

# Symbolic Routing for Location-based Services in Wireless Mesh Networks

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**Abstract**—Wireless Mesh Networks are cost-efficient medium-scale networks that have the potential to serve as an infrastructure for advanced location-based services. As a basis for these services we present a routing algorithm that allows to address intuitive symbolic coordinates. This algorithm is based on a proactively maintained geographic routing structure that mimics the structure of a symbolic location model. Message forwarding is done greedily along short paths defined by a symbolic location model and if this fails, through an hierarchical overlay network built by selected mesh routers. We show how a geocast communication mechanism that allows to send messages to all hosts within a specific location can be implemented with this routing algorithm. In extensive evaluations we show that a low proactive routing overhead allows to achieve high message delivery rates even in case of mobility. Moreover, we show that the paths achieved are only 25% longer than the theoretic optimal paths for a wide range of simulation settings.

## I. INTRODUCTION

Wireless Mesh Networks (WMN) have emerged as a cost-efficient means to build medium-scale networks covering for instance a building, or even parts of a city and serve as a basis for advanced location-based services.

In particular, we envision novel information systems that are deployed on a WMN to distribute location-based notifications, or query location-based information using location information as a key [1]. For instance, on-demand meeting detection in a room could be realized in an ad-hoc manner without dedicated infrastructure by sending a query to the nodes in the respective room. These nodes then run common meeting detection algorithms based on their local sensors, calendars and, possibly, further sensors installed in the room. Finally, the result is returned to the query issuer.

Using the mesh network as a medium to distribute or query location-based information requires a location-based communication primitive to send messages to one or all hosts at a certain location. In order to realize such a service efficiently, WMNs have to be extended to support location-based addressing and routing. We argue that for the intuitive understanding of users, in particular symbolic location information [2], e.g., room or building numbers, has to be supported as an addressing concept. Moreover, especially indoors, symbolic positioning systems as RFID are often the only means for positioning. As a consequence, we argue that geographic routing in such indoor scenarios

should be based on symbolic addresses rather than geometric coordinates.

In this paper we present a novel symbolic routing protocol for WMNs supporting anycast and geocast routing with symbolic coordinates in indoor scenarios. A simple approach to implement symbolic routing would be to introduce a location server to which each node sends its current position and which resolves symbolic addresses to node addresses. This can be used by a common routing algorithm, such as AODV [3] to establish a route to the target. However, this simple approach suffers from the introduced indirection, which requires to send possibly frequent position updates to the location server. Therefore, we develop an approach that integrates location management and routing, in the sense that symbolic location information is managed in a distributed and scalable manner, and nodes are enabled to forward messages based on symbolic location information.

Since symbolic location models are mainly built for user interaction, they do not contain directional information that is detailed enough for routing. However, we will show how to utilize a special simple symbolic location model for directed routing. Moreover, we will show how to cope with the discrete nature of symbolic addresses, which denote areas like rooms or floors rather than point coordinates and, therefore, require special mechanisms to forward messages through such areas. Our routing structure mimics the structure of the symbolic location model by using hierarchical routing structures, according to the spatial inclusion relationship, as well as short direct routes, based on a flat graph of connected locations, to build efficient and stable paths. We will show how these structures can be maintained in a dynamic environment consisting of stationary and mobile mesh routers and that routing achieves high message delivery rates and short paths compared to the theoretic optimum.

The remainder of this paper is structured as follows. In Sec. II we present some related works. Then, in Sec. III we present the system model, before we present an anycast as well as a geocast routing algorithm in Sec. IV. Then, we show in Sec. V the evaluation results and conclude the paper with conclusions and an outlook on future work in Sec. VI.

## II. RELATED WORK

There has been numerous work on routing protocols for ad-hoc networks [4]. These protocols can be divided into two

main classes: topological routing and geographic routing. Topological approaches as AODV [3] 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 only.

