Fuzzy Logical Coordinates and Location Services for Scalable Addressing in Wireless Networks

Hanno Wirtz, Muhammad Hamad Alizai, Klaus Wehrle
Chair of Communication and Distributed Systems (ComSys), RWTH Aachen University, Germany
firstname.lastname@comsys.rwth-aachen.de

***Abstract*—Multi-hop wireless networks, such as ad-hoc and mesh networks, suffer from permanent topology dynamics due to unstable wireless links and node mobility. Stable addressing, as needed for reliable routing, in such evolving, challenging network conditions is thus a difficult task. Efficient multi-hop wireless communication in these networks then requires a fully decentralized, scalable routable addressing scheme that embraces network dynamics and dynamically recovers from failures.**

This paper explores the feasibility and limits of Mobile Probabilistic Addressing (MPA), a novel addressing approach in IEEE 802.11-based multi-hop wireless networks. MPA is based on a probabilistic addressing paradigm that derives statistical distributions of hop distances between nodes to i) assign fuzzy routable regions to nodes instead of discrete addresses, and ii) provide a distributed storage service to store and retrieve node addresses. We evaluate MPA in simulation and in an 802.11 wireless mesh network of 51 nodes. Our results highlight the graceful topology maintenance and recovery of MPA in challenging networking conditions due to node mobility and unstable link conditions. Precisely, we observe that, when compared with the state-of-the-art, our proposed mechanism achieves an order of magnitude fewer address changes in the network translating into less overhead traffic and high packet success.

I. Introduction

Assigning routable addresses to nodes in multi-hop wireless networks such as ad-hoc and mesh networks is challenging. Apart from the inherent instability of wireless links, node mobility is a prominent, complementary factor that prompts unpredictable topological changes. In addition to link dynamics, these further complicate the provision and maintenance of a reliable addressing and routing topology in dynamic networks. This is because, perceived changes of node locations, whether due to link and node dynamics, typically cause the addressing scheme to trigger a change of its assigned address. Such address chances are not desired for two main reasons. First, each change of a node address sparks updates of this address and subsequent address queries across the network, resulting in substantial and expensive traffic overhead. Second, packets routed towards the respective node might never reach it due to the outdated address and typical impracticality of recovering previous addressing topologies.

With regard to existing addressing approaches, the flat and distributed topology and dynamics of wireless multi-hop networks require dedicated approaches. For example, while still used for higher-layer naming purposes, hierarchical addressing schemes such as IP can not reflect changing, distributed topologies and require centralized control, such as in DHCP, to carefully (re-)allocate addresses in case of network dynamics such as link failures. To incorporate the underlying topology, network characteristics, and notion of routing costs, geographic routing, e.g., GPSR [1] may be employed to achieve scalable routing in wireless networks. However, efficient geographic routing is dejectedly dependent upon careful (re-)configuration, may require modifications in the commodity hardware (i.e., to install GPS), and cannot accommodate large scale mobility.

Recently, the concept of location-free or logical coordinate addressing has received much attention. Logical addressing assigns routable addresses to nodes based on the underlying connectivity graph and their logical location with respect to neighboring nodes. Nodes can thereby autonomously determine their own addresses without centralized mediation. However, while meeting the requirements of wireless multi-hop addressing for routing, the problem of arbitrary address changes remains unsettled, especially in case of node mobility in ad-hoc and mesh networks.

Extending our work on location-free and probabilistic addressing [2] in static sensor nets to dynamic networks with node mobility, we thus propose a fuzzy addressing scheme that deviates from fixed, discrete addresses but allocates routable regions to nodes. In Mobile Probabilistic Addressing (MPA), regions absorb network dynamics to keep node addresses valid while they remain within a region. Each region is defined by the statistical distribution of hop distances of the respective node to a set of landmarks in the network. Indeed, a node needs to update its address in the distributed network-wide address-database only when leaving its region.

Overall, this paper makes the following key contributions:

- We propose MPA, a resilient routable addressing paradigm and distributed storage service, for challenging network environments of ad-hoc and mesh networks.
- Extending the basic probabilistic addressing scheme from the original low power and static IEEE 802.15.4 network scenario, we demonstrate that MPA is equally relevant for and applicable to the characteristics of IEEE 802.11-based networks, and thus, possesses a broader relevance in the wireless domain. Especially, we evaluate MPA's ability to account for node mobility in and outside of the networks addressing structure.
- Based on our evaluation of MPA in simulations and a real-life 802.11 testbed, we show that MPA outperforms state-of-the-art location-free addressing schemes by i) reducing the frequency and traffic overhead of address up-

dates, ii) decreasing the number of transmissions required by a packet to reach its destination, and iii) offering high packet delivery rate even under node mobility.

In Section II, we give an overview over the background, concept and related approaches of location-free, probabilistic addressing. We present the distinct parts in our design of MPA for dynamic ad-hoc and mesh networks in Section III. Section IV evaluates the characteristics of MPA in simulation as well as its performance and benefits in comparison to existing addressing schemes in real-world 802.11 and 802.15.4 networks. We conclude the paper in Section V and discuss future work, notably the combination of MPA addressing with existing multi-hop routing protocols.

