Adaptive Algorithms to Mitigate Inefficiency in Greedy Geographical Routing

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Abstract— This letter presents theoretical basis and practical algorithms for mitigating inefficiency in greedy geographical routing, which has great application potential in large scale ad hoc networks, such as sensor nets. Simulation results demonstrate the proposed algorithms' effectiveness and the capability to provide different efficiency-overhead tradeoffs.

Index Terms— Wireless networks, routing, geographical routing.

I. INTRODUCTION

GEOGRAPHICAL routing [1], [2] is a routing method that uses geometrical reasoning for forwarding packets. Typically a greedy approach is used, i.e., a packet is forwarded to the node in the neighborhood that is closest in Euclidean distance to the destination. Due to its simplicity, statelessness, scalability, and robustness against movement of relay nodes, geographical routing is a highly attractive choice for ad-hoc networks consisting of a large number of devices with constrained resources, such as sensor nets. The prerequisite of geographical routing is that nodes know their actual or virtual locations, which can be made available with or without using GPS [3]. It is reasonable to expect that the importance and applicability of geographical routing will increase with the growth of location-aware applications and large-scale networks of embedded devices.

However, the greedy approach used in currently proposed geographical routing schemes [1], [2] can produce inefficient routes. This typically occurs when no neighboring node is closer to the destination than the current node, i.e., when a void area, where no node exists, is encountered. In such case, greedy forwarding can transition to the *perimeter mode* [1], in which packets are routed along the perimeter of the void until greedy forwarding becomes possible again. In presence of voids, a greedy approach becomes doubtful. In deed, voids can be quite common due to obstacles (lakes, foliage, or other inaccessible areas), non-uniform node distribution, etc. Greedy geographical routing can be utterly inefficient in navigating around voids. An artificial yet illuminative example is given in Fig. 1. The path generated by the greedy forwarding and perimeter traversal combination ($P1$) is clearly inefficient and better paths exist (e.g., $P2$ and $P3$). In this paper, we propose mechanisms to mitigate this inefficiency of greedy geographical routing.
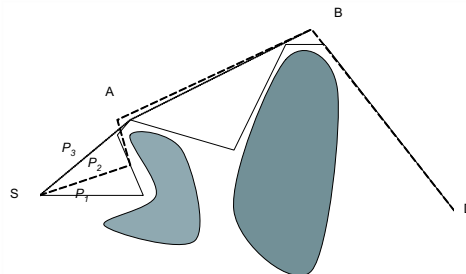
Fig. 1. Routes of three geographical routing schemes: a) greedy forwarding uses P1 (solid line); b) the single-waypoint scheme uses P2 (dashed line); c) the optimal scheme uses P3 (dotted line).

We proposed the basic scheme of adaptive geographical routing in [4]. In this letter, we further systemize the idea, provide some simulation results and show that only a few waypoints are required to achieve significant gains in efficiency. The basic scheme is as follows. A set of salient features of the network topology that are most relevant to routing efficiency are discovered in the course of a packet's journey, which are compactly encoded in the packet header and feedback to the sender either through reverse traffic or special protocol packets. Based on the feedback, the sender adapts the route accordingly. The details of features and the frequency of feedback are adjustable according to application requirement and network dynamics. Route is specified in the manner of loose source routing, i.e., by a vector of waypoints, which are the nodes the route must pass through. Between waypoints, greedy forwarding is used. By selecting different sets of waypoints, flexible, even contrived routes can be generated such as $P2$ and $P3$ in Fig. 1. Route adaptation is achieved by changing the waypoints according to the feedback. The proposed adaptive schemes are applicable to data streams that are recurrent or have a nontrivial duration, which is true to many sensor net applications, so that the cost associated with the adaptation process is justifiable. In essence, adaptation accepts the cost of maintaining vital topological state in order to attain overall efficiency. The proposed waypoint-based routing is similar with anchored geodesic forwarding of the Terminodes project [5] in that both use geographical loose source routing, the difference being that waypoints here are adapted for optimizing a route but the anchors there are used for discovering a (potentially inefficient) route (e.g., by gossiping among friends).

