by the geocast mesh routers. Our routing structure combines an hierarchical structure according to the spatial inclusion relationship between symbolic locations of the model and a flat graph structure according to the connectivity between locations.

This basic routing structure allows for forwarding messages to the locations of a single symbolic location model, for instance within a single building. Moreover, we will present two approaches for forwarding geocast messages in larger systems consisting of several locations that are covered by different non-connected local symbolic models. As an example imaging a campus with several buildings that are covered by a single WMN, each with its own symbolic location model. Within each building, geocast messages are forwarded with the symbolic geocast algorithm mentioned above. However, to forward a message from one building to another, special mechanisms are required to bridge the gap between two buildings that is not covered by a symbolic location. The first approach uses a hybrid geocast approach based on symbolic routing within the symbolic locations (indoor) as well as geometric routing between locations of different models (outdoor). The second approach creates a single symbolic model by integrating the local models and adding suitable symbolic locations for bridging the gaps between locations of different models. We will show how suitable "bridge" locations can be defined to enable our symbolic routing algorithm to forward messages between the initially non-connected models.

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The rest of this paper is structured as follows. In Section II we present related approaches. In Section III we introduce our system model before we describe the basic symbolic geocast routing approach in Section IV. Then we present the routing between multiple local models in Section V. Finally, we evaluate the symbolic routing approach in Section VI before the paper is concluded in Section VII.

II. RELATED WORK

There has been numerous work on routing protocols for ad hoc networks [6], which are most similar to WMNs. These protocols can be divided into two main classes: topological routing and geographic routing. Topological approaches such as AODV [7] are not well suited for location-based services since they do not include means for geographic addressing. In contrast, geographic routing protocols could be utilized to forward location-based messages since they utilize geographic information for routing and are highly scalable due to forwarding based on local geographic knowledge. Greedy Perimeter Stateless Routing (GPSR) [8] is a well-known representative of this class using perimeter routing if greedy routing fails. Other representatives such as [9] further improve routing performance. However, geographic routing approaches assume devices to know their geometric coordinates (longitude, latitude). Especially indoors these are not available.

Moreover, several geocast routing protocols for ad hoc networks have been proposed [4]. However, as for the geographic unicast routing protocols, most of them are tailored to geometric coordinates as well. Some protocols like GeoTORA [10] establish a unicast route to the target area and then initiate a scoped flooding in this area as in our approach. However, GeoTORA is a reactive protocol that relies on a flooding-based unicast route discovery in contrast to our approach which proactively maintains geocast routes.

Previous work on routing on symbolic coordinates covers routing in the Internet and in wireless sensor networks. Overlay networks dedicated to symbolic geocast routing have been proposed in [2] and in our previous work [3]. However, the underlying system model of an Internet infrastructure fundamentally differs from the WMN model, which can be better compared to an ad hoc network due to the integration of mobile nodes for forwarding. In [11], the authors describe a symbolic geocast approach for wireless sensor networks. Due to the limited resources of sensor nodes, the protocol is based on source routing, where a powerful node computes a source route in a centralized way. Messages are forwarded between locations based on local neighbor information. In contrast to this approach, we aim at a decentralized routing approach, where each mesh node is able to take forwarding decisions.

III. SYSTEM MODEL

The system consists of nodes that form a Wireless Mesh Network (WMN) where mobile mesh clients also have routing capability. Different local symbolic location models are defined for dedicated locations within the area of the WMN, for instance for different buildings on a campus. In this section, we first present the properties of the symbolic location models, before we present the characteristics of the WMN.

