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An autonomic bio-inspired algorithm for wireless sensor network self-organization and efficient routing

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ABSTRACT

Self-configuration and autonomy are key features required for the next generation of gadgets and networks, since regular users are willing to have computationally enabled devices pervasively spread into their environment. Sensors are among the most promising devices into this new scenario. However, their low battery and processing power raise several issues to these autonomy requirements. This paper presents BiO4SeL (Bio-Inspired Optimization for Sensor Network Lifetime), a swarm intelligence-based algorithm to perform self-organization and optimization of lifetime by means of routing into a Wireless Sensor Network. Results show that BiO4SeL achieves its objectives when compared to similar approaches: ARAMA (Ant-based Routing Algorithm for MANETs), EAR (Energy-Aware Routing) and AODV (Ad-hoc On-demand Distance Vector).

1. Introduction

In the context of Ubiquitous and Pervasive computing, sensors are the computing devices potentially most present in number. Sensors collect information from the environment, such as temperature, motion, humidity, and so on, and communicate with their neighbors in order to send the collected information towards a Base Station (BS), or sink. They can be applied in a wide gamma of applications. For instance, sensors can be distributed in a forest in order to detect and monitor fire.

One of the major issues about a sensor network is its lifetime, *i.e.*, the time from the network deployment until the first node drains its battery. During operation, some nodes may be over requested to relay information from other neighbors, causing faster energy consumption. That could generate coverage holes on its sensing area. Hence, it is desirable to have nodes balancing their loads in order to maximize lifetime. Maintaining full coverage of the area for the maximum time is an objective for many routing algorithms in sensor networks. This problem is particularly important in critical applications, such as radioactivity monitoring, which cannot have "blind" areas during operation. Solutions for this problem, or for a part of it, may be found in the literature. Most of them are based on the routing level. However, many of them rely on strong assumptions such as prior localization knowledge, centralized processing, etc.

This paper presents BiO4SeL (Biologically-inspired Optimization for Sensor Lifetime), a distributed and autonomic ant-based routing protocol that aims to maximize sensor network lifetime. It applies Swarm Intelligence concept in order to build intelligence from distributed rudimentary behavior among sensors.

BiO4SeL, just like some other approaches, bases itself on this idea to create paths on the network for sending data from nodes to BS, distributing energy consumption on nodes along the path. However, BiO4SeL is different from other algorithms because it uses battery power information not only to build routing tables from scratch, but also to update the distributed routing tables as battery power is consumed. As a consequence, the packet forwarding responsibility tends to be equally distributed, keeping the energy map variance as small as possible. This is what increases the network's lifetime. Simulation experiments comparing BiO4SeL with ARAMA (Ant-based Routing Algorithm for Manets) (Hussein et al., 2005), Energy-Aware Routing (EAR) (Shah and Rabaey, 2002) and AODV (Ad-hoc On-demand Distance Vector) (Perkins et al., 2003) show that BiO4SeL achieves its objectives while demonstrating better organization on more dense scenarios (tested with up to 320 nodes).

The remainder of this paper is organized as follows. Section 2 shows some related works on sensor networks routing. Section 3 presents some background on Ant Colony Optimization. In Section 4, the BiO4SeL approach is introduced and its specification is shown. Section 5 describes the experiments carried out, and shows and discusses their results, while Section 6 outlines some conclusions and proposes some future works.

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2. Related works

One of the most promising techniques for reaching autonomy in widely deployed networks is inspired by biological phenomena (Dobson et al., 2006). Among these biologically inspired strategies, Swarm Intelligence presents interesting feature for Wireless Sensor Networks (WSN).

Initially, Swarm Intelligence was applied on graph theory as an Artificial Intelligence approach to the Traveling Salesman problem using ants (Dorigo et al., 1991; Dorigo and Gambardella, 1997). After that, this paradigm became more and more popular. In the communication networks domain, it was initially used on packet routing, with AntNet (Caro and Dorigo, 1997). Making a comparison between nature and networks, on the routing algorithms, each ant can be seen as a control packet. When a path must be created from one node to another, some ants are deployed. They move and probabilistically select the next hop, based on the pheromone distribution along the path or on some other path heuristic. When the ant reaches the destination, it calculates the pheromone to be laid, based on the path heuristic. After that, the ant is sent back. To follow the same path, they maintain a record of the hops they have passed by along their way. On the return path, they update the pheromone on each visited node, reinforcing the network route weight and increasing the probability to have this path chosen. Hence the algorithm is based on a probabilistic routing table.

ARAMA (Ant-based Routing Algorithm for Manets) (Hussein et al., 2005) uses these probabilistic routing tables to send packets on Ad-hoc Networks. The major difference between ARAMA and AntNet is that the amount of energy from the nodes batteries influences the amount of pheromone laid on nodes within the path.

