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Swarm intelligence based routing protocol for wireless sensor networks: Survey and future directions

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ABSTRACT

Swarm intelligence is a relatively novel field. It addresses the study of the collective behaviors of systems made by many components that coordinate using decentralized controls and self-organization. A large part of the research in swarm intelligence has focused on the reverse engineering and the adaptation of collective behaviors observed in natural systems with the aim of designing effective algorithms for distributed optimization. These algorithms, like their natural systems of inspiration, show the desirable properties of being adaptive, scalable, and robust. These are key properties in the context of network routing, and in particular of routing in wireless sensor networks. Therefore, in the last decade, a number of routing protocols for wireless sensor networks have been developed according to the principles of swarm intelligence, and, in particular, taking inspiration from the foraging behaviors of ant and bee colonies. In this paper, we provide an extensive survey of these protocols. We discuss the general principles of swarm intelligence and of its application to routing. We also introduce a novel taxonomy for routing protocols in wireless sensor networks and use it to classify the surveyed protocols. We conclude the paper with a critical analysis of the status of the field, pointing out a number of fundamental issues related to the (mis) use of scientific methodology and evaluation procedures, and we identify some future research directions.

1. Introduction

Wireless sensor networks (WSNs) [3] consist of a large number of autonomous nodes equipped with sensing capabilities, wireless communication interfaces, and limited processing and energy resources. WSNs are used for distributed and cooperative sensing of physical phenomena and events of interests. Usually, the nodes are statically deployed over vast areas. However, they can also be mobile and capable of interacting with the environment. In these cases, the network is more appropriately referred to as a robotic network and/or as a sensor-actor network. WSNs can be employed in a wide spectrum of applications in both civilian and military scenarios, including environmental monitoring, surveillance for safety and security, automated health care, intelligent building control, traffic control, object tracking, etc. (see [64,83] for general overviews).

From the point of view of information processing, in WSNs, aggregation of the sensed data and its use for statistical inference can be realized in a number of ways, resulting in different network architectures. The most studied architectures [79]

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include the cases in which individual sensor nodes send their readings towards: (i) a global monitoring node (commonly indicated as a *sink*), that performs full data aggregation and inference, (ii) intermediate sink nodes, that can individually or cooperatively process the data before sending the results to the global sink or locally trigger the appropriate actions, and (iii) a global sink, but with partial data aggregation being performed on the way as data packets are forwarded hop by hop from sensor nodes towards the sink. Cases (ii)–(iii) are commonly referred to as *in-network aggregation*, and are meant to optimize energy and bandwidth resources.

In a WSN, individual nodes have limited communication range and form an ad hoc network over a shared wireless medium. Both data and control packets need to be routed in multihop modality. Data communications can be established between the nodes in the network in order to support different activities. For instance, they can be directed from a sensor node to a monitoring node for inference (which is the most common communication pattern), from a sensor/monitoring node to another sensor/monitoring node with the aim of performing some form of local cooperation, or from a monitoring node to one or more sensor nodes in order to disseminate control information. The design and implementation of *routing* schemes that are able to effectively and efficiently support information exchange and processing in WSNs is a complex task. A number of theoretical issues and practical limitations must be thoroughly taken into account. First, in order to maximize *network's lifetime*, the mechanisms adopted for route discovery and information routing need to be energy efficient. Second, since the nodes usually operate in an unattended fashion, the network is expected to display *autonomic properties* [48], meaning that the protocols in use must be self-organizing and robust to failures and losses. Last but not least, the routing protocol must be able to handle *large and dense networks*, and the associated challenges resulting from radio interference and from the need to discover, maintain, and use potentially long multihop paths.

The requirements of routing protocols for WSNs are similar to those of routing protocols for *mobile ad hoc networks* (MANETs) [69]. However, compared to MANETs, in the case of WSNs, the restrictions on energy efficiency are more compelling, nodes are usually static, and the networks are in general assumed to be much larger. Moreover, while in the case of MANETs traffic patterns strictly depend on the application and are address centric, in WSNs they are usually *data-centric* (see Section 4.5) and, mainly, are in the form of direct and reversed multicast trees rooted at monitor nodes.

So far, a large number of different routing protocols have been proposed for WSNs based on a variety of different mechanisms and optimization criteria. General overviews can be found for instance in [2,4,10,46]. In this paper, we focus on routing algorithms for WSNs that have been designed according to the principles of swarm intelligence and review the most prominent ones.

Swarm intelligence (SI) [9,27,47] is a relatively novel field that was originally defined as "*Any attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insects and other animal societies*" [9]. However, nowadays SI refers more generally to the study of the collective behavior of multi-component systems that coordinate using decentralized controls and self-organization. From an engineering point of view, SI emphasizes the bottom-up design of autonomous distributed systems that can show adaptive, robust, and scalable behaviors. The SI frameworks encompasses other popular frameworks such as *Ant Colony Optimization* (ACO) [24,22] and *Particle Swarm Optimization* (PSO) [8,47]. Most of the work in the field of SI has been and still is inspired by collective behaviors observed in natural systems such as insect societies (e.g., ACO), flocks of birds (e.g., PSO), and schools of fishes. The basic mechanisms at work in these biological systems have been reverse engineered and properly adapted to design novel algorithms for distributed optimization and control. The same process has also driven the development of the large majority of SI-based routing algorithms for WSNs. In fact, the design of most of these algorithms has been inspired by the foraging behaviors of ant colonies, and, more recently, also of bee colonies. The main rationale behind this fact lies in the observation that these insect societies, as a collective unit, do actually solve routing problems. They need to discover and establish paths that can be used by the single insects to effectively move back and forth from the nest of the colony to sources of food. These paths are the result of the synergistic interactions among a large number of relatively simple individuals that concurrently sample paths and inform others about their characteristics using a variety of communication schemes, including indirect (e.g., pheromone-mediate communication in ants) and direct (e.g., waggle dance in bees) ones. The foraging behaviors of these insect colonies are shown to be adaptive to environmental variations, robust to losses of individuals, and fully distributed and scalable.

The analogy between these biological systems and routing in networks, and in particular in WSNs, is strict. The ant/bee colony can be seen as a distributed adaptive system of smart control packets. Each of these packets makes little use of computational and energy resources to explore the network/environment. They efficiently cooperate with each other by releasing at the nodes information about the discovered paths and their estimated quality. Due to these similarities between foraging behaviors in insect societies and network routing, in the last decade, a relatively large number of SI-based routing protocols have been developed for wired networks, satellite networks, MANETs, and, more recently, WSNs. This paper is the first attempt to review and critically discuss the most prominent SI-based routing algorithms that have been developed for WSNs. This survey aims at: (i) making a wide audience aware of the existence and of the usually good performance of a number of SI-inspired WSN routing protocols, (ii) highlighting strengths and weaknesses of the proposed algorithms with respect to the central constraints and objectives of routing in WSNs, (iii) pointing out a number of methodological flaws common to many work proposing and evaluating WSN routing protocols based on SI, and (iv) identifying and proposing a scientifically sound experimental methodology and new research directions for this relatively novel research domain.