II. SOME THEORETICAL RESULTS

This section provides some relevant definitions and theoretical results that form the bases for the adaptive schemes
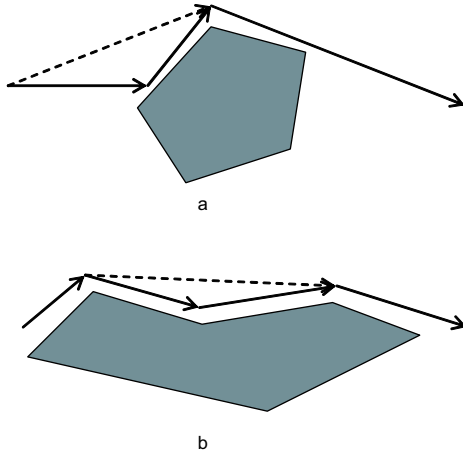
Fig. 2. Demonstration of two kinds of inefficiency: greedy forwarding (solid lines) and more efficient routes (dashed lines).

introduced in Section III. First we provide some definitions. We define a *relative coordinate system* as the one whose the x-axis is aligned with the line determined by the sender s and the receiver d. A member p in a set of points V is an $x(y)$-*extremal point* of V, if its $x(y)$ coordinate is the maximum or minimum in V. A geographical region is *convex* if all points along a straight line segment between any two points in the region are contained in the region. An alternative definition is that a region is convex if the angles spanned by the neighboring edges of a vertex and facing the inside of the region are no greater than π. A region, regardless of being convex or not, has a *convex hull*, which is defined as the smallest (in terms of both area and perimeter) convex polygon that encloses the region. We present some theoretical results below, whose proof is omitted here for lack of space but can be found in [4].

Proposition I: Geographical routing never enters the perimeter mode if both the boundary and the voids of the network are strictly convex.

Proposition II: Geographical routing can be suboptimal even if it never enters the perimeter mode.

Proposition I and *II* enlighten us as to where the inefficiency occurs in the greedy forwarding. Broadly speaking, there are two kinds of inefficiency. The first kind is late detouring, where the inefficiency originates from the packet, without foresight of the obstacles ahead, detouring at the last minute, and thus causing an unnecessarily elongated path, ref. Fig. 2 (a). The second kind is non-convex traversal, where the inefficiency comes from slavishly following the boundaries of the voids rather than taking the optimal traversal, which forms a convex hull of the voids, ref. Fig. 2 (b). *Proposition III* below provides the condition for an optimal route.

Proposition III: Optimal routing can be achieved by waypoint routing using a set of waypoints P. The optimality occurs when P, the source and the destination form either the $y > 0$ or the $y < 0$ half (in the relative coordinate system) of the convex hull of the geometrical object set S, where S consists of the source s, the destination d, and the voids between them.

Proposition IV: Geographical routing never enters the perimeter mode if the optimal routing scheme prescribed in *Proposition III* is used and the convex hull constructed is strict.

We note that not entering the perimeter mode is a very desirable characteristic since much of the difficulties associated with geographical routing occur in the perimeter mode.

III. THREE GEOGRAPHICAL ADAPTIVE SCHEMES

Based on the discussion in the previous section, we introduce three adaptive schemes with different efficiency and overhead tradeoffs.

A. Single-waypoint adaptive scheme

In this scheme, only one waypoint is used. This waypoint is the y-extremal point in the relative coordinate system in a packet's journey from the source to the destination. To calculate this waypoint, a pair of real numbers is kept in the packet header, which stores the coordinates of the temporary extremal point among the nodes visited so far. The temporary extremal point becomes final when the packet arrives at the destination and is fed back to the source as the new waypoint. This simple scheme attempts heuristically to reduce the path inefficiency associated with the largest detour with minimal overhead. In other words, this method is designed largely to deal with the inefficiency of the first kind discussed in the previous section and doing so with minimal overhead. Naturally, the single waypoint method does not eliminate all sources of inefficiency and as such is typically not optimal. An example of routes given by this method is $P2$ in Fig. 1. Note that using the single waypoint method does not prevent a packet entering the perimeter mode.

B. Optimal adaptive scheme

This scheme achieves optimal route by using a set of waypoints, which form the either the $y > 0$ or the $y < 0$ half of the convex hull of the geometrical object set consisting of the source, the destination, and the voids between them. The optimality of this scheme is based on *Proposition III*. An example of route given by this method is $P3$ in Fig. 1.

The optimal adaptive scheme can be implemented as follows. Initially, two halves of the convex hull (the $y > 0$ half and the $y < 0$ half) are probed by choosing clockwise and counter clockwise traversal in the perimeter mode [1], respectively. The half with smaller hop count is selected. The probing is repeated periodically to account for topology dynamics, but such probing need not be frequent since void configurations typically change slowly.