II. Overview

The are a few basic ingredients of the location-free addressing domain that are essential to grasp the material of this paper. Therefore, in this section, we briefly revisit location-free addressing before highlighting related work and summarizing the concept of probabilistic addressing and how we craft it into MPA to meet the challenges of 802.11 multi-hop networks.

A. Background

A multi-hop wireless network (cf. Figure 1(a)), such as an ad-hoc or mesh network, is a collection of nodes sharing a wireless broadcast medium. Nodes thus are connected with each other through a very large number of links with varying link qualities. Unlike wired networks, the dilemma in wireless networks is to decide which links and paths to use for building the network topology. This problem has been dealt with quite extensively in the past decade, starting from academic solutions [3], [4] that later developed into very mature solutions [5], [6].

Regardless of which solution we choose today, the underlying technique, which is inspired by the wired network paradigm, is to build conservative spanning trees based on consistently good quality links in the network. For example, Figure 1(b) depicts one such solution based on the logical coordinate based addressing and routing paradigm: It determines best links in the network using, for example, link quality estimation [7], [8], and converges routing to very few paths (basically just a single path) between two communicating nodes in the network. Once the link selection dilemma is solved, assigning routable addresses to nodes proceeds by determining hop distances of nodes from a set of designated landmarks (x, y, z in this case). In other words, nodes build multiple trees rooted at landmarks. Hence, a node location is an n-dimension address vector of the form $< q_1, ..., q_n >$, where q_i defines the hop distance from landmark i, and n is the total number of landmarks. Please note that this addressing mechanism primarily enables multi-hop routing and does not prohibit assigning further unique IDs to nodes, such as IP addresses.

B. Concept

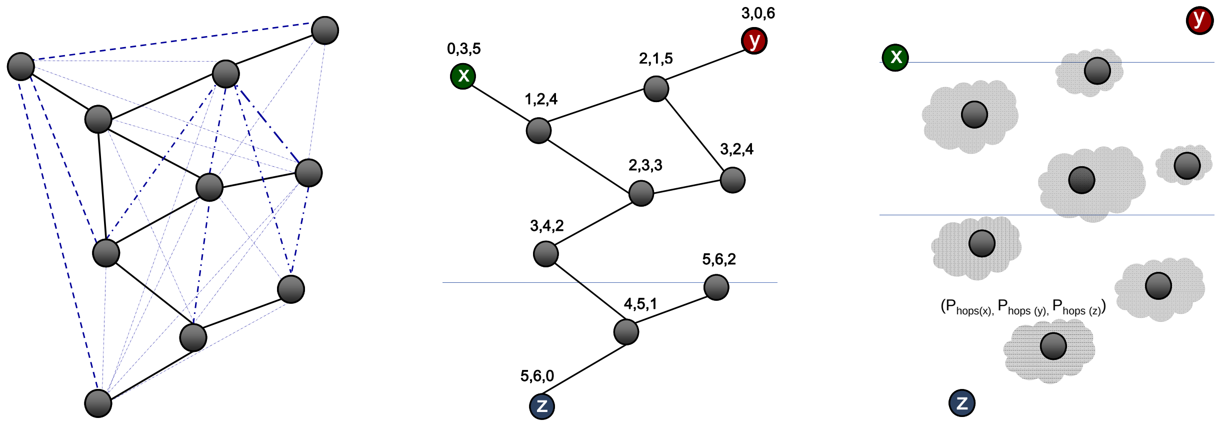
Although conservative logical addressing in principle enables wireless multi-hop routing, it has two common practical pitfalls: i) It remains highly susceptible to link instability and node mobility, and ii) it does not benefit from the wireless link diversity as only the small number of long-term stable links is regarded, aggravating the effects of, e.g., link failures or quality variations. For example, suppose the quality of a link between two nodes deteriorates or one of these nodes is mobile and changes its location. The resulting addressing and routing changes need to be disseminated throughout the network and will severely degrade its performance due to misrouted packets and management overhead.

In order to address these limitations of the existing mechanisms, we propose a probabilistic addressing-based [2] communication paradigm for IEEE 802.11 based multi-hop wireless networks. Such a communication paradigm, i.e. MPA, apprizes the broadcast nature of the wireless medium and does not exclude links from the communication process. It rather looks for variability patterns, that are due to node mobility and link quality variations, and locates and addresses a node based on these patterns.

There are three main elements to the MPA scheme: Firstly, it assigns **fuzzy addressing regions** to nodes instead of numerical coordinates (cf. Figure 1(c)), and hence, it is more resilient to typical wireless networking pathologies such as link variations and node mobility. For example, in MPA, a nodes address is made up by the probabilities of all possible hop distances (achieved over all the links shown in Figure 1(a)) from each landmark. Secondly, MPA proposes a **distributed storage service** to efficiently store and retrieve these probabilities (i.e., addresses). Each node voluntarily updates its address whenever it detects a significant change in its assigned region, and thus, enables other nodes to update their address books by querying the storage service. Finally, it proposes a simple **adaptive routing algorithm**, based on the absolute component-wise difference of logical coordinates [8], to resolve a complete multi-hop communication structure in wireless network.

