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Edge betweenness centrality: A novel algorithm for QoS-based topology control over wireless sensor networks

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ABSTRACT

In this paper we propose a novel topology-control algorithm, called *edge betweenness centrality* (EBC). EBC is based on the concept of *betweenness centrality*, which has been first introduced in the context of *social network analysis* (SNA), and measures the "importance" of each node in the network. This information allows us to achieve high *quality of service* (QoS) in wireless sensor networks by evaluating relationships between entities of the network (i.e., edges), and hence identifying different roles among them (e.g., brokers, outliers), thus controlling information flow, message delivery, latency and energy dissipation among nodes. The experimental evaluation and analysis of EBC in comparison to other state-of-the-art topology control algorithms shows that our algorithm outperforms the competitor ones in all observed cases.

1. Introduction

Recent advances in low-power and short-range-radio technology arisen during last few years have enabled a rapid development of wireless sensor networks (WSN). The range of applicability of WSN is very wide, and spans from environmental sensor networks monitoring (environmental) parameters, such as temperature and humidity, to industrial control robotics, from disaster prevention systems to emergency management systems, and so forth. Sensors are tiny, usually battery-operated devices with radio and computing capabilities, which are used to cooperatively monitor physical or environmental conditions.

As regards research issues of sensor networks, several efforts have been done by both the academic and industrial research community, mainly in the context of routing algorithms (Heinzelman et al., 2000; Intanagonwiwat et al., 2003), network coverage aspects (Thai et al., 2008; Liu et al., 2005; Shih et al., 2009), storage issues (Mathur et al., 2006; Sheng et al., 2006) and topology control (Manolopoulos et al., 2010; Shen et al., 2007; Liu and Li, 2003). The common denominator of all these efforts is represented by the goal of maximizing energy conservation across the network, in order to gain efficacy and efficiency, as maximizing energy conservation corresponds to maximizing network lifetime. For instance, as regards specific data management issues over sensor networks (Cuzzocrea, 2009), maximizing energy conservation means that multi-step maintenance and query algorithms can be executed over the target sensor network, thus involving in more effective data management capabilities rather than the case of single-step algorithms. Another motivation of the need for energy conservation in sensor networks relies on inherent technological properties of sensors. In fact, sensors are unlikely to be recharged, especially since they may be deployed in unreachable terrains, or, in some cases, they may be disposed after the monitoring application running over the target network ends its execution.

In order to reduce energy consumption, *topology-control algorithms* have been proposed in literature (Shen et al., 2007; Liu and Li, 2003; Hackmann et al., 2008; Huang et al., 2002; Liu et al., 2008; Li et al., 2005; Pan et al., 2003; Ramanathan and Rosales-Hain, 2000; Tseng et al., 2002; Wattenhofer et al., 2001; Jia et al., 2004). The final goal of these algorithms consists in reasoning-over and managing the topology of the graph modeling the target sensor network in order to reduce energy consumption as much as possible hence increase network lifetime accordingly. A different line of research, which appeared recently, proposes driving sensor network topology control in terms of *quality of service* (QoS) requirements (Liu et al., 2008) over the target sensor network itself. Several QoS-based requirements have been designed and developed in this context, depending on the particular application scenario ranging from real-time video and content provisioning to time-critical control systems, and so forth (see Liu et al., 2008 for a complete survey of typical case studies). Given a set of nodes performing a specific task which is critical for

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the target sensor network application (e.g., sink nodes in environmental sensor networks), the basic idea behind topology-control algorithms is to select from the target network appropriate *logical neighbors* of the former nodes, namely a subset of *physical neighbors* of the former nodes that can be used to perform application-specific procedures (e.g., message transmission) without the need of involving the rest of physical neighbors during the execution of these procedures. QoS-based topology-control algorithms select the suitable set of logical neighbors such that input QoS requirements can be satisfied.

Inspired by motivations above, in this paper we investigate the problem of QoS-based topology control over homogenous WSN. Given (i) a set of wireless nodes in a plane such that nodes have the same transmitting power and bandwidth capacity and (ii) QoS requirements between node pairs, our problem consists in finding a network topology that can simultaneously meet the input QoS requirements and minimize the maximal power utilization ratio of nodes. In particular, in our research QoS requirements are modeled in terms of simple-yet-effective node connectivity, so that message transmission can be ensured (while node connectivity can be preserved in order to ensure correct message delivery), and network lifetime can be increased as much as possible accordingly. In this scenario, avoidance of hotspots also needs to be carefully considered. Therefore, adaptive tasks that depend on the current logical neighbor seem to play the role of most promising strategy to be investigated in order to avoid fast battery depletion.