Greedy Perimeter Stateless Routing (GPSR) [5] is a well-known representative of this class and uses perimeter routing if greedy routing fails. Other representatives such as [6] further improve the performance of routing. However, geographic routing approaches assume devices to know their geometric coordinates (longitude, latitude). Especially indoors or if nodes are not equipped with a positioning device like GPS, these are not known. Moreover, as studies show [7], geographic routing significantly suffers from inaccuracy of location information. Therefore, these protocols are not applicable for routing on symbolic coordinates.

Approaches that rely on virtual coordinates [8] allow for geographic routing without the need for physical position information. However, these approaches suffer from high overhead for updating these coordinates in case of network dynamics. Furthermore, they introduce the unsolved problem of mapping these coordinates to a symbolic location model. A routing protocol that also relies on a hierarchical structure as our approach is [9]. However, it also does not support symbolic addressing and it relies on a central node that manages global topology information.

Previous work about routing on symbolic coordinates covers routing in wireless sensor networks. Due to the limited resources of sensor nodes, the protocol in [10] is based on source routing, where a powerful node computes a source route in a centralized way. The message is then forwarded from location to location based on local neighbor information. However, no elaborate recovery strategy is presented to deal with network dynamics. To the best of our knowledge, there are no other approaches for symbolic routing in WMNs.

Several geocast routing protocols [11] have been proposed, which mainly rely on dedicated routing structures or on flooding based mechanisms and cannot benefit from unicast routing capabilities. Some protocols like GeoTORA [12] 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. Moreover, we aim for reaching every partition of nodes in the target area. In previous work [13] we proposed mechanisms for symbolic geocast in Internet-based overlay networks where we also relied on hierarchic structures. However, characteristics of mesh networks require new routing concepts.

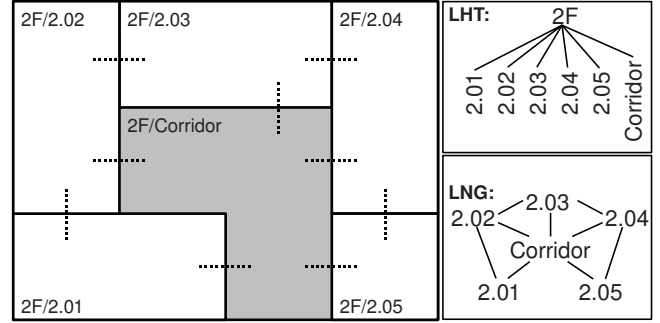


Figure 1. Symbolic Location Model (SLM)

### III. SYSTEM MODEL

The system consists of nodes that form a wireless mesh network (WMN) where mobile mesh clients also have routing capability. A symbolic location model is defined for the geographic service area that is covered by the WMN. In this section, we first present the properties of the symbolic location model, before we present the characteristics of these nodes.

#### A. Symbolic Location Model (SLM)

A symbolic location model (SLM) consists of a set of symbolic locations. Each location is assigned a unique identifier. In addition to this set of locations, 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  $L \subset M \subset P$ . Moreover, we refer to the sub-location  $L$  as a child location. We assign the locations 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 that models 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 the corresponding location model of the second floor of a building. Location 2F is the parent location of rooms 2.0X and corridor. 2F, and all of its sub-locations, compose the set of locations. Adjoining locations, i.e., connected locations in the LNG, are for instance room 2.01 and 2.02.

#### B. Mesh Nodes

The nodes in the network are either stationary mesh infrastructure nodes or mobile mesh clients. Both types of

nodes have routing capabilities and are equipped with a wireless LAN interface for inter-node communication, e.g., a 802.11bg interface. The transmission range of this interface is denoted by  $r_{tx}$ . Each node is assigned a link layer address.

Infrastructure nodes are assumed to be stationary and have a static location. Moreover, they store a copy of the SLM. Mesh clients dynamically acquire their current position with a positioning device like a RFID-based system, and retrieve the model when they enter the service area. In the following we refer to both types of nodes as mesh nodes.