The procedure to compute the half convex hull is as follows. A packet maintains a temporary list of half hull points: $v(1), v(2), v(3), \ldots$, where the first node in the list is the source and the last the destination. Assume the $y > 0$ half hull is chosen. Define $A[v(l), v(m), v(n)]$ to be the angle spanned by $v(l)$ and $v(n)$ to $v(m)$ and facing the x axis. The procedure starts to compute the half hull beginning at the second node after encountering a void (no computation and other overhead will be incurred if the packet never encounters a void), and proceeds as follows:

(a) For each newly visited vertex $v(n)$, if $A[v(n-2), v(n-1), v(n)] < \pi$, the vertex $v(n-1)$ is added to the half hull set H.
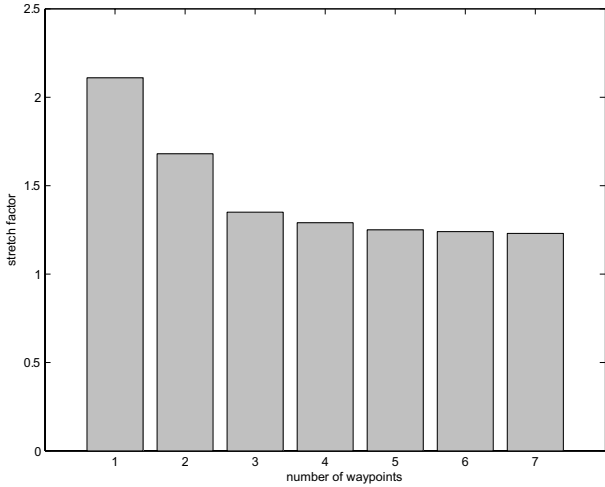
Fig. 3. Stretch factors of adaptive waypoint routing schemes using different waypoints.

(b) Otherwise, the algorithm backtracks to a vertex $v(m)$ in S, such that $A[v(m), v(m+1), v(n)] < \pi$, delete all the vertices in the range $[m+2, n-1]$ from H.

(c) The procedure stops when the destination is reached, and returns H as the half hull set.

The above procedure is carried out incrementally when each node is visited by the packet; and the destination sends back H to the sender, which uses H as the waypoints for the optimal route. The main computation involved in this scheme is to compute the angles, which is a lightweight burden. Although this scheme generates an optimal route, the overhead of keeping a complete list of half hull points becomes burdensome when the list gets long, which motivates the next scheme.

C. Multi-point adaptive scheme

The multi-point scheme uses a condensed list K that only keeps the important hull points. In this scheme, on each new discovery of a hull point m, m is added to K only if its utility function $u(m)$ is above certain threshold, i.e., $u(m) = h(m-1, m) - d(m-1, m)/e > t$. In the above, $d(m-1, m)$ is the line of sight distance between the new and the last hull points; $h(m-1, m)$ is the number of hops the packet travels between these two points (a new counter in the packet header is required to obtain this information); e is the average distance traveled by one hop, and is computed with distance and hop count information; t is a certain threshold, which represents the tradeoff between the overhead of adding the coordinates of one hull point in the packet header and the expected number of hops saved by doing this. The threshold can be adjusted according to application requirements or some other criteria.

The size of K is not bounded in the above scheme, which is not desirable since the packet header typically has a fixed length. This problem can be easily rectified by keeping at most n hull points in K that have largest utility function values.

IV. COST BENEFIT ANALYSIS

We simulated the effectiveness of the adaptive waypoint scheme using the multi-point adaptive scheme with different number of waypoints used. The single-point and the optimal adaptive schemes are special cases of the multi-point scheme with the number of waypoints being one or the smallest integer beyond which there is no efficiency gain, respectively. A random network of 400 nodes is generated, which has two voids whose combined area is 32% of the total area of the network. The result is averaged over 150 routes that encounter the voids. The efficiency of a route r is represent by the stretch factor, $l(r)/l(r_0)$, which is defined as the ratio of length of r v.s. that of an optimal route r_0 between the same source and destination. As evident from Fig. 3, adaptive waypoint routing can effectively eliminate the inefficiency in greedy geographical routing, i.e., reducing the stretch factor to nearly one. In addition, just a few waypoints can achieve the most effect; in our case 3 points are enough to bring the stretch factor down from 2.11 to 1.35. We admit such simulation has limited statistical significance, but still it indicates the potential of the adaptive scheme.

V. CONCLUSION

We expect geographical routing will play an increasingly important role in wireless ad hoc networks because of its simplicity and scalability and the popularity of large scale, location-aware applications. Improving the efficiency of geographical routing beyond that offered by greedy forwarding is sorely needed for it to truly emerge as a viable, widely applicable routing method. This paper provides an adaptive approach for that purpose and demonstrates the adaptive schemes' effectiveness and capability to provide different efficiency-overhead tradeoffs.

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