C. Related Work

Among the prominent related research efforts, GEM [9] introduces a graph-based scalable addressing scheme. However, it has a very complex address recovery process, in which a large number of nodes in the system must recalculate their addresses in case of node mobility or link deterioration. MPA targets exactly this limitation of the existing mechanism by providing fuzzy, resilient addressing and distributed storage services and thus is more robust towards such wireless networking pathologies. LCR [10], S4 [11] and BVR [8] represent the state-of-the-art in logical coordinate based addressing. These schemes assign sharp numerical coordinates to the nodes calculated over high quality links, which are determined by the underlying link estimator. Our comparative evaluation in Section IV-B shows that MPA comprehensively outperforms these schemes in real world deployments.



(a) Wireless Network (b) Logical Coordinate Establishment (c) Mobile Probabilistic Addressing

Fig. 1. Based on the long-term quality and reliability of wireless links *(a)*, logical, location-free addressing distributes discrete coordinates among nodes with respect to a set of landmarks *(b)*, assuming stability of link qualities and thus routing distances. In contrast, MPA embraces wireless link dynamics in creating probabilistic addressing regions that are resilient to node mobility and link variations and allow resilient routing.

Furthermore, NoGeo [12], DART [13] and Hop ID [14] are among the prominent location-independent addressing schemes for ad-hoc and mesh networks. In NoGeo, nodes determine their coordinates in the Cartesian coordinate space through an iterative relaxation procedure with reference to a set of parameter nodes. Its initialization scheme requires to maintain a node state in the order of $O(n)$ on $O(\sqrt{n})$ nodes, which is neither feasible nor desirable for scalable wireless deployment. DART establishes address trees where leaves of the address tree represent actual node addresses, while each inner node represents an address subtree. However, this approach heavily emphasizes the maintenance of the address trees and is evaluated only in high-level simulations. It is not yet clear how practical this approach is with regard to the rate and magnitude of change in coordinates in real deployments. Hop ID establishes a multi-dimensional virtual coordinate at each node in relation to fixed landmarks in the network, similar to BVR. However, Hop ID induces unreasonable traffic overhead to maintain the system in normal operation, in addition to the common drawbacks of sharp numerical coordinates.

From a high design point of view, establishing routing regions around nodes resembles the routing zones as proposed in the Zone Routing Protocol (ZRP) [15]. However, in contrast to the fuzzy routing in MPA, routing zones in ZRP are cluster-like collections of nodes that are directly addressed using a reactive routing protocol. Within these zones, each node still carries a fixed identifier in a proactive routing scheme. ZRP thus differs from MPA as it does neither incorporate logical addressing nor routing zones or regions for single nodes.

III. MPA Design

The term MPA symbolizes the overall system composed of the three main elements specified in the previous section. We now detail the design of each element.

A. Fuzzy Addressing Regions

MPA shares the construction of fuzzy addressing regions with the original Probabilistic Addressing scheme [2]. In MPA, we express a node's address, i.e., its coordinates in the multi-dimensional embedding setup by the landmarks, in the form of a frequency distribution. For example, a node that knows multiple paths to a landmark in the network will, in contrast to conservative addressing approaches, not derive its address for that landmark by selecting solely the best path in terms of the offered quality or the number of hops. Rather, it will represent its address in the form of a probability that expresses all the paths and the relative frequencies at which these paths are available. Hence, the notion of path quality is automatically embedded in this address.

1) Addressing Model: In MPA, an address P of a node q is a vector of n-dimensions in the logical coordinate space, where n denotes the number of landmarks in the network.

$$P(q) =< P_1(q), \dots, P_n(q) >$$

$P_i(q)$ thereby represents the frequency distribution of hop distances from the respective node to the landmark i as observed over a certain interval m. MPA derives these distributions by gathering and interpreting regular routing updates that are exchanged among nodes. Using frequency distributions allows these addresses to remain independent of link dynamics and node mobility over a path that occur at shorter time scales. In the long run, as our results in Section IV-A indicate, node's MPA addresses stabilize themselves and are not directly affected by instantaneous network conditions.

After discussing MPA's addressing model, we now discuss how to achieve and maintain such an addressing algorithmically within a wireless networking infrastructure.

2) Address Updates: Each node in the network broadcasts a beacon after every interval t with the following information.

- **Sender ID:** An arbitrary, unique ID of the packet source.

Algorithm 1 Address update algorithm after receiving a beacon.

$add\_to\_history(current\_logical\_coordinates)$
$compute(new\_address)$
$error := chi\_sq\_test(new\_address, last\_published\_address)$
if $error > max\_error$
  then
    $send\_address\_update(new\_address)$
    $last\_published\_address := new\_address$
fi
$send\_beacon(current\_logical\_coordinates)$

- **Sequence Number:** A unique sequence number assigned by the source to each address update.
- **Logical Coordinates:** A vector indicating the minimum hop distances to each landmark in the last update interval.
- **Neighbors**: A list of nodes in the immediate 1-hop vicinity of a node, from which the source node received a beacon in the last beacon interval. This is used to identify neighbors with symmetric links.