#### IV. SYMBOLIC ROUTING

Symbolic routing is a network service that allows for sending a message to a symbolically addressed location representing an area defined by the SLM. The basic idea of our approach is to proactively build a routing structure that mimics the structure of the symbolic location model. More specific, we establish routes between locations that are connected by an edge either in the LHT or in the LNG. Since connectivity of mesh nodes usually correlates with their geographic distance, a geographic routing structure resembling the SLM leads to short network paths. Since the SLM is static in contrast to the physical network topology, using the SLM as directional hints for routing is also beneficial in terms of network overhead.

This structure allows for forwarding a message from any location to any other location stepwise through a chain of intermediate locations. Each step possibly involves multiple intermediate mesh nodes as relays. However, since routing is not directly based on the physical network topology, special routing algorithms are required to successfully forward messages if locations are only sparsely covered by nodes. We present two routing primitives, Symbolic Anycast Routing (SAR) in Sec. IV-B and Symbolic Geocast Routing (SGR) in Sec. IV-C. SAR delivers a message to any node at the addressed location, while SGR delivers a message to all nodes at the addressed location. In Sec. IV-D we show how the routing structure is maintained.

##### A. Routing Structure

In this section we show how the elements of the SLM are used as a “template” for building the routing structure. The details of its maintenance are introduced in Sec. IV-D.

First, a set of nodes is associated to each location depending on its size, i.e., the level in the LHT. A higher number of nodes can be associated to larger locations on higher levels to allow for load distribution. This set is empty if no node is at the respective location. The associated nodes (*AN*) of a location know a route to each other. We refer to a node that is associated to location  $L$  as  $AN_L$ .

Second, *AN*s of locations that are direct neighbors in the LNG (cf. Sec. III-A) know a route to each other. In the following, we refer to the structure that is formed by

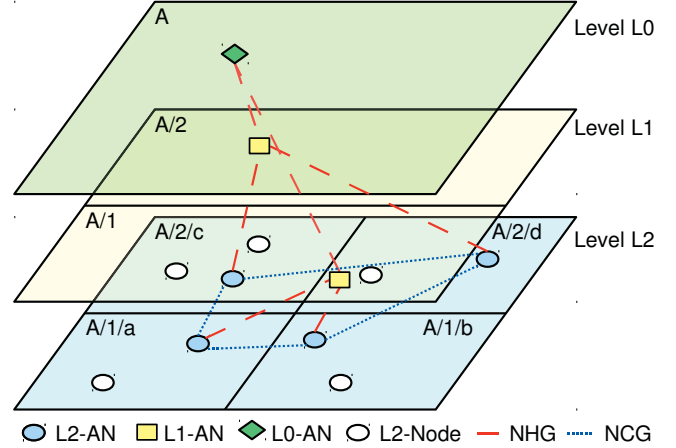


Figure 2. Routing structure consisting of NCG and NHG

the connections of *AN*s in neighboring locations as node connectivity graph (NCG).

Third, an *AN* of a location knows a route to at least one *AN* of its parent location and to the *AN*s of its child locations that are within a specific topological distance. All *AN*s of a location together know routes to all *AN*s of their 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 *AN*s at A/2/c and A/2/d can be reached through the *AN* at A/2. The routes between parent and child *AN*s form a layered hierarchic structure. In the following we refer to this structure as node hierarchy graph (NHG).

Every node knows routes to several *AN*s 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.

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

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, the link layer address and the distance ( $d_{hop}$ ) to the target, which specifies the topological distance in number of hops. Routing entries are discarded according to the soft-state principle.

##### B. Symbolic Anycast Routing

Symbolic Anycast Routing (SAR) is a network service primitive that allows to send a message to any node at a specific symbolic location, i.e., the target location, representing an

area of the SLM. Next, we first show the basic routing along the NHG structure and how it achieves effectiveness before we present an optimization to increase the efficiency of message forwarding. Then, we present mechanisms for increasing the resilience of SAR to failures.

1) *Basic Anycast Message Forwarding*: The basic anycast 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 that covers the target location. Then, the message is forwarded to the child *AN* that knows a route to the target location. This process is repeated until the target location is reached.

Although routing towards a higher level *AN* of the NHG is simple by following the route towards the parent *AN*, routing towards a lower level *AN* is more challenging since possibly multiple nodes are associated to a single location and, therefore, can be chosen for forwarding. Several cases of routing down the hierarchy can be distinguished.

