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A fully-decentralized semantic mechanism for autonomous wireless sensor nodes

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ABSTRACT

Semantic sensor neighborhood has been used to organize nodes into clusters in wireless sensor networks. Semantic clusters are self-adaptable according to information collected/gathered from sensor nodes and collaboratively processed. In this paper, we show that semantic clustering based on fully-decentralized semantic neighborhood mechanisms provides an energy-efficient solution, thus contributing to increase the autonomy of sensors. Our results show that fully-decentralized semantic clustering outperforms partially decentralized semantic clustering algorithms besides traditional clustering algorithms regarding the energy consumed to establish and maintain the clusters.

1. Introduction

Wireless Sensor Networks (WSNs), composed of sensors, actuators and embedded communication hardware, play a fundamental role in the connection of the physical and digital worlds as they monitor physical variables, gather, transmit and eventually process the collected data and may even act upon the environment (Delicato et al., 2013). An important requirement in WSN is using devices that allow self-management and self-adaptation in the face of unpredictable conditions, such as hardware or software failures, or the intrinsic variability of the dynamic environment and of such networks. Moreover, most deployments of WSNs require an unattended operation. Considering this requirement of unattended operation in a highly dynamic environment, the autonomic computing (Kephart and Chess, 2003) paradigm is a promising solution to be adopted in such networks in order to enable self-management of the nodes. The autonomic computing paradigm defines computational systems able to manage themselves with none or minimal human intervention. Self-organization, self-configuration, self-optimization, self-healing, and self-protecting are some basic properties of autonomic computing systems (the so-called self-* properties). In the context of WSN, the autonomic properties can provide functions such as improvement of the network performance, repair hardware or software failures and protection against malicious attacks. More information about how the autonomic properties can be applied to the WSN can be found in Portocarrero et al. (2014).

In general, the autonomy of the networking systems is achieved through the collaboration of a set of self-managed entities (Denko et al., 2009). Enabling sensor nodes to perform self-management functions is a challenge since the energy constraint is still a critical issue in WSNs. Despite the fact that researchers have been investigating the use of alternative possibilities for power sources to sensor nodes, such as solar cells, thermal energy, piezoelectric, and several techniques of energy harvesting (Seah et al., 2009; Sudevalayam and Kulkarni, 2011), the most common power source is still a battery (Hermeto et al., 2014). External power sources often exhibit a non-continuous behavior so that a battery is still required even when adopting those sources (Sachan et al., 2012). Thus, sensor nodes have to rely on batteries for communication and information gathering. Therefore, using the scarce energy resources in an efficient and optimized way is always a key requirement in any wireless sensor network design. Any protocol, algorithm or architecture for such networks must take into account this requirement. For large-scale networks and to achieve higher energy efficiency related to data transmission, a commonly used technique is the clustering of the network, generating a hierarchical logical topology. In such approach, the whole set of network nodes is divided (according to some criterion, often the geographical proximity) in partitions controlled by an elected leader node, often called cluster head (CH). Nodes inside a cluster

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only communicate with their respective CH. Thus, nodes in a cluster save transmission energy since the distance among cluster members and their respective CH is usually smaller than the distance between these cluster members and the sink node. Clustering can also be beneficial for purposes of energy saving since it favors data aggregation procedures. Cluster members can collaborate about recent data measurements and determine how much information should be transmitted to the application. By averaging data values collected within the cluster, the algorithm can trade data resolution for transmission power (Zomaya and Lee, 2012). Also for energy saving, in areas where there is a redundant number of sensors, a clustering algorithm can be used to select which nodes better represent data samples for the region and which ones can be put in a power-save mode.

Comparing with flat routing techniques, clustering approaches are potentially more effective in dense networks and for periodic applications. Flat-routing techniques build an optimal (with added complexity) path topology before the network starts working (Lindsey et al., 2002; Lin et al., 2010; Tan and Körpeoğlu, 2003). But, as these techniques need a global routing information, they suffer from density issues. For example, in SHM domain (see Section 5) high densities of sensor nodes are common. Besides, flat routing presents collision overhead and does not guarantee fairness. To mitigate all of these problems, cluster-based strategies (Heinzelman et al., 2002; Younis and Fahmy, 2004; Wei et al., 2011) form groups (clusters) of neighboring nodes via local message gossiping from a flat topology. Therefore, for periodic reporting we would say that it is better to have cluster organized networks than flat ones.