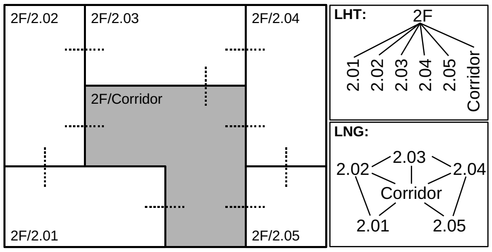

Figure 1. Symbolic Location Model (SLM)

A. Symbolic Location Model (SLM)

A *symbolic location model (SLM)* consists of a set of symbolic locations. Each location is assigned a unique identifier. Moreover, we assume the model to support two relations. First, a relation that models the inclusion relation ($\subset$) between single locations resulting in a *Location Hierarchy Tree (LHT)*. We write $L \subset P$ if the geographic area of P covers the geographic area of L. We say a location P is a parent location of L, if $L \subset P$ and there is no location M that satisfies $L \subset M \subset P$. We refer to the sub-location L as a child location. Locations are assigned to hierarchy levels according to the depth of the respective location in the LHT. We refer to the transitive extension of parent and child relations as k-parent and k-child respectively, where k refers to the distance of the levels in the LHT. Second, we assume a graph modeling the neighborhood relation of the leaves in the LHT. This information is derived from a floor plan where adjoining locations are defined to be neighbors. On this *Location Neighbor Graph (LNG)* we define the geographic distance between two locations d_{geo} as the length of the shortest path between them.

Fig. 1 shows a sample floor plan and location model of the second floor of a building. Location 2F is the parent location of rooms 2.0X and corridor. Adjoining locations, i.e, connected locations in the LNG, are for instance room 2.01 and 2.02.

We assume that separate local SLMs are defined for different *top-level locations* such as different buildings on a campus. These models cover their top-level location – e.g., the building – completely, however, between these top-level locations, gaps like the free space between two buildings exist that are not covered by any symbolic location of the models. The result is a set of non-connected SLMs where in particular no single LNG exists connecting the locations of different SLMs.

B. Mesh Nodes

The nodes in the network are either stationary mesh infrastructure nodes or mobile mesh clients. Both node types have routing capabilities and are equipped with a wireless LAN interface for inter-node communication.

Infrastructure nodes are assumed to be stationary and are manually assigned a static location. They store a copy of the SLM of their top-level location, e.g. the SLM of a building. Mesh clients dynamically acquire their current position with positioning devices. We assume that they have a symbolic position according to the SLM indoors, e.g. using an RFID-based positioning system; outdoors clients have geometric coordinates using for instance GPS. Clients retrieve the SLM of the current location from a stationary node when they enter the area of the top-level location, e.g. when entering a building. In the following we refer to both types of nodes as mesh nodes.

IV. SYMBOLIC ROUTING ALGORITHM

In this section we describe the symbolic geocast routing algorithm that is used for forwarding messages to a given target location within the area covered by a local SLM, e.g. within a building. In order to enable mesh nodes to make forwarding decisions, we first introduce a routing infrastructure that is based on the SLM. Then we present two routing approaches: a hierarchic routing algorithm and a flat routing algorithm.

A. Routing Structure

The basic idea of the approach is to establish routes between nodes of locations that are connected either by an edge of the LHT or the LNG. The results are two routing structures: the Node Hierarchy Graph (NHG) resembling the LHT, and the Node Connectivity Graph (NCG) resembling the LNG. Then messages can be routed either hierarchically along the NHG or flat along the NCG. Since it is reasonable to assume that network connectivity between mesh nodes usually corresponds to geographic distance, such structures resembling the location model will also lead to short network paths in most cases.

To establish these structures, we have to assign nodes to locations. For each location, a node within that location is elected as *Associated Node* (AN). For larger locations, we can assign multiple ANs to one location for load balancing, however, here we assume that at most one AN is elected per location as long as a location is not partitioned. For empty locations, no AN is assigned. Only ANs form the routing structures and actively participate in maintaining routes to reduce the induced overhead. The election process is based on periodic advertisement messages that each node floods within its location as long as it did not receive an advertisement from the AN of this location. These advertisements can also contain further information about the nodes, for instance to prefer stationary mesh nodes over mobile ones to reduce the overhead of maintaining the routing structures under mobility. We refer to a node that is associated to location L as AN_L.

