Biologically Inspired Communication Network Control

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1. Introduction

The research group of Osaka University in the field of information technologies and bioinformatics engineering started a project entitled "New Information Technologies for Building a Networked Symbiosis Environment" in 2002 [1]. The aim of our project is to develop new information systems based on biologically inspired approaches with the knowledge gained through analyzing the cell behavior of various living organisms, and the author's group concentrates on biologically inspired communication network control. However, we have noticed that a direct application of those studies into our study is still immature. Meanwhile, we have decided to use well-established, biologically inspired mathematical models and apply those to the control methods for communication networks, especially for new emerging networks like P2P (peer-to-peer) networks, (mobile) wireless ad hoc networks and sensor networks.

Historically, in computer networks, including the Internet, it has been assumed that static nodes (i.e., routers) serve packet forwarding based on the routing protocol. Then, new infrastructures like IntServ and DiffServ were developed, though those are still not spreading in use as expected. The adequate operation of those networks require careful network planning in order to satisfy the objectives of those networks: QoS (Quality of Service) guarantees in IntServ and QoS differentiation in DiffServ, respectively.

On the other hand, the above-mentioned new emerging networking technologies have a quite different structure from the traditional networks; the node itself may move, and on-demand search is necessary for finding the shared information in P2P networks and the peer location in ad hoc networks. For those networks, we consider that the following three characteristics for network control are mandatory:

Expandability (or scalability): We need to cope with the growing number of nodes and end users, and a wide variety of devices attached to the network. More importantly, the number of nodes and terminals has never been predicted in advance. This means that the conventional network planning method becomes meaningless.

Mobility: In addition to the users' mobility, we should also consider the mobility of network nodes in ad hoc and sensor networks. This implies that stable packet forwarding by nodes cannot be expected.

Diversity: We need to support a wide variety of network devices generating traffic in a quite different nature from existing network applications, implying that a single, universal network infrastructure like IntServ and DiffServ has no means to meet the different demands in newly emerging network applications.

The only solution to meet the above characteristics seems to be that end hosts must be equipped with adaptability to the current network status for finding peers and/or for controlling congestion. From this reason, the biologically inspired approach is promising since it is known that it has the excellent feature of adaptability, though it is rather slow to adapt to environmental changes. Of course, biologically inspired approaches for information technologies are not new, but most of those have been concentrated on the optimization problems of network controls. On the contrary, we are focusing on the adaptability, robustness, and self-organization properties of the biological system. Especially, our main purpose of the project is to learn the symbiotic nature of the biological system [2].

In this article, we introduce a new network control method inspired by biology, in order to explain why we need self-organized control in the sensor network. We are now developing the experimental system using the developer's toolkit for the sensor networks. Based on our experiences, we also report the lessons learned in the actual implementation of the biologically inspired approach. Lastly, we present the future direction of our project.

2. Self-Organized Sensor Networks: An Example

2.1. Requirements on Sensor Network Design

With the development of low-cost microsensor equipment that has the capability of wireless communication, sensor network technology has attracted the attention of many researchers and developers [3]. By deploying a large number of multifunctional sensors in a monitored region and composing a sensor network of them, one can remotely obtain information on the behavior, condition, and position of elements in the region, using wireless channels.

Sensor nodes are distributed in a region in an uncontrolled and unorganized way to decrease the installation cost and eliminate the need for careful planning. Thus, the method used to gather sensored information should be scalable to the number of sensor nodes; robust to the failure and disruption of sensor nodes; adaptable to addition, removal, and movement of sensor nodes; inexpensive in power consumption; and fully distributed and self-organizing without a centralized control mechanism. Several research works have been done in developing schemes for data fusion in sensor networks (see [4]). However, they require so-called global information such as the number of sensor nodes in the whole region, the optimal number of clusters, the locations of all sensor nodes, and the residual energy of all sensor nodes. Consequently, they need an additional — and possibly expensive and unscalable — communication protocol to collect and share the global information. Thus, it is difficult to adapt to the dynamic addition, removal, and movement of sensor nodes.

2.2. Our Approach

We have proposed an efficient scheme for data fusion in sensor networks where a large number of sensor nodes are deployed [5]; in such networks, nodes are randomly introduced, and occasionally die, or sometimes change their locations. We consider an application that sensored information is periodically propagated from the edge of a sensor network to the sink node. We do not assume that all sensor nodes are visible to each other, as in other research work. An administrator does not need to configure sensor nodes before deployment.

In periodic data fusion, power consumption can be effectively saved by reducing the amount of data to send, avoiding unnecessary data emission, and turning off unused components of a sensor node between data emissions. As an example, such data fusion can be attained by the following strategy on a sensor network where sensor nodes organize a tree whose root is the sink node in a distributed manner. First, leaves — i.e., sensor nodes — that are the most distant from the sink node, simultaneously emit their sensored information to their parent nodes at a regular interval. The parent nodes, which are closer to the sink node, receive information from their children. They aggregate the received information with locally sensored information to reduce the amount of data to send. Then, they emit it at a timing that is synchronized with the other sensor nodes at the same level in the tree. Likewise, sensored information is propagated and aggregated to the sink node. As a result, we observe a concentric circular wave of information propagation centered at the sink node.