Class I is the simplest case where only one node is associated to a location. Class II represents the case where multiple nodes are associated to a certain location but no partitioning occurs within that location. Class III represents structures that occur in case of partitions within single locations, where *ANs* of a location are only connected through higher level *ANs*.

To select a route for forwarding at branching routes (Class II to III) according to this classification, we propose a strategy that is based on the reachability summaries and on the geographic distance metric  $d_{geo}$ . In essence, we forward a message to the associated node  $AN_C$  of the child location  $C$  for which the geographic distance  $d_{geo}$  to the target is minimal and that knows a route to the target. If multiple *ANs* have the same distance to the target, we forward the message to the *AN* that is topologically closer.

If a target location is not included in the reachability summary of a node, it forwards the message to an *AN* with possibly more global information, i.e., one of its parents (root *ANs* forward to siblings). The selection is performed based on  $d_{geo}$  as introduced in the previous paragraph.

With this mechanisms, a message that cannot be delivered would be finally routed to a root *AN*. However, depending on the number of root *ANs* they might become bottlenecks. Therefore, the sender can specify a priority for the message that is interpreted as the maximum number of hops to take for reaching a higher level *AN*. This allows to trade-off the probability for successful delivery and routing overhead. For smaller priorities, gaps between nodes of a partitioned location possibly cannot be bridged by forwarding via nodes of higher level locations.

2) *Exploiting Shortcuts for Forwarding*: Although forwarding along the NHG is effective, we show next how to exploit shortcuts in the routing structure to reduce the overall path length, e.g., a direct route between two *ANs*

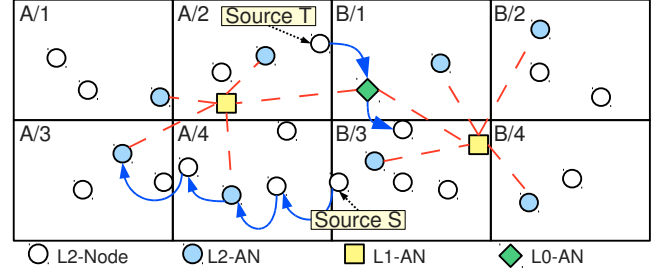


Figure 3. Shortcuts for path length optimization

can be used skipping several intermediate *ANs*. Moreover, this optimization also relies on the NCG, i.e., routes between neighboring locations, to get closer to the target location, rather than taking indirections via NHG routes.

The idea is to greedily decrease the geographic distance  $d_{geo}$  to the target while limiting the effort for recovery by forwarding along the hierarchy if the greedy route turns out to be a "dead end" in the next (greedy) routing step. Therefore, we define the hierarchic distance  $d_{hier}$  to estimate the cost to reach the target along a route of the NHG. A destination is only considered in the greedy algorithm if its distance  $d_{hier}$  to the target does not exceed that of the current node. We approximate  $d_{hier}$  according to the LHT.

$$d_{hier}(S, T) = l_T - l_P$$

In this equation,  $l_X$  denotes the level of location  $X$ . The metric is based on the number of hierarchy levels that are between the target  $T$  and the smallest common parent  $P$  of target  $T$  and source  $S$ .

Fig. 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 directly forward the message to the target.

3) *Resilience to Failures*: Failures of the routing structure can be caused by message loss or node mobility. If a node learns that a message cannot be forwarded successfully to a neighbor, for instance if it does not receive an ACK on the MAC layer, it discards the corresponding routing entry. If there is no alternative route to the target location, a reactive discovery mechanism can be initiated to find a route to a node in the target location. For instance, AODV [3] uses expanding ring search for this purpose. To prevent a high overhead of the discovery when the target cannot be reached, we restrict the discovery with a TTL.

### C. Symbolic Geocast Routing

Symbolic Geocast Routing (SGR) is a network service primitive that allows to send a message to all nodes within the target location. The idea is to use anycast for routing

to the target location and then distribute the message within this area.

