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Dealing with Non-Convexity in Geographic Routing in Smart Dust Networks

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Abstract. The paper proposes a new approach to greedy geographic routing for sensor networks with non-convex covering structure.

Keywords. Smart dust, geographic routing, non-convexity, sensor-covered areas areas

1 Introduction

The advent of smart dust started a new chapter in the development of computer networks, intelligent sensor networks, wireless communication and distributed processing. A smart dust mote is a unit equipped with an energy source, sensing hardware, memory, a processor, and a data transmission unit. Motes are capable of establishing a network of hundreds, thousands, and even hundreds of thousands of nodes, communicating with one or more “base stations” and/or with one another. Such networks can find multiple applications in environment monitoring (e.g. natural habitat analysis, pollution tracking), in military (e.g. object tracking) and fire fighting operations, as components of intelligent clothes, in monitoring mechanical parts of engines, industrial installations (e.g. assembly line fault-detection), e-home (e.g. motion detection), digital lifestyle (e.g. parking spot tracking), e-commerce (e.g. tracing goods taken by clients) etc.

The design of a smart dust network brings with it a number of serious challenges. First of all, the immense, frequently unprecedented sizes of the networks, including hundreds, thousands, or even hundreds of thousands of modes, that need to be joined into the network instantly. Fault tolerance and scalability of solutions are among the major issues here. The network has to self-organize itself, each mote has to detect its own spatial position. Frequently, the motes are deployed in a bit random fashion. The network must possess capabilities of information collection and dissemination. Querying and summarizing of data sensed by the network have to be designed.

An essential (and, in fact, the most energy consuming) part of mote activity is communication between motes and between motes and base stations.

We can face various modes of such communication. On one hand, we may have to do with single-hop and multi-hop communication. A mote can communicate solely with the base station or with other motes in the network. A message can be directed towards a single receiver or broadcast over the whole network (or a specific area). As a special case we can have a communication mode of motes with the base station consisting in synchronous sending of the same signal to the base station, so that the signal is powerful enough to reach it.

In this research, we are interested, however, in multi-hop communication between motes, as, with the growing processing power of single nodes, a distributed processing task can be assigned to the network without engagement of the base station.

An important element of any communication system is the routing strategy. Though there exist a lot of alternatives, like fixed routing tables, or rumour routing [Braginsky], the sensor networks seem to be suitable for geographic routing strategies. See [Kuhn] for an overview and a comparative study of a dozen of them. In such routing strategies, in principle, the target of a message is determined by its geographic coordinates, and, at each in-between point, the message is passed to the node closest to the target. Some variations include e.g. additional condition of closeness to the straight line connecting the sender and the receiver or to a quadratic spline curve in more complex approaches (like that of avoidance of energetically weak areas [Machando]).

A recent paper by Xing et al. [Xing] deals with such a routing strategy, while it presumes that the area, where the sensors are deployed, is sensor-covered (that is each point is within the sensing range of at least one mote), that is the communication range is at least twice as large as the sensing range, and the sensed area is convex.

In fact, many smart dust applications like distributed detection [Varshney], distributed tracking and classification introduce the important requirement of sensing coverage, which was not present in traditional ad-hoc networks. To match this requirement, there were research works reported concerning achievement of sensing coverage during deployment [Chakrabarty], or maintenance of the coverage by energy saving usage of only a subset of actually deployed sensors [Tian].

In geographic routing algorithms, the convexity violation leads to situations where a message either needs to be abandoned or more complex routing strategies must be applied [Karp], if the message has to pass areas not covered by the sensors.

In this paper we present an idea how to overcome such a limitation. First, we will recall briefly the algorithm of Xing et al., then we will show that circle-like holes do not violate their algorithm, and then we will discuss how to overcome inner and outer concavity.

2 Xing's Algorithm

Xing et al. proposed a greedy geographic routing algorithm based on the idea of Voronoi diagram and Delaunay triangulation, with special handling of area borders. They assume that each mote has an identical sensing range and identical communication range. Thus, the Voronoi diagram region contains points within the sensing range of the mote being the centre of the region. The message is passed by a mote to the one in a Voronoi region on the straight line towards the goal (see Figure 1). They show that in a sensor-covered network, if the area is convex, and the double range condition is met (the quotient of communication range to sensing range is at least 2, which ensures that motes from neighbouring regions can communicate), their greedy routing algorithm is always successful (message can always be delivered based on the strategy alone).

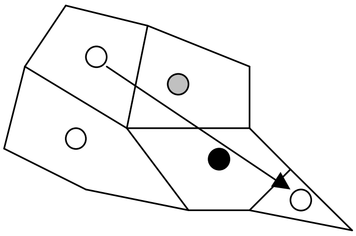

Figure 1. The idea of Veronoi diagram routing. The grey and the black nodes are candidates for carrying the message as they lie in Veronoi regions on the pathway of the message

3 Handling Circular Holes

The fundamental assumption behind Xing et al. algorithm is that two communicating motes can always be connected by a straight line segment lying completely within the sensing area of the network. Furthermore, this straight line segment passes through at least one sender's neighbouring Voronoi region, which is closer to the receiver of the message, and the mote lying within this neighbouring region can be reached by the sender directly. This property may be violated if the sensing region is not convex. The Xing's original approach does not work any more, if the outside border is concave (Figure 4) or if there are "big holes" within the sensing area (Figure 2).