The use of *sender ID* and *sequence number* is trivial, i.e., to identify the source of beacons and uniquely identify each beacon from a particular source, respectively. The size of the beacon-packet depends upon the number of landmark nodes in the network and the number of neighbors.

3) Address Calculation: At the end of each update-interval t, i.e., right before sending a beacon for the next interval, a node first derives new *logical coordinates* by calculating the minimum hop distances to each landmark in the network. To ensure uniform routing progress over these distances, a node will only include neighbors with which it shares a symmetric link for calculating these minima. Using the calculated logical coordinates and its history m of logical coordinates, a node then updates its MPA address, removing the oldest logical coordinate from the history. We use a moving average over a history of m intervals to calculate MPA addresses, i.e., fuzzy addressing regions.

After calculating the new MPA address, a node will only trigger an update in its address across the network, if the previous and the newly calculated address are statistically significantly different, i.e., belong to different regions. The pseudo-code for the address update mechanism is show in Algorithm 1. We use Pearson's χ^2-test to determine the statistical difference between the new and old address. The χ^2-test is based on a test statistic that measures divergence of the observed data from a given null hypothesis.

B. Distributed Storage Service

Establishing a scalable distributed storage is pivotal in self-organizing, decentralized ad hoc and mesh networking setups. We need a storage service to allow the nodes to efficiently publish their own and retrieve other node's routable addresses. A number of design choices are available in developing such a service with varying levels of reliability, efficiency, and communication overhead. For example, a straight forward solution could be that when a node changes its address, it proactively floods the whole network to update all the participant nodes. However, this is prohibitive in terms of communication overhead and scalability. On the contrary, a node could simply ignore sending such updates. This is inefficient and, in the worst case, produces the same overhead as the previous approach due to address requests initiated by other nodes.

Our initial design goals for the prototypical implementation of a distributed storage service emphasize simplicity and low communication overhead:

- Each node stores, i.e., publishes, its address at the coordinate-wise nearest landmark, the *home landmark*. The home landmark is the nearest location in the network that is globally known, as all nodes in the network know the addresses of landmarks.
- If a node wants to communicate with another node whose address is not known, it queries its own home landmark. This landmark then either delivers the address directly or queries other landmarks iteratively to avoid flooding the networking with address queries.

Please note that our design choice of using the home landmark as the storage point is deliberate for this scenario because of i) its simplicity in design, implementation, and communication, and ii) its minimization of the overhead traffic associated with address updates. For example, hash function-based distributed storage approaches that map node IDs on to their address storage location aim to ensure a fair distribution of storage load among landmarks. However, it is inefficient in terms of guaranteeing a nearby storage point that can minimize the overhead of expensive address updates. In our previous work [2], we have empirically observed that, in challenging networking scenarios, this overhead could make up a significant portion of the overall network traffic. Moreover, a fair distribution of landmarks[1] across the network automatically ensures a balanced storage load at all landmarks.

C. Adaptive Routing

Routing is performed greedily over the logical coordinate space by computing the absolute component-wise difference of MPA addresses between the neighboring nodes and destination. The neighboring node with the minimum remaining difference is then selected as the best next hop. Algorithm 2 outlines our routing decision making process. If the destination is among the node's 1-hop neighborhood, the packet is directly delivered to it. Otherwise, the node queries the destination's coordinates and determines the closest neighbor to the destination. In case, if there is no neighbor closer to the destination in the logical coordinate space than the node itself, the packet is delivered using a *fall-back* mode [8]: The packet is forwarded to the landmark closest to the destination. The landmark then initiates a scoped flooding that is restricted by the number of hops the destination is away from that landmark. The two

[1] Landmark selection is a well addressed research problem and beyond the scope of discussion in this paper.

Algorithm 2 Routing algorithm

```
if is_neighbor(dest)
  then send_directly(packet, dest)
  else
      if dest_coordinate_unknown()
        then request_coordinate()
        else
            next_hop := closest_neighbor_to(dest)
            if dist_to(dest) < dist(next_hop, dest)
              then send_in_fallback_mode(packet)
              else send_directly(packet, next_hop)
            fi
      fi
```

important factors that influence MPA's routing decisions are *link availability* and *link asymmetry* of a neighbor at the time of sending a packet.

1) Link Availability: First, we consider the availability, and transitively its reliability, for transmission, which has to be checked for every link with a particular neighbor. We derive and keep a minimal reception history of past transmissions, based on which we declare a link reliable for transmission. This is because our design objective is to allow for maximum adaptability to the underlying link conditions in the network. MPA allows us to achieve this objective, while it defines addresses in the form of probabilities and decouples packet forwarding from addressing in the network. To check for the availability of a link, we adapt our previous approach of link estimation [16], which determines the fate of the future transmission over a link on the basis of the last three transmissions over the same link. We introduce an *aging* factor for each neighboring link: A link is only considered reliable for transmission if it has an age of 3, i.e., if the last three beacon-packets were successfully received over that link. However, these packet forwarding decisions do not change the probability distribution of a node's location. Hence, MPA allows us to maintain a stable addressing while adapting transmissions in routing quickly to the current link conditions, i.e., over the duration of three beacon-packet intervals.