However, simple message distribution within the target area using scoped flooding restricted to the target location fails in case of a partitioned target area (Class III; cf. Sec. IV-B1). When a message is at an *AN* of one branch it has to be routed via a parent *AN* to reach the *AN* in the second branch. Therefore, the idea is to route a SAR message to a node that is associated to the *k*-parent location of the target. The SAR message triggers every *AN* whose summary indicates the reachability of the target to forward the message to its respective child *AN*s. Duplicate forwardings are suppressed. The *AN*s of the target location initiate a scoped flooding in their location. As long as at least one route to each part within the target location is known, the message can be delivered to the complete location.

The selection of *k* influences the effectiveness of the SGR algorithm. A small value may result in the delivery of the message to only a subset of the *AN*s that represent the target, e.g., when a partition within the target is only resolved at a higher level of the hierarchy. Therefore, the sender of a message specifies *k* as the priority. Typically, a value of one is sufficient and a higher value is only needed in few special cases where large locations are partitioned.

#### D. Routing Structure Maintenance

The algorithm for maintaining the routing structure as described in Sec. IV-A consists of three mechanisms. First, we reduce the number of nodes actively participating in maintenance by electing the *AN*s. Second, we build the node connectivity graph (NCG) of *AN*s of neighboring locations and, finally, we build the node hierarchy graph (NHG). All of these three mechanisms are based on periodic advertisement messages and are described in the following sections.

1) *Election of Associated Nodes*: In order to adjust the number of *AN*s and balance between overhead and resilience, we introduce the tuning parameter *e*, which allows to specify the “eagerness” of nodes to be associated with a location. A node sends advertisements if it does not receive one for this location for more than  $t_{adv}$  from a node with higher or equal eagerness. An *AN* that receives an advertisement for its associated location, stops sending advertisements for this location if its eagerness is lower than or equal to that of the advertisement. Moreover, an *AN* stops sending advertisements when it leaves the location with which it is associated.

The eagerness is influenced by several aspects. First, the mobility of the node. To keep *AN*s more stable, stationary nodes increase their eagerness. Second, the load of the node. To reduce its load, and prevent it from becoming a bottleneck, a node decreases its eagerness. Third, strategic value of a node’s location. For instance, nodes that are at a central location, increase their eagerness to reduce the overall path length in the network. Fourth, number

of associated locations. A node that already is associated to some locations, increases its eagerness to profit from synergies through combined advertisements, i.e., one node instead of several nodes has to broadcast advertisements. Finally, a user configurable value. A user or an application sets this value to indicate whether this node should be integrated tightly into the routing structure or not.

Advertisements are sent as periodic broadcast messages with a period of  $t_{adv}$  to all direct topological neighbors and are forwarded with a certain TTL by every node at the advertised location. The value for  $t_{adv}$  is chosen according to node mobility, which influences the probability for a route to break, and the available bandwidth. To prevent the concurrent sending of advertisements, nodes randomly delay sending reciprocal to their eagerness.

The TTL is correlated with the location size and set to the number of hops that are needed for a message to traverse a location. The size of a location is specified by the SLM. For load distribution, a smaller hop value can be chosen resulting in multiple nodes associated to a single location. Duplicate forwardings are suppressed and multiple advertisements of a single node are included into a single message.

Depending on the hop limit of an advertisement and depending on partitions within locations, multiple *AN*s may represent a single location. A node that receives an advertisement adds a route to the sender. Although we select the shortest route if multiple advertisements are received, other mechanisms can be incorporated to prefer more stable routes. However, these are beyond the scope of this paper.

To allow for efficient processing of an advertisement, it includes only location identifiers. For instance, the location /BuildingA/Floor2/Room2.223 is simply represented by the unique identifier 2578 within the scope of the SLM. Hereby, an advertisement’s size and processing complexity is reduced. It includes a set of location identifiers, a TTL value, an eagerness value, and its sender.

2) *Connectivity Graph Building*: The connectivity graph building mechanism maintains the NCG structure and establishes routes between *AN*s of neighbor locations in the LNG by forwarding the advertisements to *AN*s of the direct neighbor locations of the sender.