Second, we assure that ANs of locations being direct neighbors in the LNG know a route to each other. To establish these routes, advertisements from the AN of a location are forwarded to nodes in neighboring locations. The resulting network structure is the *Node Connectivity Graph (NCG)*.

Third, an AN of a location knows a route to the AN of its parent location and to the ANs of its child locations. Moreover, an AN knows recursively which child AN knows a route to which sub-location, i.e., through which child which sub-location can be reached. In the following we refer to this as reachability summaries, e.g., in Fig. 2 the AN of A knows that the ANs at A/2/c and A/2/d can be reached through the AN at A/2. Parent-child routes are created when a child AN receives an advertisement from an AN of its parent location; the child AN replies on the reverse path with its own advertisement including its reachability summary. The routes between parent and child ANs form a layered hierarchic structure called the *Node Hierarchy Graph (NHG)*.

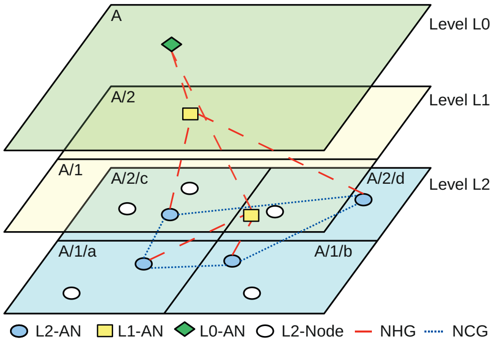

Figure 2. Routing structure consisting of NCG and NHG

Every node knows routes to several ANs that are its entry points to the NHG and NCG structures. First, each node knows at least the AN of its current position as entry point for the NCG. In addition, every node knows at least one AN for each of its parent locations as entry point to the NHG.

Figure 2 shows a simple network, where each location of the three level hierarchy has one AN, and the routes between these ANs. The ANs on the lowest level form the NCG, while the NHG is formed by all ANs.

Each node manages a routing table where it stores entries for its direct neighbors in the NCG and NHG structures or entries for its entry points to these structures. An entry includes the symbolic location, link layer address, and topological distance d_{hop} in hops to the target.

B. Routing Algorithm

The basic idea of the symbolic geocast routing algorithm is to route the message along the NHG or NCG to any node within the target area in a first phase and then to distribute the message within the area using scoped flooding in a second phase. Since the second phase is straightforward, the following description concentrates on the first phase. First we show, how messages are forwarded along the NHG before we show how to improve message forwarding by routing along the NCG.

Hierarchic Routing: The hierarchic routing algorithm forwards a message along the NHG. First, the sender forwards it to an AN of the sender's location. From there, it is forwarded stepwise to a parent AN until an AN of a location is reached covering the target location. Then, the message is forwarded recursively to the child AN that knows a route to the target location until the target location is reached.

Although this process looks simple at first sight, it becomes more challenging if the target area is partitioned since now we have to reach each part of the partitioned target area. In this case multiple ANs might be assigned to the partitioned location since advertisements from one part could not reach

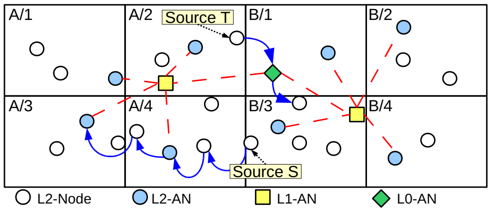

Figure 3. Shortcuts for path length optimization

the other. To reach all parts, the message has to be routed up in the hierarchy to a parent AN of the target area from which both parts of the partition can be reached. This router can forward the message to the children from which the parts can be reached. Unfortunately, a partition might only be resolved at the root AN of the hierarchy. Therefore, the idea is to route the message to a node that is associated to the k-parent location of the target. This message triggers every AN whose summary indicates the reachability of the target to forward the message to its respective child ANs. k defines a trade-off between robustness to network partitioning and message overhead. Smaller values of k lead to less overhead but might fail to deliver messages to every node when a partitioning can only be resolved at higher levels of the NHG.

