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Multi-dimensional recursive routing with guaranteed delivery in Wireless Sensor Networks

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ABSTRACT

The use of geographic routing protocols in Wireless Sensor Networks (WSN) is widely considered a viable alternative to more conventional routing protocols. However, guaranteeing delivery with geographic routing in arbitrary dimensional WSN is still a challenge due to the complexity of available solutions. In this work we propose an approach that assigns virtual coordinates to the sensors based on recursive partitioning of the network. We then give a routing protocol that works on this space of virtual coordinates and that guarantees delivery in both two dimensional and three dimensional WSN. We prove by simulation that, as compared to the shortest path, the path length obtained by the routing protocol is only slightly larger and, with an appropriate configuration of the partitioning, smaller than other comparable routing approaches.

1. Introduction

A Wireless Sensor Network (WSN) is a specialized ad hoc network composed by a large number of low power, low cost sensors (also called nodes) [1]. A sensor comprises one or more sensing units, a processor and a radio transceiver, and it is powered by an embedded battery. Sensors collect information about the surrounding environment (sensor field) and they self-organize into a wireless ad hoc network in order to exchange sensed data and connect with external sink nodes that issue queries to the network. WSN have been successfully used in a large number of different applications, ranging from structure health monitoring, surveillance, ambient assisted living, smart homes and pervasive computing, etc.

The effective development of scalable WSN presents a number of research challenges ranging from routing protocols to algorithms for data collection, fusion, and stream processing. In simple settings, WSN employ a query distribution and data collection based on a simple model known as data diffusion [2]. This model assumes that the sink node has a permanent connection with the network and performs most of the data analysis, while the role of the network is limited to data acquisition and, in some cases, to simple data processing.

However, in the effort of improving the management of data streams produced by sensor networks, it has been proposed to integrate database and sensor network technologies [3,4]. The integration of database technologies with sensor networks and the use of data-centric paradigms require the support of efficient and robust routing protocols that are more general than those used to support data diffusion. In order to reduce the burden of maintaining routing tables in the sensors and to avoid the cost of route discovery in existing protocols for ad hoc networks, such as [5,6], routing protocols based on geographic location information of the sensors [7] have been proposed. Although geographic routing may contribute to reduce the routing overhead on the sensors, it requires that the sensors are aware of their physical position. This information can be obtained by equipping the sensors with devices such as GPS; however, cheapest (and approximate) solutions may be obtained by equipping with GPS only a limited subset of sensors and using this information to infer the position of the other nodes. For this reason, the problem of inferring nodes' location in sensor networks in which just a few (or no) nodes know their geographic position is of great practical interest. Proposed solutions are based on different assumptions on node capabilities and knowledge, and each offers a different result accuracy. Traditional approaches are aimed at deriving coordinates resembling the real ones, when services like GPS are not present. Metrics measuring the quality of a solution are computational and communication complexities, precision, and accuracy. A complete survey of methods and solutions

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to approximately compute the real position of nodes is presented in [8]. Commonly, a few nodes (often called anchors) are assumed to know their exact position, by means of special hardware or because they are positioned in well known points, and consequently programmed. The other nodes infer their positions, using ranging techniques such as time of arrival, angle of arrival, and signal strength, or range-free techniques based on hop distances [8].

In [9–11] the requirements of the coordinate assignment are somehow relaxed. In fact, the authors study how to define virtual coordinates that preserve some interesting properties of the network. In the virtual coordinates approaches the nodes are assigned with (virtual) coordinates unrelated to the nodes' physical positions, and which are used exclusively to the purpose of data delivery. The rationale for this approach is that the routing layer provides only data delivery services, leaving to the upper layers the responsibility of relating sensed data with location information. In particular, data centric storage mechanisms based on geographic hash tables [12–14] exploit hashing to determine the geographic locations of the sensors where the sensed data have to be stored and retrieved, and hence they remove the need for the senders to execute expensive route discovery algorithms to discover the coordinate of the destinations. We observe that the approaches based on virtual coordinates may result very effective in all the cases in which obtaining the geographic location of the sensors is unfeasible, for instance because GPS is considered too expensive with respect to the target application or because it is not available at all.