To prevent flooding in neighbor locations, we introduce an optimized forwarding mechanism for advertisements in neighbor locations. A node that can deliver a message to an *AN* of a neighbor location includes this location in the advertisement before forwarding. Another node that is at one of the locations included in the advertisement does not need to forward it anymore. Moreover, duplicate forwardings are suppressed.

3) *Hierarchy Graph Building*: The hierarchy graph building mechanism maintains the NHG structure that mimics the LHT by establishing routes between parent and child *AN*s. When a child *AN* receives an advertisement of a parent, it replies with its advertisement and its reachability summary



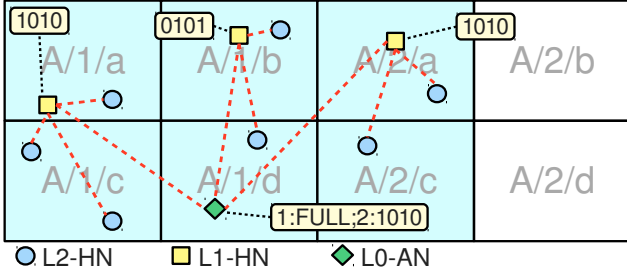


Figure 4. Encoding of reachability summaries

on the reverse path. The reply is randomly delayed to reduce the risk of message loss through collisions.

We encode the summaries efficiently using a bit-vector. A node sorts its sub-locations according to their unique identifier, for instance in lexicographical order. The  $i$ -th sub-location is assigned to the  $i$ -th bit of the vector. We depict a sample for this encoding in Fig. 4, where a 1 indicates a route to the respective sub-location. In addition, the case when a node knows a route to all of its sub-locations can be encoded by setting a single flag (*FULL*) and skipping the bit-vector. To further limit the size of summaries at level  $n$ , locations below level  $n + k$  can be omitted, leading to false positives that need to be resolved at a lower level. The summary size is limited by the number of locations in the SLM, e.g., in case of 1000 locations the size is limited to 125 Bytes.

In addition to the NHG we aim to detect sibling *ANs*, i.e., *ANs* of the same location. In principle, a node that receives an advertisement for a location for which it already knows another valid route, forwards this advertisement to the *AN* of this route. For efficiency reasons, we restrict this sibling detection to *ANs*. With this mechanism, sibling *ANs* get to know each other. Especially, *ANs* at the root level need to know their siblings, because no higher level *AN* is available with more global knowledge.

## V. EVALUATION

In this section, we evaluate the performance of our symbolic anycast routing algorithm (denoted as SAR). We implemented the following variations using the network simulator ns-2:

- **SAR:** The mesh nodes send advertisements and build up the routing structure as described in Sec. IV. However, we leave out the reactive route discovery mechanism (see Sec. IV-B3) to get unbiased results for the performance of the proactively sent routing control messages.
- **FLAT:** In contrast to SAR, advertisements are only sent for leaf locations, i.e., no NHG is established and, therefore, routing is done in a greedy way as explained in Sec. IV-B2. If the greedy mode fails, the message is discarded.

We evaluated these approaches with respect to packet delivery ratio, routing overhead, and path length.

- **Packet delivery ratio:** The ratio between successfully delivered messages and the number of initiated message transfers.
- **Routing overhead:** Average number of routing control messages sent to build up the routing structure per node and second. This metric includes advertisements, replies to advertisements, and forwarding of advertisements to siblings.
- **Path length stretch:** The average path length of successfully delivered messages divided by the minimum path length, according to the network topology.

To determine the performance according to these metrics, each node sends a message with maximum priority every ten seconds to a randomly chosen destination location within its own partition. The payload size is set to 100 Bytes representing for instance short location-based notifications. To prevent this measuring to interfere with the mechanisms for routing structure maintenance, we do not simulate collisions in message transmission. Therefore, messages delivery is only affected by errors in the routing structure, which allows for measuring unbiased routing performance.

