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Fast track article

Curve-based planar graph routing with guaranteed delivery in multihop wireless networks[☆]

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ABSTRACT

Localized geographic routing schemes operating on planar graphs promise scalability for use within large multihop wireless networks. However, none of the existing schemes is flexible enough to adapt the sequence of faces visited by the constructed path. Thus, real-world constraints may severely impact the network performance.

To address this problem, we extend planar graph routing to allow the algorithm to forward packets along a sequence of faces intersected by any arbitrary curve. We analytically prove that this extended scheme is loop free and allows for guaranteed delivery. Furthermore, we investigate schemes for choosing curves dealing with imperfections in the network.

1. Introduction

Geographic routing schemes that operate on local state information have been proposed to meet the challenge of scalable routing within large-scale multihop wireless networks. By utilizing local state, these schemes avoid costly exchange of routing updates, which helps conserving the limited bandwidth of wireless environments. Instead of pinpointing a node's position in the network via an IP address, geolocation serves as a location identifier and allows to forward packets towards the intended destination. In fact, following a trivial approach, nodes – without any knowledge about the rest of the network but their direct neighborhood – can relay packets to neighboring nodes that present some positive progress towards the destination in terms of geographical distance. This allows for a scalable operation within large multihop wireless networks.

The simplest form of geographic routing is greedy forwarding, where a packet is sent to the neighbor node minimizing a certain cost function (e.g. distance to the destination). However, greedy routing cannot guarantee delivery, since local minima in the graph can lead to dead ends, for example, if a node has no neighbor which is closer to the destination than itself. Greedy routing can be beneficially combined with face routing [1], which uses the direct line connecting source and destination as a reference to escape from local minima. Its key concept is routing packets along faces, which are the polygons formed by the edges of a planar network graph.

Face routing is confronted with a number of challenges if operating under realistic topology assumptions, as observed, for example, in wireless mesh/sensor networks:

- Dynamic optimization such as interference-aware or congestion-aware routing cannot easily be realized.

[☆] This paper is an extended version of Frey et al. (2012) [2], which appeared in IEEE WoWMoM 2012 and has been selected for a fast-track publication in Elsevier PMC.

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- Usage of limited resources such as the energy of battery powered nodes cannot be balanced or optimized.
- Non-cooperative or misbehaving nodes can fatally affect the resiliency of the routing system.

The above issues are particularly critical, since existing face routing schemes are non-adaptive, i.e., if the planar graph is not changing, the sequence of visited faces will always be the same. If by chance the face sequence passes a region that only allows for substandard and inferior service, the quality of the forwarding service is likewise. Even worse, adverse and hostile network conditions in certain parts of the network can disallow the packet forwarding entirely. Without additional mechanisms to control the visited face sequence, face routing is not able to deal with such challenges.

In contrast, if the visited face sequence can be adjusted, nodes can adapt to the network conditions and deviate for instance from the direct line trajectory (which is the most popular approach so far) to optimize the routing performance w.r.t. certain network constraints. For example, if most of the traffic in a battery powered network always follows the same face sequence, energy depletion of the nodes on the route might lead to network partitioning. Having the freedom to adjust the sequence of visited faces, a node could send packets over an alternative path to avoid low energy regions.

In this work we enhance localized routing schemes to follow global forwarding rules, while avoiding the inherent drawbacks of global routing schemes. In particular, we presented an approach, which expands the concept of localized geographic routing by allowing curved trajectories between source and destination. Similar to conventional face routing, our scheme maintains its locality, because it only requires nodes to know about their immediate neighbors. At the same time, our scheme allows to exercise global control over the routing/forwarding path, since nodes can define end-to-end trajectories that indirectly control which regions in the network to visit or to evade. By choosing different enough curves, packets follow different paths. In a sense, our curve-based routing can be seen as a form of geo-traffic-engineering for multihop wireless networks. In contrast to the control and optimization of traditional traffic engineering, the focus is on controlling the traffic flow with respect to geographical regions that are impacting on the performance of the multihop wireless network.

Our contribution is the design of a curve-based, localized, geographic routing scheme for planar graphs. In particular, we design a robust algorithm based on face routing and give a rigorous mathematical definition of our scheme, which enables the source of a packet to define an arbitrary curve as an abstract trajectory. We prove that the curve-based planar graph routing is loop free and allows for guaranteed delivery of packets in planar graphs. While our routing mechanism is localized, defining the curve itself might require global knowledge. However, together with a global scheme, we also discuss a distributed strategy to find trajectories. As an extension to [2], we deepen our understanding on the relationship between the shape of regions to evade in the network and the underlying planar graph. We show why approaches designed for non-planar graph routing are unsuitable and explain how to design regions in the case of face routing. Moreover, we also include an extended description of protocol operation, where we delve into the details of how to design curved trajectories efficiently. As a proof-of-concept, we implement curve-based planar graph routing and study its performance using simulation. In particular, we analyze the scenario of malicious nodes in the network. Compared to [2], we include additional experimental results which help understanding the performance of the strategies we present for finding curved trajectories.

The remainder of this work is organized as follows. Section 2 is dedicated to related work and provides a short introduction to face routing. We define and mathematically formulate the basis for our scheme in Section 3. The algorithms for curve-based routing are presented in Section 4, while in Section 5, we prove that our scheme operates loop-free and can provide delivery guarantees. In Section 6 we present our scenario for the proof-of-concept implementation. Section 7 investigates how exclusion areas must be shaped in order to guarantee that packets evade regions providing only substandard service when using face routing. We then present a detailed discussion on how to construct curved paths in Section 8, both for our distributed as well as for our centralized approach. We further design and implement a system using curve-based routing in a network simulator. We study and analyze its performance in Section 9. Finally, Section 10 presents conclusions and an outlook on future work.

2. Related work

2.1. Trajectory-based forwarding

Using trajectories or just a sequence of anchor points to guide localized geographic routing has been considered in connection with geographic greedy routing so far [3–5]. While [3] focuses on the forwarding protocol itself and thus does not delve into how the trajectories are calculated, [4,6,7] present multiple techniques for encoding trajectories. Specifically, in [7] curves based on polynomials are found using multiple linear regression. However, this approach is challenged when trying to fit complex trajectories, as the order of the polynomials becomes very large. In [4], this problem is tackled by splitting higher order Bézier curves into multiple dual-control point representations. First, the source determines a high order curve which fits the desired trajectory. This curve is then encoded into a probe packet, which is flooded in the network. Nodes close to this curve are elected as intermediate nodes and recalculate the curve segment to the next intermediate node as a dual-control point curve. Hence, the header of the actual data packet only needs to encode Bézier curves with two control points, which are updated at each intermediate node. However, the signaling and handshaking messages required during the probing phase incur a significant overhead. In [6], an analogous approach using segmented straight lines is used, i.e. instead of connecting intermediate nodes with dual-control Bézier curves, direct straight lines are used.

Yet, none of the known approaches supports curve-based forwarding while providing delivery guarantees at the same time. In fact, existing localized schemes require mechanisms to recover from the well known greedy routing failure [8].