Review of nature-inspired methods for wake-up scheduling in wireless sensor networks

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ABSTRACT

Over the last few decades, algorithms inspired by nature have matured into a widely used class of computing methods. They have shown the ability to adjust to variety of conditions, and have been frequently employed for solving complex, real-world optimization problems. They are especially suitable for problems that require adaptation, and that involve optimization of complex, distributed systems, operating in dynamic environments. Among other application domains, nature-inspired methods have been extensively used in the areas of networking in general, and wireless sensor networks in particular. Energy management and network lifetime optimization are two great research and implementation challenges for wireless sensor networks. Duty cycle management, synchronization, and wake-up scheduling are complementary approaches that facilitate this complex optimization process. This review focuses on the intersection of nature-inspired computing and wake-up scheduling algorithms for wireless sensor networks. It describes the state-of-the-art in these fields and provides an up-to-date review of the most recent developments in this interdisciplinary domain. It discusses the motivation for using nature-inspired methods for wake-up scheduling, and presents related open issues and research challenges.

1. Introduction

The ability of nature-inspired computing methods to handle complex, multimodal problems has lead to their widespread use in many non-trivial, real-world optimization applications. Two major classes of nature-inspired methods, evolutionary computing and swarm intelligence, are based on two different types of natural systems, and represent two diverse problem-solving strategies. Evolutionary computation draws inspiration from Lamarckian and Darwinian understanding of biological evolution, Mendelian inheritance, and survival of the fittest. Methods from this family excel in solving global, centrally managed optimization tasks [1–3]. Swarm intelligence, on the other hand, is inspired by the social behaviour of groups of insects, fish, amphibians, mammals, and even human communities. It is designed to solve problems in a decentralized, distributed way, through interactions and local communication of many simple agents. It mimics emergent behaviours, such as self-organization [2,4,5], observed in complex biological systems. Intuitively, swarm intelligence can be applied in areas that benefit from these features. Other types of nature-inspired algorithms are also gaining on importance. For example, cellular and developmental systems [6] use simple rules and local interactions to provide self-organization for practical applications in complex, distributed systems.

Although global optimization and distributed self-organization methods are, in principle, suitable for different types of tasks, their application areas often overlap. The applications of these methods include various real-world and industrial problems [5,7], as well as traditional, well-studied problems such as real-parameter optimization [8], vehicle routing [9], linear ordering [10], independent task scheduling [11], travelling salesman problems, and many others. Nature inspired methods have been recently applied also in the area of Wireless Sensor Networks (WSN). This association is very natural, as the distributed nature of WSN emphasizes the need for self-organization, automatic configuration, and adaptation to local conditions – attributes found in many nature-inspired methods [12]. These requirements arise on many different levels and for various tasks, including resource sharing, structure formation/coverage optimization, and system behaviour [13].

Nature-inspired methods have been extensively used to provide required functionality in the areas of networking in general [14], and WSN in particular [13,15–20]. For example, Charalambous and Cui [16] used a clustering algorithm inspired by

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biological intercell signalling schemes and a cluster head selection scheme based on biological lateral inhibition model for energy-aware WSN topology management. Another nature inspired approach to WSN clustering based on evolutionary computation was proposed by Kuila et al. [21]. A method for data aggregation, propagation, relaying, and correlation, based on the observation of the effects that different types and intensity of pinpricks have on human limbs was proposed in [22]. A bio-inspired method for time synchronization in acoustic event detection systems based on the behaviour of groups of flashing fireflies was developed by Nunez et al. [23]. An overview of applications of ant-inspired methods for solving different tasks in the area of WSN was prepared by Hong et al. [17]. Nature-inspired methods have also been used to address routing [24–26] and broadcasting problems [20,27].

These examples clearly demonstrate that nature-inspired approaches are becoming a well-established class of methods suitable for solving various problems in the area of WSN. Indeed, the novel structures, architectures, and properties of WSNs facilitate innovation. However, at the same time, they bring new development challenges that require a complex multi-layer design and optimization approaches [28].

1.1. Related reviews

One of the most important non-functional requirements for WSNs is the maximization of their operational lifetime. In order to conserve energy, such networks often operate with low duty-cycle, where nodes alternate between sleeping and active modes. The transmission, reception, and listening states of current wireless modules have comparable power requirements. As a result, keeping the radio in any of the active states is one of the most significant factors contributing to high energy consumption of a wireless sensor node. Conversely, putting the wireless module to a sleep mode can reduce the power consumption of the node by several orders of magnitude. Therefore it is essential for the energy-restricted wireless node to exploit low-power modes and put its wireless module to sleep as much as possible.