Flat Routing: The idea of the flat routing is to greedily decrease the geographic distance d_{geo} to the target by forwarding the message to a neighbor in the NCG that is closer to the target than the current node according to the LNG. If no such node is found, hierarchical routing along the NHG is used.

Figure 3 shows two examples of optimized forwarding. Instead of addressing a message from source T to B/3, a direct route to the root AN can be used. From there, a direct route to the AN of the target B/3 allows to skip an intermediate AN for location B. A message from source S to A/3 is forwarded to A/4, which is closer to the target and, finally, allows to forward the message directly to the target.

V. ROUTING BETWEEN LOCAL SYMBOLIC MODELS

The symbolic routing algorithm presented in the previous section manages to forward messages within a single local SLM. However, as introduced in Section III, we assume that a WMN might cover several non-connected SLMs. As an example consider several buildings on a campus that are covered by a single WMN. Each building is modeled by a separate SLM. However, symbolic routing between these buildings fails because of two reasons. First, there is no direct connection between the locations of different SLMs. In the example, there is free space between the buildings that is not covered by any location of the models. Second, even if there was a single symbolic location model covering the whole campus including locations for the free space between the buildings, nodes might not be able to determine their symbolic position outdoors, since we assume that nodes use GPS for positioning outdoors, which returns geometric coordinates.

In order to build routes between top-level locations, we propose two approaches. In Section V-A we present a hybrid routing approach integrating geometric routing with symbolic routing. In Section V-B we propose to build a single SLM for routing integrating all local SLMs.

A. Hybrid Location-based Routing

The basic idea of hybrid location-based routing is to use symbolic routing within areas covered by an SLM and geometric routing to forward messages between top-level locations of different SLMs. For routing within an SLM, the routing algorithm of the previous section can be used. For geometric routing, we can use any position-based geometric routing algorithm from the literature like GPSR [8].

In order to use geometric routing, we have to assign geometric positions to top-level locations. For our purpose, a simple point coordinate is sufficient as shown below. This point must be located within the top-level location of the respective SLM in order to assure correct routing. Such a point coordinate can be easily assigned manually to each building.

Routing from one symbolic location in one SLM, say room B1/F1/R1 in building B1, to another location in another SLM, say room B2/F2/R2 in building B2, then requires three phases (cf. Figure 4). Phase 1: symbolic routing from B1/F1/R1 to a node at the border of the building knowing a geometric coordinate. Phase 2: geometric routing from this border node to another node at the border of building B2 that has a neighbor node within building B2. Phase 3: symbolic routing within building B2 to room B2/F2/R2.

Phase 1 can be achieved in different ways. One simple solution is to let the sender issue a query for a node with a geometric coordinate outside the building by using an expanding ring search, i.e. sending broadcasts with increasing time to live values (TTL) until such a node is found. If multiple nodes are found, the sender can choose the one with a coordinate closest to the position of the target building. Another possibility is to learn geometric coordinates of *border locations* of the building and store them with the SLM. For instance, when a node enters a building at a certain symbolic location, it can assign the last known GPS coordinate to this location. Then the sender can directly send messages via symbolic geocast to a border location of its SLM with a geometric position close to the target building. If a node at this border location has a neighbor outside the building, it will start Phase 2. In order to assure that actually a node outside the building has been found at this location, this geocast should be acknowledged by the node starting Phase 2. Otherwise another border location is chosen.