2) Link Asymmetry: Link asymmetry is a major issue in wireless networks where routing demands each packet to be acknowledged by the receiving neighbor. In MPA, each node S maintains a set of those neighbors to which it has symmetric links. A neighbor T is considered to be alive and on a symmetric link as long as at least one of its beacons arrives within m beacon intervals and lists S as a neighbor of T. Consequently, a neighbor's validity expires automatically after m beacon intervals, if no beacon is received from it during this time. Another mechanism to test for link symmetry is to actively monitor ACKs over a link. ACKs are a useful and automatic test for link symmetry and are also employed in our prototype implementation.

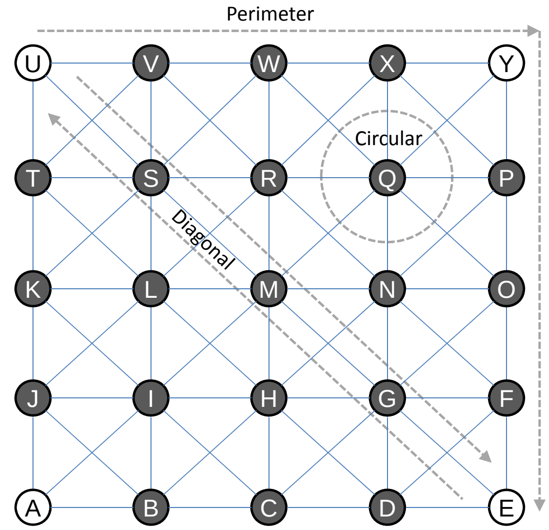


Fig. 2. Simulation setup and mobility patterns.

IV. MPA Evaluation

We now focus on the evaluation of MPA in IEEE 802.11-based multi-hop networks. We note that this evaluation only aims at establishing the basic understanding and providing initial insights into the generality and feasibility of MPA in wireless networks. MPA is implemented for the OMNeT++ simulator, TinyOS and Linux-based wireless network devices.

We first evaluate MPA from a mobility perspective to see if it can be considered as a suitable candidate for routing in ad-hoc and mesh networks with mobile nodes. To this end, we use the OMNeT++ simulator to create and evaluate different mobility patterns to judge MPA's performance. Afterwards, we perform a comparative evaluation of our actual implementation of MPA in the UMIC mesh network [17] to assess the impact of real-world physical wireless links and their dynamics on distributed addressing. UMIC is a Linux-based wireless network deployed at RWTH Aachen University. It consists of 51 IEEE 802.11a/b/g mesh routers deployed over various rooms and floors at the department of computer science. Each node has a 500 MHz CPU and 256 MB of RAM.

A. MPA vs. Mobility

In this section we evaluate MPA in a simulated mesh network with mobile nodes. A typical mesh network consists of two types of nodes, *mesh nodes* (or routers) and *mobile clients*. Mesh nodes are stationary and form the basic infrastructure of a mesh network. These nodes provide services, such as Internet access, and can communicate with each other, possibly over multiple wireless hops. Mobile clients, on the other hand, are not permanent members of the network. These nodes can join the network to use a service and are free to move within the covered range of the mesh network. They may thereby be restricted to mere client functionality, i.e., only accessing but not contributing to the network topology, or may become part of the mesh topology to add to the network. In MPA, we

Property	Static	Circular	Perimeter	Diagonal
Delivery rate	1	0.96	0.90	0.88
Average Hop-count	4	3.96	4.95	3.52
% Fallback-mode packets	0	1.8	3.75	1.5
Address change rate	3.48	8.58	12.50	12.42

TABLE I
SUMMARY OF MOBILITY RESULTS

choose the latter, more challenging case as mobility support is an inherent design goal. In this, we allow mobile clients to be part of the logical addressing scheme and to assign themselves a routable address. As this also influences the addresses of mesh nodes in the vicinity of the client, MPA has to incorporate both the initial addressing as well as address maintenance under client mobility.

One of the key challenges in wireless networks is to support mobility while maintaining a high end-to-end delivery reliability. We believe that MPA can support mobility in mesh networks because of its fuzzy addressing scheme that incorporates multiple paths leading towards a node in its address distribution. Therefore, we perform some basic experiments to asses the utility of MPA in such mobile environments.

We create a simple 5x5 linked grid topology of static mesh nodes in OMNeT++, as shown in Figure 2. Nodes A, E, U and Y are the designated landmarks. In this underlying mesh-infrastructure topology, we add one mobile node to the network with the following mobility patterns (cf. Figure 2).

- **Circular:** The mobile nodes revolves around one mesh node (i.e., node Q) in the network.
- **Perimeter:** The mobile node follows the perimeter of the network.
- **Diagonal:** The mobile node moves across the network forming a diagonal path.