Semantic clustering (Rocha et al., 2012) is a recent technique that utilizes the semantic of the data collected from nodes according to the semantic of applications instead of using only the distance as a similarity criterion to group sensor nodes in a cluster (like traditional clustering mechanisms, Liu, 2012; Katiyar et al., 2011; Schaffer et al., 2012). The set of semantically related sensors is defined as semantic neighbors. Semantic neighbors into a semantic cluster are responsible for sensing the target area at intervals specified by the application and are subordinated to their semantic collectors. Semantic collectors are responsible for receiving their collected data and forwarding the received data directly to the sink node via a multihop transmission. The semantic clustering has the following advantages when compared to the traditional clustering methods (Rocha et al., 2012): (i) improves collaborative information processing so that the communication, costs, and energy consumption can be reduced and the self-management can be achieved; (ii) favors applying aggregation methods only to semantically related data and thus, eliminate redundancy before sending messages to the sink; and (iii) improves the data accuracy provided to the application.

On one hand, the design of self-organization and self-configuration schemes is considered as the most likely solution to the challenges of using WSN in recent environments (e.g. Internet of things). Such environments, in general, call for distributed intelligence and make smart objects autonomously react and adapt to a wide range of different situations without human interventions, besides providing an additional degree of flexibility (Ding et al., 2013; Miorandi et al., 2012). On the other hand, the large scale of WSN deployed in this type of scenarios calls for solutions that are highly energy efficient so that the system can operate continually and still meeting application requirements properly. In this work, we leverage both concepts of autonomic computing and semantic clustering in order to endow WSN with autonomic properties such as self-organization, self-configuration and self-adaptation aiming at energy efficiency.

In this paper, we describe DSENSE (Decentralized SElf-organization mechaNism for Sensor nEtworks), a fully decentralized semantic clustering mechanism providing autonomic properties. DSENSE is responsible for self-grouping a set of semantic neighbors into clusters based on neighborhood relationships established using the semantic of the target applications. Each node has a fuzzy inference system (FIS) implemented on it and makes a collaborative decision about semantic neighborhood relationships on the network. A fuzzy inference system is a well-suited approach for WSNs for providing a node level abstraction to interpret the meaning of the values collected from sensor nodes. Moreover, FIS systems use a small portion of the nodes' memory, demand a smaller execution time for completion, and adopts simpler flat mathematics than other controlling approaches (Sabri et al., 2012).

Besides self-organization, DSENSE provides the nodes with self-configuration and self-adaptation properties. The self-configuration characteristic provides a configuration of the nodes related to energy consumption according to their semantic neighborhood relationships. For example, the unrelated nodes can be self-configured to remain working at a lower duty cycle in order to save energy since they are not involved to the target event monitored by the applications. Depending on the target application, we can have an opposite scenario where the related nodes (semantic neighbors) can be self-configured to operate according to a duty cycle in order to save energy and do not deplete their batteries. Duty cycling is a well-known technique for saving energy in WSNs and can be defined as the fraction of time the nodes are active during their lifetimes (Anastasi et al., 2009). Self-adapting characteristic is related to the activity of clustering the nodes. Self-adapting is responsible for creating a semantic cluster whenever a new event occurs. An event can be a new occurrence of the event monitored by the target application, the arrival of a new application in the WSN and consequently, creation of a new domain rule, or the death of some semantic neighbors. DSENSE improves the sensor autonomy by providing collaborative information processing, refined data aggregation and self-management aiming to save energy.

This work extends our previous work (Rocha et al., 2012) in several ways. Specifically, we make the following main contributions in this paper: (i) a semantic clustering mechanism (called DSENSE) based on a fully-decentralized semantic neighborhood relationships specification process in which we eliminated the need of an extra phase of hierarchic clustering present in Rocha et al. (2012), thus bringing benefits such as avoiding the communication overhead of the setup phase; (ii) provision of a foundation for the proposed mechanism that relies on the autonomic computing theory; and (iii) use of our algorithm in conjunction with a totally decentralized version of a damage localization application (called DSensorSHM). Besides, we performed several experiments to evaluate the consumption of energy resources from the network, including experiments concerning the energy save of our clustering mechanism related to another semantic clustering.

In this paper, we used the real implementation of an application for structural health monitoring (SHM) domain as a case study. A lot of WSN nodes in SHM applications work in environments where a direct power supply is not available (e.g. nodes located upon spinning wind power blades, Wang et al., 2012). Therefore, any enhancement of the nodes lifetime through the use of low-power technology is a major benefit. We performed some experiments using Micaz nodes powered by batteries in order to demonstrate that DSENSE can provide an energy-efficient and collaborative data processing among sensor nodes in such a scenario. In that context, our proposal can be considered a mechanism using low-cost and self-organized sensors to process data collected from sensors and determine if some variable falls outside of its expected values. The data can be automatically sent to a gateway node that can then warn the user of potential structural