Looking at deeper details, in our research we propose a *weighted, bidirectional topology-control algorithm*, called *edge betweenness centrality* (EBC), and experimentally evaluate this protocol against a set of low complexity, distributed topology-control algorithms, namely Gabriel Graph (GG) (Gabriel and Sokal, 1969), Relative Neighborhood Graph (Toussaint, 1980) and Closeness Centrality (Freeman, 1979). Fundamentals of our approach can be found in the conceptual basis drawn by several centrality measures that have been proposed in order to model and evaluate the *importance* of a node in a network (Girvan and Newman, 2002; Brandes, 2008). These measures have been initially applied in the context of *social network analysis* (SNA), and later to other areas as well, such as biological networks (Yoon et al., 2006).

Freeman (1977, 1979) defines the *betweenness* of a node as a possible centrality measure for detecting the importance of that node within the target network, thus achieving the fundamental concept of *betweenness centrality*. This concept found on the property stating that vertices that occur on many shortest paths between other vertices have higher betweenness than those with lower occurrences. Closeness centrality (Freeman, 1979) pinpoints vertices that tend to have short geodesic distances from other vertices with in the network. In network analysis, closeness is preferred over shortest-path length, as closeness gives higher values to more central vertices (Freeman, 1979). Finally, Eigenvector centrality (Bonacich, 1972) assigns relative scores to all nodes in the network based on the principle that connections to high-scoring nodes provide to the global score of the actual node a higher contribution rather than the one provided by connections to low-scoring nodes. For instance, Google's PageRank (Brin et al., 1999) is a variant of the eigenvector centrality measure. Our research focuses on a meaningful variation of the betweenness centrality concept, namely *edge betweenness centrality* (Girvan and Newman, 2002; Newman, 2004), and its application to the leading context of sensor networks.

Summarizing, the contributions of this paper are the following:

- an innovative weighted, bidirectional topology-control algorithm, EBC, and its application to the leading context of sensor networks;
- a comprehensive experimental evaluation of algorithm EBC, and its comparison with a very popular topology-control algorithm, GG, on top of the well-known simulation environment *JSim* (Sobeih et al., 2006);
- critical analysis and discussion on performance of the two comparison topology-control algorithms, EBC and GG.

The rest of the paper is organized as follows. In Section 2 we discuss related work on topology control algorithms over networks. Section 3 describes in detail algorithm EBC. Section 4 focuses on state-of-the-art distributed and low complexity methods for topology control that is related to our research. Section 5 is devoted to the experimental evaluation and analysis of EBC in comparison to other state-of-the-art topology-control algorithms. Finally, Section 6 contains conclusions and future work of our research.

2. Related work

There exists considerable related work addressing topology-control issues over networks, even focalizing on QoS-based topology control. As regards studies on topology management for energy conservation in networks, it has been demonstrated that both powering off redundant nodes and lowering radio power while maintaining node connections can contribute to efficient power saving. In light of this assumption, Shen et al. (2007) introduced the Local Shortest Path (LSP) algorithm. In the LSP approach, each node makes use of link weights in order to compute the shortest paths between itself and neighboring nodes. Then, all second nodes on these shortest paths are selected as logical neighbors. The final step of algorithm LSP involves in adjusting the power transmission of so-selected logical nodes to save energy.

Li et al. (2005) instead propose algorithm Localized Minimum Spanning Tree (LMST), which computes a "power-reduced" network topology by constructing a minimum spanning tree over the network in a fully distributed manner. The aim of this approach relies in the evidence that the power-reduced network is less energy-consuming than the original network.

EasiTPQ (Liu et al., 2008) is another QoS-based topology-control algorithm. EasiTPQ found on the assumption that each node in the network has different functionalities during data transmission, e.g., some nodes bear more data relay tasks whereas some other nodes only transmit data generated by themselves. In order to achieve the desired QoS, EasiTPQ schedules as active nodes that are more involved in relaying data tasks rather than generating data flows.

Wattenhofer et al. (2001) propose a simple-yet-effective distributed algorithm according to which each node makes local decisions about its transmission power, such that these local decisions then collectively guarantee global connectivity of the network. Specifically, based on directional information, a node grows it transmission power until it finds a neighbor node in every possible direction. The resulting network topology increases network lifetime by reducing transmission power, and, in turn, even traffic interference, thanks to the deriving availability of low-degree nodes. Huang et al. (2002) further extend Wattenhofer et al. (2001) to the case of using directional antennas.

Ramanathan and Rosales-Hain (2000) describe a centralized spanning tree algorithm for building connected and bi-connected networks with the goal of minimizing the maximum transmission power for each node. Two optimal, centralized algorithms, namely CONNECT and BICONN-AUGMENT, are proposed for the case of static networks. Both are greedy algorithms, and resemble