Various sleeping techniques for reducing energy dissipation are discussed in [29]. The authors classify wake-up techniques into three groups, depending on the source of the wake-up event. Systems driven by *internal events*, generated by a controller software, rely on an alarm set according to a schedule. The node is put to a low-power state until the alarm expires. The device then performs pre-programmed tasks and goes back to sleep. The externally generated events include radio-controlled and environmentally controlled wake-ups. The *radio-controlled* techniques assume that the node is equipped with a low-power wake-up radio, capable of waking-up the node remotely. The *environmentally controlled* wake-ups react to events generated either by sensors or by an energy harvesting unit of the node. The remaining part of [29] provides an overview of sleeping and routing techniques. The sleeping approaches are classified to groups by layers of the wireless protocol stack. The authors present a typical representative of each protocol and then provide extensions that target various energy efficiency-related weaknesses.

A typical wireless sensor node relies on batteries to cover its energy needs. Once the batteries are depleted, the node is not operational anymore and requires maintenance to restore its functionality. An alternative is to implement energy harvesting to collect ambient energy from the environment. Harvested energy can be used directly or transferred to an energy buffer for future use. The possibility of recharging the energy storage dramatically changes the objectives of energy management in wireless sensor nodes [30]. While the battery-powered nodes strive to minimize their energy consumption and thus to prolong their operational life as much as possible, the harvesting-enabled, environmentally powered nodes focus on adaptive and efficient use of available energy. In other words, harvesting-enabled nodes must match their energy consumption patterns to environmental energy availability, rather than to minimize the overall amount of energy they consume.

Wake-up scheduling techniques for WSNs with energy harvesting capabilities are reviewed in [31]. This survey first explains hardware differences between battery-powered WSNs and environmentally powered wireless sensor networks (EPWSNs), and provides a brief overview of energy harvesting and storage technologies. The authors then introduce a classification of wake-up scheduling and explain its basic principles. Each scheduling scheme is explained and discussed from an energy harvesting perspective. The survey covers synchronous, asynchronous and hybrid scheduling techniques, all driven by internal events.

Another notable review on energy conservation in WSNs [32] covers not only wake-up scheduling, but also techniques of data acquisition and reduction. This comprehensive article puts wake-up scheduling in a broader perspective of energy-restricted WSN issues and challenges.

Jabbar et al. [33] explicitly show the strong connection between the world of nature and WSNs. Their review describes a number of biologically inspired algorithms and their counterparts in nature. The authors then identify various areas of WSN research and development where nature-inspired algorithms can be applied and provide examples. They select the Ant Colony Optimization (ACO) as a representative of biologically inspired algorithms, show the relationship between ACO and WSN, and provide reasons why ACO is suitable for WSN optimization tasks.

This new review focuses on the intersection of nature-inspired computing and wake-up scheduling algorithms for WSNs. It describes the state-of-the-art in both domains and provides an up-to-date review of the most recent developments in this area. As such, it outlines new application possibilities for nature-inspired methods and, at the same time, contributes to a systematic expansion of tools available for wake-up scheduling and synchronization in WSNs.

1.2. Organization

This review is organized as follows. Section 2 provides the background information on the subject of this survey. In particular, it introduces WSNs, defines the problem of wake-up scheduling, and provides a concise overview of major nature-inspired methods often used to solve this problem. The main body of the review in Section 4 provides an account of nature-inspired approaches to wake-up scheduling in WSN over the last decade. The survey is organized along the nature-inspired methods introduced earlier. Section 5 provides a different perspective of the reviewed articles by grouping them according to their functions in the communication protocol stack. It also integrates the findings presented in the review and discusses the reasons behind using nature-inspired methods for wake-up scheduling. The review concludes with a summary of open issues and challenges.

2. Wake-up scheduling in wireless sensor networks

2.1. Wireless sensor networks

Wireless sensor networks have recently emerged as a new distributed computing paradigm, sometimes seen as a step towards ambient intelligence [34] and Internet of Things (IoT). They provide an efficient connection between physical and virtual