Fault-tolerant and energy-efficient routing protocols for a virtual three-dimensional wireless sensor network∗

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ARTICLE INFO

Keywords:
Wireless sensor network
3D virtual architecture
Moving actuators
Collision avoidance
Connectivity
Routing
Fault tolerance

ABSTRACT

In this paper, we consider a low-density, three-dimensional Wireless Sensor Network (3D WSN) for short in which the distribution of the sensors is poor, and the 3D virtual architecture proposed in our previous work. This later architecture provides a powerful, fast and economic partitioning of the network into a set of easily manageable clusters. We derive a fault-tolerant and energy-efficient routing protocol that allows efficient broadcasts of the data collected by the sensor nodes to a base station – a sink node located at the center of the network. Unlike existing routing protocols that run only on dense Networks ours is reliable on any type of 3D WSN: dense, sparse or non-connected. It can lead to the development of efficient algorithms for many applications as multicast, geocast, data aggregation, data collection with authentication and security.

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1. Introduction

During its evolution, the wireless paradigm has seen the birth of various derived architectures such as cellular networks, wireless local area networks, and wireless sensor networks (WSNs). WSNs are the result of a fusion of two poles of modern computing: embedded systems and wireless communications. A WSN consists of a set of embedded processing units, called sensors, with limited resources (e.g., bandwidth, computing power, available memory, and embedded energy) and communicating via wireless links. Its purpose is generally to collect data fitting a set of parameters describing the deployment environment (such as temperature or atmospheric pressure) to route them to a base station (BS) for processing. This technology has imposes itself as a key actor in current network architectures [1,2]. Often considered the successors of ad hoc networks, WSNs are based on a collaborative effort of a large number of sensors operating autonomously and communicating with each other via short-range transmissions [3]. The vulnerability of the radio communication that sensors use added to their resource limitations are factors that raise many problems (e.g., interference, intrusion, disconnection, and data integrity).

1.1. Related work

Several studies have already been conducted on the field of energy saving in sensor networks to extend their lifespan for 2 D WSN [4–7]. However, a 2 D sensor network has drawbacks; in most papers, it is assumed to have been deployed

∗ Reviews processed and recommended for publication to the Editor-in-Chief by Associate Editor Dr. M. H. Rehmani.
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https://doi.org/10.1016/j.compeleceng.2018.02.012
0045-7906/© 2018 Published by Elsevier Ltd.

Please cite this article as: J.F. Myoupo et al., Fault-tolerant and energy-efficient routing protocols for a virtual three-dimensional wireless sensor network, Computers and Electrical Engineering (2018),
https://doi.org/10.1016/j.compeleceng.2018.02.012
in a plane without obstacles or mountains, which is not a realistic assumption in the general case. Furthermore, in real applications such as underwater applications, 3D networks are more suitable.

Once deployed, a fundamental prerequisite for self-organization is that sensors must acquire some form of location awareness [8]. Most but not all applications benefit from the sensed data being supplemented with location information. A sensor knowing its location in the network is crucial in an anonymous network One interesting paper on the self-organization of a two-dimensional WSN is [4]. A sensor is trained to acquire its coordinates. A cluster is, then, a set of sensors having the same coordinates, resulting in a 2D or 3D virtual WSN ([9]). However, few other papers exist on the design routing algorithms for 3D WSNs [10,11]. The approach of the authors in [12] is to find the flat metric of the triangular mesh, which can be embedded on a 2D or 3D plane. The distributed Yamabe flow-based mapping [13] is a good candidate to reach this goal. It yields the virtual coordinates for every node in the network, which are used for greedy routing. The properties of Yamabe flow-based conformal mapping ensure the success of such greedy routing between any pair of nodes in the network and achieve low stretch factors at the same time. However it is assumed that the WSN is dense and hence always connected, and if even the network still connected with holes. Given the high energy cost to perform the distributed Yamabe flow and the fact that this algorithm is greedy, it is clear that it is globally energy inefficient. A point-to-point routing in wireless sensor networks is proposed in [14]: A distributed virtual coordinate assignment algorithm, called Particle Swarm Virtual Coordinates (PSVC), that employs Particle Swarm Optimization to compute virtual coordinates for geographic routing is presented. As in [12] the routing proposed in this paper not only does not support the fault tolerance but also does not minimize the energy consumption. Moreover if some nodes break down (by lack of energy) creating holes that disconnect the network the algorithms in [12,14] fail. In contrary our algorithm can carry out this situation by a self-organization (without help of GPS) using actuators to reconnect the network. However, one challenging problem is to find how to make these algorithms in [12,14] energy efficient.

1.2. Our contribution

In this paper, we show how routing can be performed efficiently in a low-density, three-dimensional sensor-actuator network. To reach this goal, our starting point is the 3D virtual low-density network (in which several clusters can be empty), introduced by Tchendji et al. [9] for cluster network partitioning. To route effectively the data collected by each sensor to the base station, we first propose a technique using multiple communication channels to reduce collisions greatly during communications. Second, we propose a distributed empty-cluster detection algorithm that allows knowing the area actually covered by the sensors after the deployment and that therefore provides the BS the ability to react accordingly. Third, a strategy is set up to allow mobile sensors (actuators) to move for example to save the connectivity of the WSN, improve the routing of collected data, save the energy of the sensors, improve the coverage of the area of interest, and reduce the time taken by packets to reach the BS. Finally, we present a set of fault tolerant mechanisms used by our protocol to solve possible problems in the data collection phase. Experimental results highlight our work.

The remainder of this paper is organized as follows: in Section 2, we present the virtual architecture in which we work. Then in Section 3, we present our collision avoidance mechanisms. In Section 4 we present a technique to detect empty clusters and a distributed cluster-head election protocol, followed in Section 5 by our method of strengthening strategic points with the actuators and the technique used to move the actuators properly. Section 6 presents the overall structure of our fault tolerant, fast and energy efficient routing protocol. In Section 7, we present other fault tolerant mechanisms to maintain the connectivity and functionalities of a network. Examples and simulation results are presented in Section 8. Finally, a conclusion and discussion section ends the paper.

2. A virtual 3D wireless sensor-actuator network

We briefly recall the 3D network in [9]. We assume that the sink node can make l omnidirectional transmissions, m horizontal directional transmissions, and n vertical directional transmissions. The coordinate system divides the sensor network area into equiangular wedges (or sections). In turn, these wedges are divided into sectors by means of concentric spheres or coronas centered at the sink. The sector radii are configured to optimize the transmission efficiency of sensor-to-sink transmission. Sensors in a given sector are mapped to a cluster; the mapping between clusters and sectors is one-to-one. With reference to Fig. 1b, the task of training a sensor network involves establishment of the following:

1. **Coronas:** The deployment area is covered by l coronas determined by l concentric spheres of radii \( r_1 < r_2 < \cdots < r_l \) centered at the sink node;
2. **Horizontal wedges:** The deployment area is ruled into m horizontal angular wedges centered at the sink node;
3. **Vertical wedges:** The deployment area is ruled into n vertical angular wedges centered at the sink node.

As illustrated in Fig. 1, at the end of the training period, each sensor node has acquired three coordinates: the identity of the corona in which it lies and the identity of the horizontal and vertical wedges to which it belongs. Importantly, the locus of all of the sensor nodes that have the same coordinates determines a cluster. Readers interested in this training protocol can find details in [4,9].

Once deployed in a three-dimensional area as shown in Fig. 1a, the sensors can be grouped in clusters using the method described in [9]. We thus consider a special sensor called the sink or base station unconstrained by common sensor limits.
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