Among the three mobility patterns, *diagonal* is the most challenging for to reasons: i) The large variation of movement induces address updates, address maintenance, and packet delivery to occur over across the complete network, thereby affecting a large number of nodes and requiring numerous multi-hop transmissions which in turn induces interference for subsequent transmissions, and ii) the client movement while participating in the network and addressing topology significantly impacts the logical addresses of the meshnodes. This is because the mobile client creates and advertises additional paths towards landmarks while moving through the network.

We did not employ any transport layer protocol, such as TCP, to ensure that the delivery rates of MPA are not influenced by the end-to-end retransmissions mechanisms of these protocols. In detail, our experimental setup has the following key characteristics: i) Node A acts as a sender in all experiments. ii) Each node sends a beacon every 2 seconds. iii) The payload length of each packet is 800 bytes to emulate a medium-size payload packet without risk of fragmentation. iv) Each experiment lasts for 200 seconds,which is the time it takes the mobile node to complete one traversal of the path.

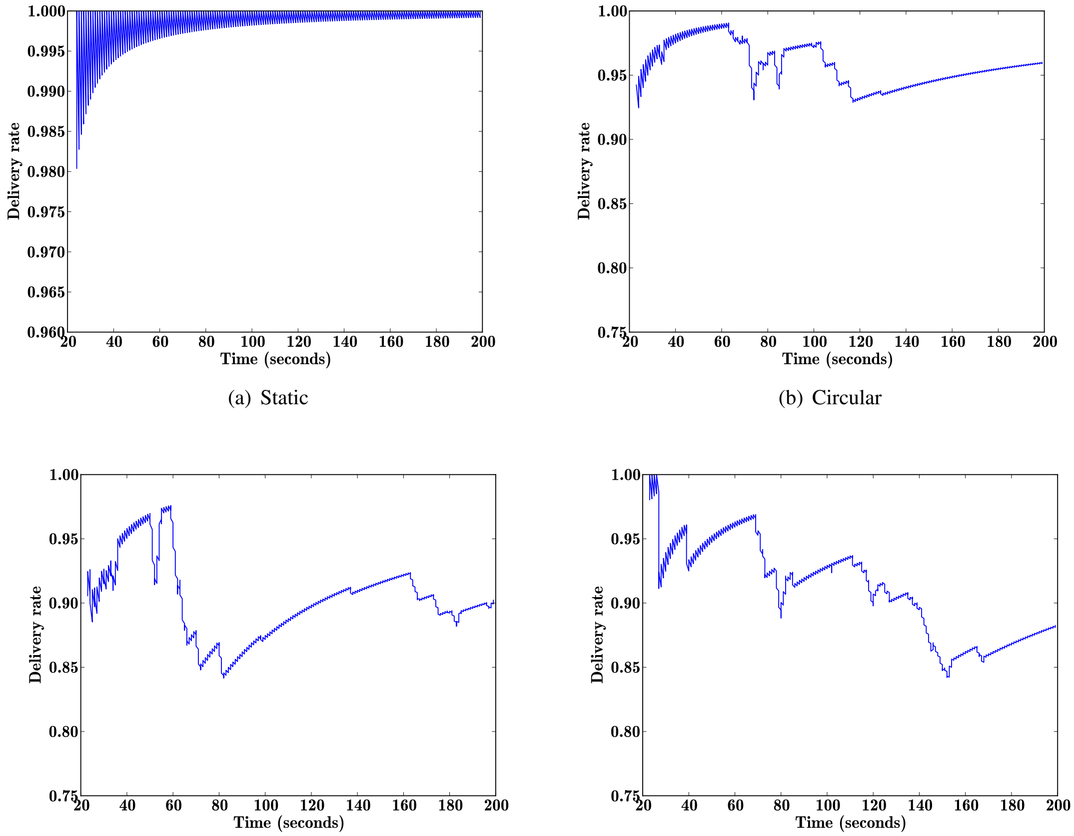
Table I summarizes the results for the different applied mobility patterns. In order to establish a basis for comparison, we first performed an experiment to observe the delivery rate of MPA in a static mesh network, i.e., when the client node is not moving. Figure 3(a) shows that MPA achieves a packet delivery rate of $\sim$100% in the static network scenario. Furthermore, as the mobile client is always reachable via its published address, packet delivery in this scenario never regresses to the fallback mode. This result implies that, in experiments which a mobile client under different mobility patterns, the incurred packet loss will be due to the network dynamics introduced by the mobile node.

We further evaluate the address change rate over the course of the simulation, measured in the percentage of beacon intervals in which a node needs to change its address. We refer to Section III-A2 for the definition of address change rate in the context of MPA routing and addressing. In the static scenario, a node only experiences an address change rate of 3.48%. We attribute this very low rate to the fact that simulated wireless links typically do not reflect the same dynamics as physical links. Furthermore, there is no additional traffic in the network.

Figure 3 shows, in high resolution, that MPA quickly achieves and maintains a very high delivery rate in all evaluated scenarios. While the circular mobility does not induce significant packet loss due to its very restricted movement and therefore limited change in the logical address, the more extensive movement in the perimeter and diagonal patterns causes more extensive drops. This effect becomes visible also in the perceived higher address change rate in these two movement patterns, as the mobile client frequently changes its neighboring nodes. It thus needs to assign itself a new coordinate to remain reachable in the network.