In Phase 2, the message is routed geometrically towards the position of the target top-level location (cf. Figure 4). The goal in this step is to find a node having a symbolic coordinate within the target top-level location (building B2) that can be used to start Phase 3. To find such a node, we use the perimeter forwarding mode of geometric routing algorithms like GPSR. Perimeter forwarding is used, when greedy forwarding fails and no neighbor node with a position can be found that is closer to the target position than the position of the current node. In our case this mode is triggered at the border of building B2 since the position of the target top-level location

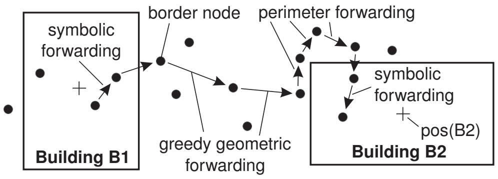

Figure 4. Hybrid Routing Approach

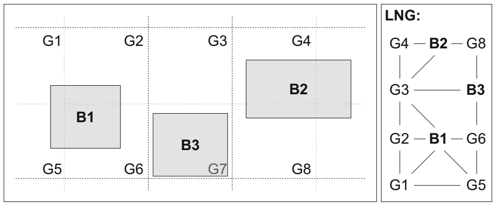

Figure 5. Integrated symbolic location model with learnd LNG

is within the building and cannot be reached directly by geometric routing. Perimeter forwarding forwards the message to nodes at the border of the building (cf. Figure 4). If one of these nodes has a neighbor inside the building, it will forward the message to this node and start Phase 3.

Finally, Phase 3 uses symbolic routing within the building.

B. Integrated Symbolic Location Model

The second approach constructs a single SLM from the SLMs of top-level locations. On first sight, the solution seems to be trivial. We could simply insert a root location “campus” and link the top-level locations of the building SLMs as children to the campus location to build one single SLM. However, this might lead to sub-optimal routing structures since the resulting LNG is not connected – there is no flat path between the buildings. Therefore only hierarchical routing can be used possibly leading to long indirections.

Therefore, we do not only add a new root location, but also additional *symbolic bridge locations* to define flat paths between the top-level locations. To define bridge locations, we introduce a regular grid structure. Each grid cell is interpreted as a symbolic location that is a child location of the root location (campus). We choose the grid structure such that GPS coordinates can be mapped to grid cells using a predefined formula known to all nodes.

To allow for flat routing, we have to define an LNG including links between grid cells and locations of the SLMs. Depending on the cell size, it might be inefficient to define links only between neighboring cells of the original grid structure. If cells are small, long flat paths might be the result. If cells are big, paths are also long since routing within a cell does not take the direct path anymore. Therefore, we propose to start with a fine-grained grid structure and then learn the links between cells based on the typical network connectivity. Consider two nodes within one-hop communication range, say $n1$ and $n2$, located in two different – not necessarily neighboring – grid cells. Since these two nodes are able to communicate, we add a link between these two locations to the LNG. With this method, the links of the LNG reflect typical network connectivity. Since now flat routing can directly jump to another grid cell without traversing all the intermediate cells of the original grid, paths are shorter. For example, in Fig. 5 a node at B1 has a direct neighbor at G3. Therefore a connection between these two locations is added to the LNG in addition to the connection between adjoining locations. At the same time the risk of reaching a dead-end is reduced since we follow paths having a higher chance of network connectivity.

VI. EVALUATION

In this section, we evaluate the proposed symbolic routing approach with respect to the achieved path lengths. We implemented both the hierarchic and the flat routing algorithms for the network simulator ns2, denoted as SAR and FLAT, respectively. In order to evaluate the robustness of flat greedy routing, FLAT drops the message instead of switching to hierarchical routing if it reaches a dead end.

We derived the symbolic location model for the experiments from the floor-plan of our institute, which has a size of 75 m x 75 m. The floor-plan is divided into four quadrants, which are in turn divided into 151 leaf locations. On the lowest level, this three level model consists of locations of different sizes: rooms, floors, and four large inner courtyards. The LNG is modeled based on adjoining locations. We simulated a varying number of stationary mesh nodes. The mesh nodes store a copy of the SLM and know their current position.

We use 802.11b network interfaces configured to a bandwidth of 11 MBits and a maximum transmission range of 15 meters. All simulations have a duration of 600 seconds and the reported values are averaged over 100 different simulation runs. We did not simulate message collisions. Therefore, message delivery is only affected by errors in the routing structure, which allows for measuring unbiased routing performance.