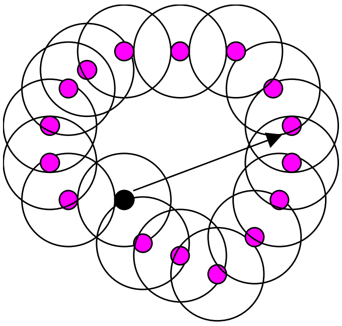

Figure 2. The greedy routing problem with non-sensed areas. Black node is closest to the receiver of its neighbourhood, but they are outside of each other communication rage

However, if we have the special case where a "hole" in the sensing area is circular in the sense that there are motes on its bordering circle such that the motes neighbouring on the circle can communicate (so the network between them encloses the hole), then we can get an easy remedy. We can extend the Xing's Voronoi regions of these motes so that all of them meet in the centre of the circle (Figure 3). In this way, we get a convex coverage of the concave sensing area with Voronoi regions. We immediately see that we recover in this way the original functionality of Xing et al. routing algorithm because any straight line segment leading out of any of the motes on the circle into the hole will enter one of its two neighbours, which are by definition reachable. On the other hand, straight path leading from any other mote to the "hole" will pass through one of circle border mote regions.

In fact, the border of the hole does not need to be circular, and may be of any convex shape.

There is of course a fee we have to pay for this extension of the original Xing's approach: The motes around the "hole" have to agree upon their Voronoi regions on a not strictly local level (all border motes need to be engaged together).

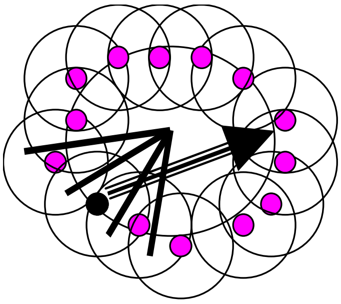

Figure 3. Splitting "non-sensed" area into Veronoi regions of motes on the enclosing circle. The straight line path always passes through reachable mote region

What we gain, however, is not only a swift method of geographic routing, engaging only local information. Beside this, we get a concept how to handle general inner and outer concavity. We will explain this in the next section.

4 Handling Concaveness Of Border Areas

What we have done in the previous section means more than just a geometrical transformation. It is a conceptual transformation of the Xing's Voronoi diagrams. The original ones represented sensed areas closest to a given mote. The double communication range properties guarantied that motes from Voronoi diagram neighbouring regions can communicate. We have to stress that the fact that they can communicate, and that the Voronoi regions are convex, is essential, not the covering of the sensing area. So, we have just extended the Voronoi regions to areas not sensed, only caring that the neighbours can communicate and that the regions remain convex.

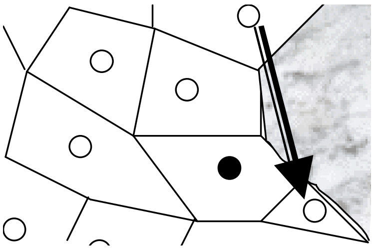

Figure 4. A concave sensing area

So a straight forward idea to enable geographic routing in concave sensing areas (Figure 4) would be to device a convex area including the sensing area, and to extend the bordering Voronoi regions so that they cover the additional space. This would not work, however.

To solve the general concavity problem, we need to go still one step further. We cannot just extend existing Voronoi regions to cover a convex area because the modified Voronoi regions would not be convex so that passing a message to the next region on the path would not guarantee progress of the message (It could be captured in a circulating trap).

What we can do now, is to move the motes "virtually" (changing their apparent geographical location) towards the non-sensed areas so that we can design new convex regions surrounding the motes, keeping old neighbours, and not adding any new ones (Figure 5).

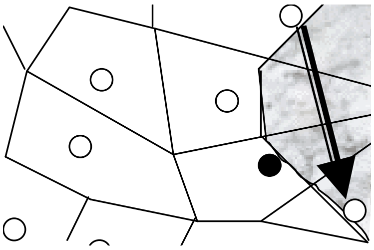

Figure 5. Stretching a concave area

Now motes would be addressed by their new virtual geographic locations, and the Xing's routing strategy can be applied without obstacles.

The disadvantage of this shift is that it needs to be done by a central station combining geographic information from all the motes.

Another disadvantage is that the real routs of the messages will not be straight lines any more, but will rather reflect the stretching effect imposed on the sensed area.

5 Covering outside regions for the sake of convexity

Figure 6 illustrates the basic algorithmic ideas behind the process of removal of concaveness from the outside borders.