A variant of ARAMA, called Ant-Based On-Demand Energy Routing (AOER), described in Shuang et al. (2007), aims to adjust routing in order to increase Ad-Hoc networks' lifetimes. With this approach, ants collect remaining battery power information on each node, as well as forward capability and hops counting. This information is used to build an inverted probabilistic routing table. The routing table is inverted because the more ants walk through a specific way, the less energy power this path has. Moreover, an ant does not keep its visited path, reducing its size and consequently the power consumed to send, receive and process it. Unfortunately, the article does not provide enough implementation details to allow a comparison with BiO4SeL.

Some other ant-based algorithms for WSN can also be found in the literature, which are based on energy conservation and connectivity maintainability, each of them with its own particularities. In Guo et al. (2010), authors use distance as a main criteria for pheromone accumulation.

Some other algorithms found in the literature present different ways to reach WSN lifetime optimization using ants. In Ok et al. (2009), integer programming is used instead of pheromone. Clusters are created and ants perform routing among clusters. Although this strategy helps scalability, cluster organization is required, that decreases the distribution level. Moreover, the need to maintain cluster organization is not well suited for dynamic sensor scenarios. Other ant approaches can be found in the literature with the same requirements on cluster organization, such as in Shen et al. (2009).

In Xia and Wu (2009), an approach based on the ACS (Ant Colony System) (Dorigo and Gambardella, 1997) for multipath routing in WSN where energy on the nodes' batteries are taken into account to build paths. It maintains two parameters for updating pheromones, one local on each node and another one held by the entire network. In this case, the drawback is the need to keep and update a centralized parameter for the entire network, which breaks the distribution feature. Also, the algorithm does not take into account dynamic (moving) nodes.

In Wang et al. (2010), ants are also applied for WSN. However, the authors focus on optimizing the energy on nodes closer to the sink, which are the first nodes to die. There is no considerable enhancement on routing among the rest of the network.

Besides ants, other strategies can be found in the literature for energy-saving routing on sensor networks. One of these strategies, also related to BiO4SeL, is load-balancing (Puccinelli and Haenggi, 2009), a solution inherited from the telecommunications domain. Using any kind of infrastructure makes load-balancing task simpler. For instance, approaches found in Moussaoui and Naïmi (2005), Al-Karaki and Al-Mashaqbeh (2007), Iqbal et al. (2006) employ clustering in order to perform data fusion and head node relaying, and, consequently, to save energy.

Some other approaches for energy aware routing in WSN that do not necessarily employ computational intelligence can be found in the literature. For instance, in Shah and Rabaey (2002), the authors present the Energy Aware Routing (EAR) protocol, a reactive routing protocol for WSN where energy is considered for probabilistically choosing a path between source and destination. The EAR Addressing scheme relies on nodes' location information in order to perform routing. It was designed for low duty cycle ($\approx 1\%$) applications. As such, it may not be suitable for regular (continuous) monitoring. In order to save battery, sensor nodes are equipped with two radios: one low-power and low-bandwidth that remains constantly active, and other with higher bandwidth, consuming more power, however with a low duty cycle. Also, EAR assumes that nodes are aware of their location. This assumption could lead to inconsistent routing when sensor location is not available or is not reliable.

The EOLSR routing protocol (Mahfoudh and Minet, 2010) is an energy efficient enhancement of the Optimized Link State Routing (OLSR) (Clausen and Jacquet, 2003) for WSN and ad-hoc networks. Like other link state routing algorithms, EOLSR relies on topology dissemination in order to perform route discovery. This could lead to significant routing overhead, mainly when WSN has dynamic topology.

Another energy aware approach, called Reliable Energy Aware Routing (REAR) (Shin et al., 2007), is a distributed, on-demand, reactive routing protocol for Wireless Sensor Networks. Energy is taken into consideration in order to perform route selection. However, the main goal of the algorithm is reliability, and the network lifetime was not evaluated.

In Maleki et al. (2002), the authors propose Power-aware Source Routing (PSR), a source-initiated, on demand routing protocol for mobile ad-hoc networks aiming to maximize network lifetime. Unfortunately, the article does not provide enough design details that could allow the evaluation of PSR against other approaches.

From a deep evaluation of the features and drawbacks found in these approaches from the literature, we have noticed that ACO (Ant Colony Optimization) (Dorigo et al., 2006; Dorigo and Caro, 1999), described in further details in the next section, is indeed a promising method for optimizing resources in a WSN. However, it is hard to find one solution where the following premises are met at the same time: distribution, robustness, autonomy, dynamic behavior support, intelligence, multipath with load-balancing, and support for multiple sinks. This paper tries to fill this gap by proposing a new ant-based self-organization and routing protocol, named BiO4SeL (Biologically-Inspired Optimization for Sensor Lifetime), described in detail in Section 4, which aims to increase sensor network lifetime while featuring the above-cited characteristics. Aiming to facilitate the understanding of our proposal, the next section presents some background on ant