However, we can differentiate the perimeter and the diagonal movement pattern by their influence on the *overall* address distribution. This is because the mobile client can simultaneously impact the coordinates of all the nodes in the network, and thereby the routing topology. In the *circular* and *perimeter* mobility patterns, the mobile client does not necessarily influence the coordinates of the nodes, because it is either limited to a certain node neighborhood or, by moving outside of the network, does not influence the set of links between nodes in the interior. For example, a neighboring node will only change its coordinates if the mobile client offers a shorter path towards a landmark than the current paths in its address distribution. This rarely happens for *circular* and *perimeter* mobility patterns.

Moreover, we can see a trend in the delivery rate for all the three mobility patterns: It is that there is a sudden drop in the delivery rate followed by a sustained improvement. For example, in the case of *circular* and *perimeter* mobility patterns, this drop occurs at time 120s and 80s, respectively. However, for diagonal mobility, this trends repeats more often. This sudden drop in the delivery rate occurs due to sudden address changes in the network triggered by the movement of mobile node. Similarly, the sustained improvement in delivery rate afterwards points to the quick recovery of MPA from such



(a) Static (b) Circular (c) Perimeter (d) Diagonal

Fig. 3. Evaluating MPA in a simulated mesh network with different mobility patterns. MPA maintains a very high delivery rate over all mobility patterns.

address dynamics in the network.

Overall, these results demonstrate the principle feasibility of MPA in multi-hop wireless networks.

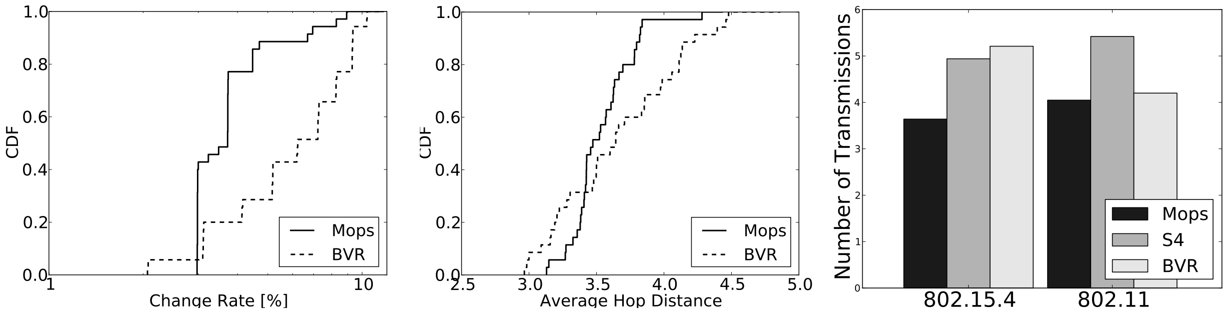
B. Testbed Evaluation

Our UMIC mesh network evaluation compares MPA with BVR and S4, which are considered the state-of-the-art in logical coordinate-based addressing and routing in wireless multi-hop networks. This part of our evaluation focuses on the following three important aspects:

Address Change Rate: Similar to the simulation-based evaluation, we are interested in the frequency of address changes induced by the instability of wireless links. Figure 4(a) thus shows the cumulative distribution of address change rates over all stationary nodes in the IEEE 802.11 UMIC network. Address change rate is defined as the number of beacon intervals in which the nodes change their addresses throughout an experiment. This result clearly shows that MPA outperforms BVR in IEEE 802.11 networks. This is due to MPA incorporating link dynamics and the resulting changes in the topology in contrast to discrete coordinates in BVR that instantly need to be adapted and thus change. For this evaluation, we compare MPA only with BVR because S4 uses BVR's addressing mechanism and only differs in how routing is performed on top of these coordinates.

Hop Distance: The hop distance metric determines the number of hops between a node and all landmarks in the network. Figure 4(b) depicts the CDF of average hop distances to all landmark nodes. It can be seen that MPA achieves lower hop distances than BVR, as MPA always enables shortest paths to dominate its coordinate distributions. Whereas, BVR only selects good quality paths that are chosen based on longer lasting PRR-based link estimation. Hence, MPA reduces the overall distance of nodes from landmarks (i.e., the depth of the tree in conventional approaches). In routing towards or from a landmark, this results in reduced hop distances and thus a reduction of the number of transmissions required by a packet. Especially, the short-term link estimation technique employed in MPA helps to accurately predict the fate of the transmissions on shorter but more unreliable paths.

Routing Cost: We finally evaluate if the increased address stability and smaller average hop distances of MPA addresses and our adaptive routing algorithm benefits the overall routing performance in the network. To abstract from a single network topology (and lacking another 802.11 mesh network), we deploy and evaluate MPA on an 802.15.4-based sensor network. Next to a different network topology, this also allows assessing the benefits of or resilient addressing scheme on



(a) Coordinate change rate (b) Average hop distance (c) Average transmissions per packet

Fig. 4. Addressing results from IEEE 802.11 test. PAD maintains its superior performance across multiple wireless network classes.

a platform with different physical and medium access layer characteristics.