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 in total. On the lowest level, this three level model consists of locations of different sizes: small rooms, medium-sized floors, and four large inner courtyards. The LNG is modeled based on adjoining locations. The mesh nodes store a copy of the SLM and they know their current position. Unless stated differently, nodes randomly select a destination location and move with pedestrian speed towards it. Then, after a pause time between one and five minutes, they select another destination and move towards it.

The ns-2 extension of a 802.11b interface is configured to a bandwidth of 11 MBits and a default maximum transmission range of 15 meters. All simulations have a duration of 600 seconds and the reported values are averaged over at least 15 different simulation runs.

### A. Stationary Scenario

In this experiment we first study the performance with stationary nodes to get results that are not biased through node mobility. Therefore, we measure the percentage of delivered messages and the path length stretch for different numbers of nodes in the network. Although no periodic retransmission of advertisements is necessary for the effectiveness, we set the advertisement interval to 32 seconds to get averaged results that are more expressive. In addition, the reported values are averaged over 100 simulation runs.

Fig. 5a shows the delivery rate for different numbers of nodes in the network. SAR achieves to deliver always

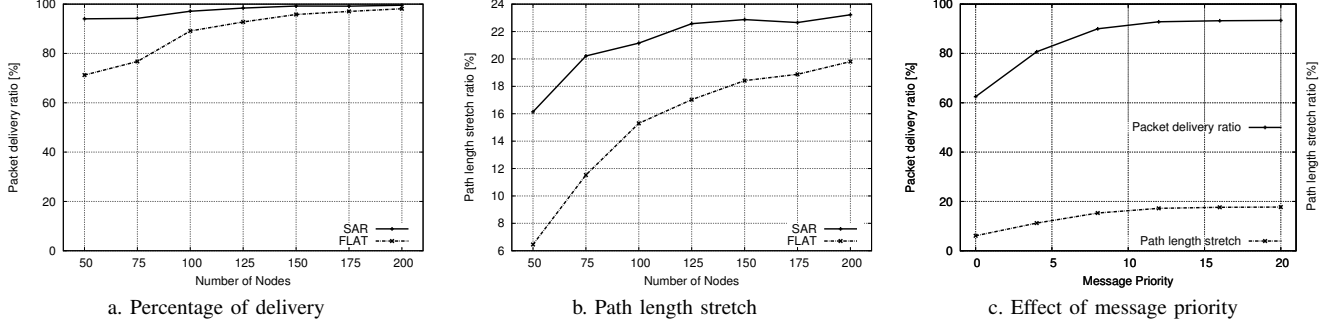


Figure 5. Stationary scenario with transmission range 15m.

more than 95% of the messages. This number increases when more nodes are in the network to nearly 100%. 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, as expected, below that of SAR, because greedy routing suffers from void areas in the network. Since perimeter routing is not applicable due to the inaccuracy of position information, a message is discarded if no neighbor is at least as close to the target as the current node. 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 in the network, 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.

Fig. 5b depicts the path length stretch compared to the minimum path length for different numbers of nodes in the network. FLAT achieves a lower path stretch compared to SAR. This is due to the property of the greedy forwarding: if it successfully delivers a message it achieves this on a 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 path length stretch, the simulation results show that optimized forwarding achieves to limit the stretch ratio to a 23% bound of the minimum path length. The reason for both approaches to perform better with fewer nodes in the network is the reduced redundancy of paths. That is, in case of fewer alternative paths it is more likely that the shortest path is chosen.

In Fig. 5c, we study the effect of the message priority value. We measure delivery rate and path length stretch for different priority values in simulation runs with 50 nodes. We choose this low number to increase the ratio of partitioned locations to see the effect of the priority onto the robustness of our approach. Obviously, the delivery rate

suffers from low priority values. With a priority of zero, the delivery rate is more than 30% lower compared to a priority of 20. The distance of an *AN* to its parent grows, on average, exponentially with its level in the hierarchy. Therefore, the delivery rate depends logarithmically on the priority value.