First of all, we must know whether or not a given node is a border node of a concave border fragment or not. In order to obtain this information, the node has to check whether or not all its neighbours can communicate with one another. If they can, the node is simply an "insider" node.

But if two of them A, B of the node C cannot, and there happens to be no neighbouring node of C in the angle ACB, then C is a border node at a concave border fragment and should inform nodes A and B to seek the extent, to which this concaveness holds (in our figure from D to E). As soon as the frontiers of the fragment are established, the concave area is divided into sectors with a central point H lying on the line between D and E, and from now on H represents all nodes between D and E and is deemed to be a neighbour of D and E not connected to neighbours of D and E except for those identified as elements of the concave border fragment between D and E.

This procedure is continued until no node finds itself as lying on a concave border fragment.

The fact that E represents among other A,B,C means that all the area assigned to node E in the not sensed area is "equally" split among them and added to their "virtual" Veronoi regions.

Note that this procedure can be run in a local manner – the communication involved should be confined by quadratic complexity in the number of local nodes belonging to concave fragments.

Note also that each node has to expand its virtual area a number of times, the number being proportional at most to the logarithm of the number of nodes engaged in the given border concaveness.

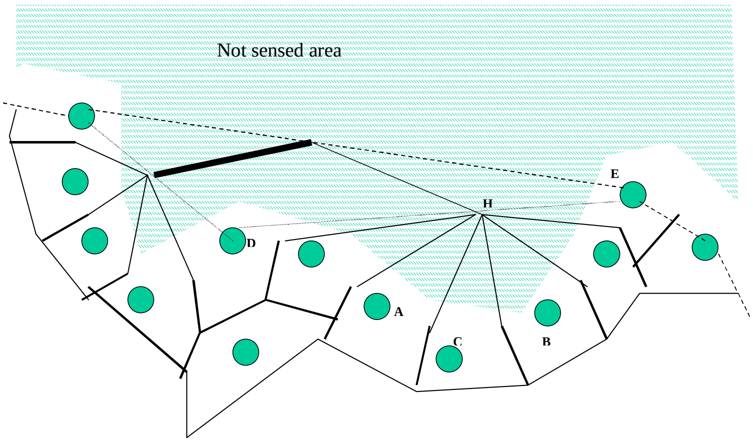

Figure 6 . “Local” approach

6 Conclusions

Our initial study of the concaveness problem in geographic routing shows that there exist possibilities of establishment of “artificial” convexity via “geometrical stretching” of the positions of the motes.

Though the routes may turn out not to be optimal in some cases, the important goal of establishing communication between all motes is achieved.

Further research should be concerned with energy related issues. We conjecture, that the “geometric stretching” may be useful from the point of view of uniform energy consumption in communication processes. This needs, however, to be proved mathematically and verified in a simulation study.

Another future research direction would be to invent a distributed algorithm carrying out the “virtual shift”.

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http://www.ipipan.waw.pl/~klopotek/mak/current_research/KBN2003/KBN2003Translation.htm

References

[Braginsky] D. Braginsky, D. Estrin: Rumor routing algorithm for sensor networks. In Proceedings of the First ACM Workshop on Sensor Networks and Applications, pages 22-31, Atlanta, GA, USA, October 2002. ACM.

[Chakrabarty] K. Chakrabarty, S.S. Iyengar, H. Qi and E. Cho: "Grid coverage for surveillance and target location in distributed sensor networks", IEEE Transactions on Computers, vol. 51, pp. 1448-1453, December 2002.

[Dan] Y.H.H. Dan Li, Kerry Wong and A. Sayeed: Detection, classification and tracking of targets in distributed sensor networks. IEEE Signal Processing Magazine, 19(2), Mar 2002.

[Karp] B. Karp and H.T. Kung, GPSR: Greedy Perimeter Stateless Routing for wireless networks, in: Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2000.

[Kuhn] F. Kuhn, R. Wattenhofer, and A. Zollinger: Worst-Case Optimal and Average-Case Efficient Geometric Ad-Hoc Routing. In MobiHoc, 2003

[Machando] M. Machado, et al.: Data dissemination using the energy map. URL doi.ieeecomputersociety.org/10.1109/WONS.2005.11

[Tian] D. Tian and N. Georganas: A coverage-preserved node scheduling scheme for large wireless sensor networks. In Proceedings of First International Workshop on Wireless Sensor Networks and Applications (WSNA'02), Atlanta, USA, Sep 2002.

[Varshney] P.K. Varshney: Distributed Detection and Data Fusion. Springer-Verlag, New York, NY, 1997

[Xing] G. Xing, C. Liu, R. Pless: On greedy geographic routing algorithms in sensing covered networks. InternationalSymposium on Mobile Ad Hoc Networking & Computing archive Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing Roppongi Hills, Tokyo, Japan SESSION: Routing and content distribution table of contents Pages: 31-42URL: www2.parc.com/spl/projects/ecca/pubs/greedy.pdf