A. Path Length

First we evaluate the path lengths of SAR and FLAT. As performance metric we use the stretch factor of the path length defined as the path length of successfully delivered messages divided by the minimum path length of the mesh topology.

Figure 6 shows the stretch factors of SAR and FLAT. FLAT achieves a lower stretch compared to SAR due to the property of greedy forwarding: if it successfully delivers a message it achieves this on an almost direct path. In contrast, SAR establishes a routing structure to effectively deliver messages in case of arbitrary network topologies. Although routing along the hierarchy potentially leads to a high stretch factor, the simulation results show that optimized forwarding achieves to limit the stretch to a 23% bound of the minimum path length.

B. Delivery Ratio

Next we are going to evaluate the effectiveness of the two routing approaches. As performance metric, we use the *packet delivery ratio* defined as the ratio of successfully delivered messages and the number of initiated message transfers. The results are depicted in Fig. 7. SAR achieves to deliver always

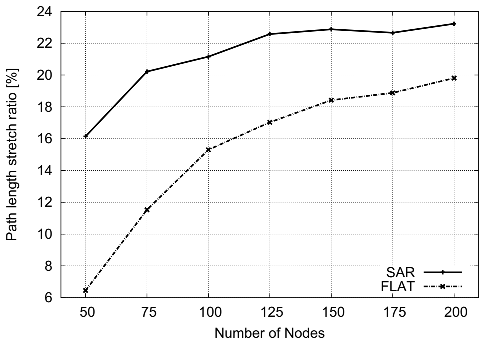

Figure 6. Path Length Stretch

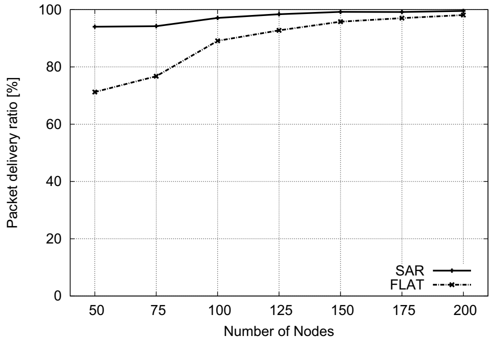

Figure 7. Delivery Ratio

more than 95% of the messages. This number increases to almost 100% if more nodes are in the network. Not every message is delivered due to the unreliable transmission of advertisements, which leads to anomalies in the routing structure. When the node density is low, redundant routes between locations are more unlikely. In that case, if the routing structure is broken due to undelivered advertisements, a message cannot be forwarded on an alternative route.

The performance of FLAT is below that of SAR because greedy routing suffers from void areas in the network. In particular FLAT suffers from low node density since greedy forwarding is likely to fail. Although the delivery rate increases with increasing number of nodes, FLAT still performs worse. As the analysis of the simulation shows this is due to the problem that position information of nodes in large locations does not allow to derive directional information for forwarding.

VII. SUMMARY AND FUTURE WORK

We presented a geocast routing algorithm for WMNs tailored to forwarding symbolically addressed messages. Since in particular indoors no geometric position information can be used for forwarding, we built our routing algorithms on basis of a symbolic location model. We proposed two symbolic routing approaches: hierarchical routing along a forwarding structure resembling the inclusion relationship between symbolic locations, and flat routing forwarding messages along paths defined by the neighbor relationship between locations. We presented two approaches to forward messages between different local symbolic models through areas where initially no symbolic location information is available. The first approach uses a combination of geometric and symbolic routing, to route messages through areas where nodes have geometric coordinates. The second approach uses an extended symbolic location model defining "bridge locations" between originally non-connected symbolic models.

In future work, we are going to extend the hybrid routing approach. In particular, suitable recovery strategies are necessary for situations where a sub-optimal border node has been chosen during the switch from symbolic to greedy routing.

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