The path length stretch shows a similar behavior. When the priority is low, fewer messages are forwarded through possibly long detours through the hierarchy. In addition, when the delivery rate is low, the average path length is reduced resulting in a reduced path length stretch.

### B. Mobile Scenario

Now, we study the performance with mobile nodes. We investigate the effect of the advertisement interval on the delivery rate, the routing overhead and the path length. Since network dynamics are high when nodes move at pedestrian speed while the transmission range is limited to 15 meters, this scenario shows the behavior of our algorithm under challenging conditions. The number of nodes is set to 100.

Fig. 6a depicts the delivery rate. Similar to the results of the previous section, SAR performs better than FLAT. Both approaches depend on the advertisement interval. An interval of two seconds is small enough to almost fully compensate the mobility, i.e., the delivery rate is only slightly lower than in the experiment with stationary nodes. The delivery rate drops when *AN*s send advertisements at a lower rate.

The effect of the advertisement interval on the path length stretch is depicted in Fig. 6b. The gap between SAR and FLAT is caused by the same reasons as in the stationary experiment. More interesting is the behavior that the path length stretch is increased with the interval. This is due to the increased probability of route breaks. Consequently, longer alternative routes were chosen by the algorithm. This effect allows to trade-off cost of proactive routing overhead for the cost of reactive message forwarding. This effect also explains the small drop of the delivery rate (cf. Fig. 6a).

Fig. 6c shows that the routing overhead increases with the advertisement rate. However, FLAT sends less management messages, because advertisements are only sent for the leaf locations and because no hierarchy needs to be maintained. Although the routing overhead of SAR is higher than that of

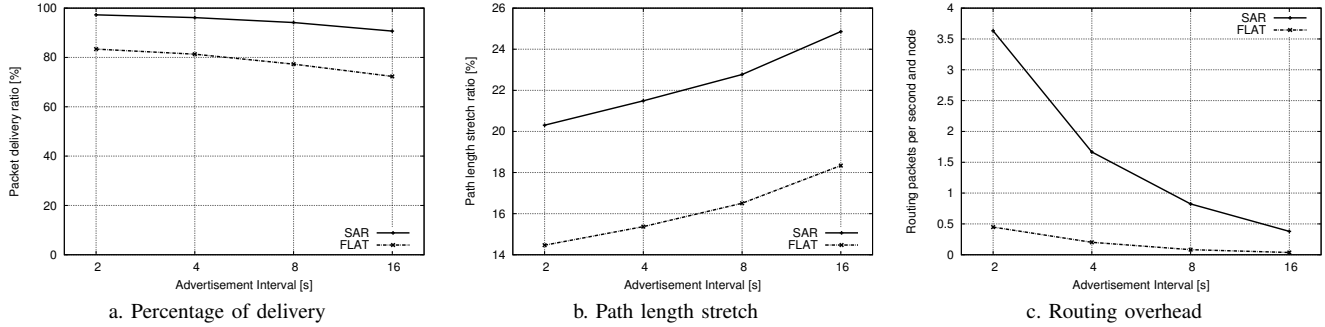


Figure 6. Mobile scenario with transmission range 15m.

FLAT, it achieves a performance nearly as good as without mobility with an interval of two seconds and at a cost of only about 3.5 messages per node and second. With an interval of 16 seconds SAR still achieves to deliver more than 90% of the messages with a routing overhead of less than 0.5 messages per node and second. With this small proactive overhead the number of expensive reactive flooding-based route discoveries can be significantly reduced.

## VI. CONCLUSIONS

In this paper we proposed routing algorithms for WMNs for sending messages to symbolically addressed locations. Our approach is based on a hierarchic routing structure and a connectivity graph between dedicated nodes, both proactively maintained and structured according to a simple symbolic location model. Message forwarding is done greedily along paths of the connectivity graph and if this fails, through the hierarchic routing structure. We showed that routing achieves high message delivery rates at low routing overhead in terms of routing messages and path length stretch.

In future work we plan to improve our approach further by dynamically integrating network connectivity information between nodes into the connectivity graph that currently is defined solely on static location information. Furthermore, we plan to extend our work on outdoor scenarios.

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