Figure 4 summarizes our results for the routing cost evaluation on two different radio technologies. It is clearly visible that MPA indeed reduces the number of transmission in the network and comprehensively outperforms both BVR and S4 both in IEEE 802.15.4 and 802.11 networks. This is due to MPA's ability to better reflect and incorporate changes and dynamics in the network topology that are relevant for routing. Short-term loss of link quality to a given neighbor, for example, will be treated as a single underperforming link in contrast to treating it as a reason to change the whole address and thus the routing topology.

V. Conclusion and Future Work

We presented a robust and scalable addressing mechanism for wireless multi-hop networks that incorporates node mobility with negligible maintenance overhead. When compared with other addressing mechanisms, MPA increases the stability and reduces the magnitude of change in addresses. An adaptive routing strategy over MPA allows quick adaptation of the routing paths based on very recent link conditions. Our results from testbed environments demonstrate that even an unoptimized version of routing over MPA can enhance packet delivery over multiple hops. Similarly, our tests under challenging environments such as in MoteLab show that MPA can realize its advantages in real world deployments.

We are still in the early phases of investigating suitable routing algorithms and distance functions, such as Gaussian distance, that can operate on MPA's addresses even more efficiently. So far, our evaluation on IEEE 802.11 based testbeds only compares MPA with virtual coordinates based protocols such as BVR and S4. A thorough comparative evaluation with IP based multi-hop routing protocols, such as OLSR and AODV, is important to establish a deep understanding of MPA's performance.

References

[1] B. Karp and H. T. Kung, "Gpsr: greedy perimeter stateless routing for wireless networks," in *MobiCom*. ACM, 2000.

[2] M. H. Alizai, T. Vaegs, O. Landsiedel, S. Goetz, J. A. B. Link, and K. Wehrle, "Probabilistic addressing: Stable addresses in unstable wireless networks," in *IPSN 2011: Proceedings of the 10th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2011.

[3] C. E. Perkins, E. M. Royer, and S. R. Das, "Ad hoc on-demand distance vector (aodv) routing," in *2nd IEEE Workshop on Mobile Computing Systems and Applications*, 1999.

[4] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*. Kluwer Academic Publishers, 1996, pp. 153–181.

[5] I. Chakeres and C. Perkins, "Dynamic MANET on-demand (DYMO) routing," Internet Draft, Mar. 2009. [Online]. Available: http://tools.ietf.org/html/draft-ietf-manet-dymo-17

[6] T. Clausen and P. Jacquet, "The optimized link state routing protocol (OLSR)," RFC 3626, Oct. 2003. [Online]. Available: http://www.ietf.org/rfc/rfc3626.txt

[7] R. Fonseca, O. Gnawali, K. Jamieson, and P. Levis, "Four-bit wireless link estimation," in *HotNets*, 2007.

[8] R. Fonseca, S. Ratnasamy, J. Zhao, C. T. Ee, D. Culler, S. Shenker, and I. Stoica, "Beacon vector routing: Scalable point-to-point routing in wireless sensornets," in *NSDI*, May 2005.

[9] J. Newsome and D. Song, "Gem: Graph embedding for routing and data-centric storage in sensor networks without geographic information," in *SenSys '03*, 2003.

[10] Q. Cao and T. Abdelzaher, "Scalable logical coordinates framework for routing in wireless sensor networks," *ACM Trans. Sen. Netw.*, vol. 2, no. 4, 2006.

[11] Y. Mao, F. Wang, L. Qiu, S. S. Lam, and J. M. Smith, "S4: Small state and small stretch routing protocol for large wireless sensor networks," in *NSDI*, 2007.

[12] A. Rao, S. Ratnasamy, C. Papadimitriou, S. Shenker, and I. Stoica, "Geographic routing without location information," in *MobiCom*, 2003.

[13] J. Eriksson, M. Faloutsos, and S. V. Krishnamurthy, "Dart: dynamic address routing for scalable ad hoc and mesh networks," *IEEE/ACM Trans. Netw.*, vol. 15, no. 1, 2007.

[14] Y. Zhao, Y. Chen, B. Li, and Q. Zhang, "Hop ID: A Virtual Coordinate based Routing for Sparse Mobile Ad Hoc Networks," *Mobile Computing, IEEE Transactions on*, vol. 6, no. 9, pp. 1075–1089, 2007.

[15] Z. J. Haas, M. R. Pearlman, and P. Samar, "The Zone Routing Protocol (ZRP) for Ad Hoc Networks," IETF Internet Draft, Jul. 2002.

[16] M. H. Alizai, O. Landsiedel, J. A. Bitsch Link, S. Goetz, and K. Wehrle, "Bursty traffic over bursty links," in *SenSys'09*, Nov. 2009.

[17] A. Zimmermann, M. Günes, M. Wenig, J. Ritzerfeld, and U. Meis, "Architecture of the hybrid mcg-mesh testbed," in *Proceedings of the 1st international workshop on Wireless network testbeds, experimental evaluation & characterization*, ser. WiNTECH '06, 2006.