In this paper, we consider the approach of virtual coordinate-based routing in sensor networks composed by a very large number of sensors, deployed in a sensing field of arbitrary dimensionality, and where the sensors do not have any preliminary information about the network topology, the boundary, and their position. We can find scenarios that exhibit a high network density, high-dimensionality, and very large scale in the context of smart cities [15], where the cost of using GPS devices on a large scale just for routing purposes would be unacceptable. For these scenarios, we present the Multi-dimensional Recursive Routing protocol (MRecR), that combines a virtual coordinate assignment protocol and a routing protocol on this set of coordinates that guarantees delivery in sensor networks of two and three dimensions. The coordinate assignment protocol of MRecR exploits a recursive partition of the network to assign the coordinates to the sensors, and has a very small requirement in terms of memory overhead on the sensors. Based on these coordinates, the routing protocol of MRecR exploits simple rules to guarantee 100% packet delivery in both two and three dimensional networks.

The rest of the paper is organized as follows. Section 2 presents the related works, Sections 3 and 4 introduce the MRecR protocol and prove its correctness, respectively. The simulation results on the path length, packet delivery, robustness and messages overhead is presented in Section 5. Finally, Section 6 draws the conclusions and future works.

2. Related work

Geographic routing protocols enable efficient packet delivery between a pair of nodes by exploiting information of their geographical locations to guide the choice of the next hop in WSN. It was originally proposed by Finn [16] and later used in GPSR [17] and, independently, in [18]. A good survey about geographic routing can be found in [7].

To make a packet advance towards the destination, geographic routing protocols use both greedy and recovery modes. The greedy mode allows the progress of a packet based on the locations of the forwarding node, its 1-hop neighbors, and the destination. For the purpose of selecting the next hop, the forwarding node uses some metric such as Euclidean distance, most forward within radius (MFR) or nearest forward progress (NFP). Obviously, the greedy mode fails when a forwarding node is actually the closest node to the destination and, therefore, the packet cannot progress. The forwarding node is known, in this case, as local minimum. To escape a local minimum, the recovery mode is then used. This mode defines how to get out the packet when it stacks at a local minimum. For this purpose, different strategies are used such as flooding and face/perimeter routing protocols [17–21], which forward the packets to the boundary nodes in a planar network graph to reach the destination. The combination of both modes guarantees packet delivery.

Geographic routing protocols provide good performance and scalability since they use only local information to determine the next hop. On the other hand, they present two drawbacks: (1) the cost could be prohibitive in large networks, since a set of nodes must be equipped with expensive devices (e.g. GPS) to acquire their physical coordinates and to be able to derive the location of the others; and (2) paths can be long if a wrong direction is taken at a local minimum. Additionally, unstable wireless links, inaccurate positions when radio range is irregular and obstacles that prevent communication impact on the reliability of these networks. As a consequence, network connectivity does not always go hand-in-hand with geographic positions. Several studies [22,23] have used simulations and real world experiments to measure the effect of errors on the networks reliability. To improve the reliability of geographic routing protocols in realistic scenarios with lossy links, in [24,25] different routing metrics are proposed. The first one uses local information based on packet reception rate and distance ($PRR \times d$) and the second one proposes a global metric based on the expected number of transmissions (ETX). For high-density networks both may achieve 100% packet delivery while it cannot be guaranteed for densities lower than 80 neighbors/range. Recently proposed, Greedy Distance Vector (GDV) [26] is a geographic routing protocol that is based on distance vectors and that also works in 3D networks. Although GDV ensures packet delivery and optimizes the end-to-end path costs, it could require each node to store large routing tables which result in a high memory overhead.

The challenge of providing delivery guarantee in extremely resource-constrained WSN has stimulated a lot of research on routing protocols based on virtual coordinates in recent years. Virtual coordinates represent the alternative approach to physical coordinates, where nodes only rely on neighbor connectivity to establish a coordinate system. Based on these virtual coordinates, some greedy and recovery routing strategies [27,28] are then used for enabling routing between nodes. NoGeo [9] and GEM [10] are two of the earliest approaches for routing based on virtual coordinates. The first one computes the virtual coordinates for each node from the rubberband representation of a graph that matches the network connectivity, while the latter obtains the virtual coordinates of each node within a tree representation of the network, by concatenating its level (i.e., minimum hop count to the root of the tree), and its angle range. However, the most general approach to compute a virtual coordinate system is to find a small subset of reference nodes in the network called *anchors*. The rest of the nodes may determine their virtual coordinates by computing their hop distance to these anchors and, then, employ a revised greedy routing metric to account for the higher space dimensionality and in-network anchor placement.

Beacon Vector Routing (BVR) [29] and Logical Coordinate-Based Routing (LCR) [30] are two routing protocols described independently but at the same time, based on anchors. In BVR and LCR, each node computes its hop distance to the anchors forming a vector. The distance between two nodes is determined as the difference between their vectors. The routing protocol forwards