Self-Organization in Sensor Networks using Bio-Inspired Mechanisms

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Abstract

Bio-inspired communication methodologies promise to enable more scalable self-organizing network infrastructures. Especially in the area of mobile ad hoc sensor networks, such solutions are required in order to qualify them for simplified development and deployment based on autonomously evolving mechanisms to work on global tasks, i.e. to show an emergent behavior. In this paper, we introduce the ongoing research of our Autonomic Networking group focused on the developments on efficient data dissemination in sensor networks. A particular example of how to study biological processes and to adapt the results in communication networks, the feedback loop mechanism, depicts the potentials of this research area.

1 Introduction

In recent years, many efforts have been made in developing algorithms and methodologies for building efficient network mechanisms for communications in mobile ad hoc sensor networks. This work is mainly driven by the spreading of wireless network technologies addressing requirements such as efficiency, adaptability, and scalability. It became obvious, that new communication paradigms are needed for the forthcoming pervasive networking world. For example, mechanisms and technologies for achieving optimum data rates while addressing issues such as power-consumption and reorganization during the data transfer are required [1, 4, 13]. The focus of our Autonomic Networking group lies on efficient communication methods designed for autonomously working mobile network nodes. We address these issues using mobile robot systems in conjunction with wireless sensor networks. The goal is to teach the nodes to self-organize for performing the requested tasks such as monitoring and exploration with time and energy constraints, i.e. showing an emergent global behavior.

Since a couple of decades, researchers think about applying the natural principles to engineering and computer science, especially for self-organization. The combination of nature and self-organizing technical systems was first introduced by Eigen [10]. Reviews of current research on biological self-organization can be found in [12]. The development in the area of bio-inspired engineering is relying basically on the artificial immune system [15], swarm intelligence [3], and evolutionary (genetic) algorithms [5]. An emerging research area looks for cell and molecular biology based approaches [8]. The structure of organisms and computer networks is very similar and this is also true for the cellular signaling pathways and communication in data networks. Therefore, research on biological methodologies promises high potentials for computer networking in general and adaptive sensor networks and network security in particular [7, 8, 17]. The potential of bio-inspired research was already shown in various research areas, e.g. pervasive computing [22] and routing issues. Le Boudec [18] introduced artificial immune system approaches for misbehavior detection in mobile ad hoc networks. First attempts are in progress to study the behavior of swarms of insects, typically ants and bees, and to adapt the discoveries to build more efficient sensor networks [16, 20]. Organic computing [19] is attempting to build high-scalable architectures, which are self-organizing, self-maintaining, and self-healing [12].

We are studying the processes in computer networks using methodologies known from cell and molecular biology as key paradigms [6]. Based on the knowledge about the cellular communication, new concepts for the behavior patterns of the different kinds of networking nodes can be deduced and the efficiency of individual sub-systems can be increased

[9, 17]. Besides an introduction of our ongoing research in the field of bio-inspired networking and self-organization in mobile sensor networks, this paper focuses on adaptive feedback-loops for communication over unreliable data paths. The standard behavior of available communication protocols known from Internet and MANET (mobile ad hoc networks) research are very insufficient for network paths with high loss rates, time variations of the reliability, and asymmetric loss distribution [2]. To cope with these issues, we investigate in methodologies known in cell and molecular biology. Here, we propose a new communications paradigm for protocols in sensor networks based on these analyses: the feedback-loop mechanism.

The rest of the paper is organized as follows. Our work is motivated in section 2 including a presentation of our research objectives. Section 3 details some specific biological mechanisms for information exchange. The application of these bio-inspired methodologies to communication networks is discussed in section 4 followed by a short overview to ongoing experimental work in this area. A conclusion in section 6 summarizes this paper.

2 Motivation and Research Objectives

Among others, we are focusing on self-organization, task-allocation, and energy-aware communication in mobile wireless sensor networks. Sensor networks are composed of multiple, independent autonomously working nodes. These individual entities form a self-organizing compound that is able to solve required tasks described at a higher level. A typical sensor network is shown in Fig. 1. Routing and clustering methodologies are used to establish communication paths between distant nodes. Existing mechanisms rarely incorporate cross-cutting concerns such as available resources, e.g. energy, error detection mechanisms, and location information for providing self-controlled reliable communication.