To accomplish the synchronized data fusion without any centralized controls, however, each sensor node should independently determine the cycle and the timing at which it emits a message to advertise its sensored information based on locally available information. The ideal synchronization can be attained by configuring sensor nodes prior to the deployment, provided that the clocks of sensor nodes are completely synchronized, sensor nodes are placed at the appropriate locations, and that they maintain their clocks through their lifetime. However, we cannot realistically expect such an ideal condition. This is the reason that we introduce the biologically inspired self-organizing approach to the sensor network.

Self-organized and fully-distributed synchronization can be found in nature, as is widely known in the literature. For example, fireflies flash independently, at their own interval, when they are apart from each other. However, when a firefly meets a group, it adjusts an internal timer to flash at the same rate as its neighbors by being stimulated by their flashes. Consequently, fireflies in a group flash in synchrony. Mutual synchronization in a biological system is modeled as pulse-coupled oscillators [6]. In [7], the authors proposed a management policy distribution protocol based on firefly synchronization theory. The protocol is based on gossip protocols to achieve weak consistency of information among nodes. The rate of updates is synchronized in a network through pulse-coupled interactions. They verified that their protocol is scalable to the number of nodes in terms of the average update latency. They attempted to distribute a management policy, whereas our application is designed to collect sensored information to a sink node. By adapting the pulse-coupled oscillator model, we can obtain a fully distributed, self-organizing, robust, adaptable, scalable, and energy-efficient scheme for data fusion in wireless sensor networks. By observing the signals that neighboring sensor nodes emit, each sensor node independently determines the cycle and the timing at which it emits a message to achieve synchronization with those neighboring sensors and thus draw a concentric circle.

2.3. Our Experiences

By conducting simulation experiments with several modeling assumptions, we confirmed that our proposed method works well, which means that mathematical model is good for achieving self-organized, scalable control for data fusion. Furthermore, we have developed the method using MOTE, the developer's toolkit for the sensor network [8], to verify our method in the actual environment. However, we found that our method did not work properly without careful tuning of the protocol in implementation. A most difficult problem was due to the unreliable nature of the wireless links. In the case of a firefly, the light can reach other fireflies without attenuation. On the other hand, on the wireless link, messages sometimes reach the neighbor nodes and sometime not. The determination on the level of sensor nodes relies on whether each node can receive the control message from the upper level of nodes, originated by the sink node. However, the sensor node sometimes receives unexpected messages from the other node, which was originally recognized to be located far from the node. Our solution is to filter out those messages in order to treat it as an exceptional one. Then, we obtained the results that we expected. The remaining problem is that a simple filtering method does not still work correctly in unreliable air circumstances, e.g., in a room where a reflected wave carries the message over a long distance. It is clear that the sole biologically inspired approach cannot solve our problem and the other robust protocols should be incorporated for the entire data fusion network. In our current case, the robust tree construction method is at least necessary.

3. Biologically Inspired Symbiotic Networks

Essentially, the network users are competitive in the sense that they want to dominate network resources in order to maximize the individual's QoS during its communication. Then, it becomes important to achieve a fair share of the network resources among active users. The mathematical ecology says that the system would be stable if the effect of self-inhibitive action is larger than the effect of inhibitive action by others. This implies that if we successfully incorporate such a mechanism into the communication network field, we are able to establish a stably operated and fairly shared network, which we call the symbiotic network.

TCP is a good example for considering network symbiosis. Of course, TCP is originally implemented in a distributed manner, and it is self-adaptive to the network congestion because each TCP sender determines its window size according to the network congestion status, which is inspected by returned ACKs. It is an essential property originated from the design principle of the Internet, named an "end-to-end principle" [9]. However, as widely known, TCP, especially the currently most-used version of TCP Reno, is too aggressive in the sense that it increases its window size (equivalently, packet transmission rate) continuously until it experiences packet loss due to the buffer overflow, which results in other existing TCP connections also being damaged and throughput performance becoming quite low, especially in high-speed networks [10]. We are now developing a more elegant solution to this problem. A key idea is that the TCP connection itself investigates the available bandwidth and increases the window size up to the available bandwidth gradually [11]. Then, packet losses can be avoided to a large extent, which is very important —especially in high-speed networks where packet losses decrease the window size and lose the throughput. We model the TCP window size changes by a logistic curve through which we can employ the discussion on system stability in the biology field.

Another example can be found in a wireless ad hoc network, including the above-mentioned sensor network. The medium access control (ALOHA or CSMA/CA) used in the ad hoc network is competitive, and the rate control in the data link layer is necessary for keeping the maximum throughput due to its bifurcation property [12]. We are now developing various network control methods that have a symbiotic nature.

The other direction of our research is to study the adaptive complex networks. As a result of the symbiotic control in each communication layer, we consider that the network would be an adaptive complex system. The rationale behind it is due to the recent study in [2], where the authors point out that the power-law property observed in the biological system is a result of the adaptive nature of the biological systems. It is now widely known that the Internet exhibits the power-law property in various aspects, including the AS-level topology and the packet-level traffic behavior. The author feels that similar arguments can be applied to the network system, and building the adaptive and robust network can be built by virtue of the insights obtained by the biology, but that it requires further research.

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