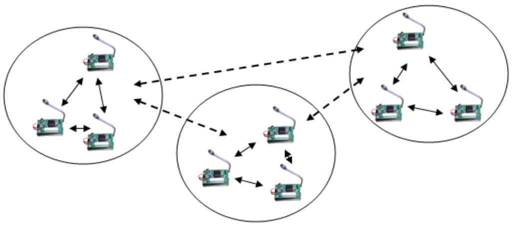

Fig. 1. A typical wireless multi-hop ad hoc sensor network. The communication between different clusters is provided by dedicated nodes

Before we concentrate on the application of a particular mechanism known from cell biology to communication in mobile ad hoc sensor networks, our ongoing research activities in the research fields of sensor networks and bio-inspired networking are briefly described.

2.1 ROSES – Robot Assisted Sensor Networks

The development and the control of self-organizing, self-configuring, self-healing, self-managing, and adaptive communication systems and networks showing an emergent behavior are the primary research aspects of our Autonomic Networking group. We are studying these aspects in the area of autonomous sensor/actuator networks, i.e. a combination of mobile robot systems and stationary sensor networks. The introduction of mobility as well as the limited resources of typical sensor nodes leads to new problems, challenges, and solution spaces in terms of efficient data management and communication. We distinguish between sensor assisted teams of robots and robot assisted mobile sensor networks. The former means that robots might use the sensor network for more accurate localization and navigation or as an infrastructure for successful communication. The latter means the employment of robot systems for maintenance in sensor network or for providing communication relays.

Research Goals:

- Energy efficient operation, communication, and navigation
- Sensor network assisted localization and navigation of the robots
- Utilization of the robots as a communication relay between a sensor network and a global network, e.g. the Internet
- Quality of service aware communication in heterogeneous mobile networks with dynamic topology
- Optimized task allocation and communication based on application and energy constraints
- Secure communication and data management in mobile sensor networks

In order to address these objectives, we work on novel models and methodologies for energy and application aware communication, combine different localization techniques for optimized high-precision navigation, integrate mobile robots and stationary sensor nodes to autonomous sensor/actuator networks, and research on bio-inspired communication methods. In our lab, we use the Robertino[1] robot platform as well as the Mica2 sensor motes running TinyOS[2].

Our primary application scenario in our project is the exploration and supervision of unknown surroundings. In Fig. 2, the most challenging issues

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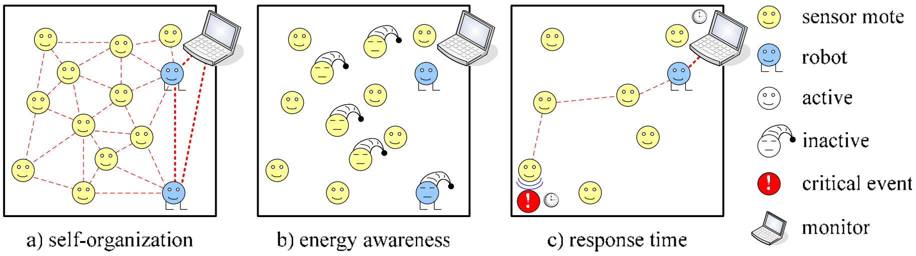
[1] Robertino was developed at the Fraunhofer Institute for Autonomous Intelligent Systems AIS

[2] Mica motes and TinyOS were developed at the University of Berkeley



a) self-organization b) energy awareness c) response time

Fig. 2. Challenges and research directions in the area of mobile ad hoc sensor networks

are depicted. Self-organization (a) means, that global tasks are solved without the need of a central control or management, i.e. the network notes explore their neighborhood and distribute the decomposed task in an appropriate way. Energy awareness (b) is a key property of the systems in focus. Sensor networks should be available over a long time period without external maintenance. Finally, the response time (c) of the system, i.e. the time between the occurrence of an event and the appropriate response, is an important aspect.

Current Activities: We equip our mobile robot systems with a modular control system allowing them to act completely autonomous. In order to achieve this goal, modules for accessing the sensor facilities, for movement, localization and navigation, and task allocation are work in progress. Mostly finished is the energy control module composed of a battery management and the corresponding characteristics. In collaboration with the Fraunhofer Institute for Integrated Circuits IIS, a special circuit for voltage and current control was developed. The energy module allows an approximation of the remaining energy and an estimation of energy requirement of forthcoming tasks. Additionally, the connection to the sensor network is provided by another module used for more precise localization techniques. In the field of sensor networks, we are evaluating ad hoc routing algorithms with the focus on energy constraints and timeliness of the communications. To achieve this goal, we interconnect “real” sensor motes with our simulations to achieve more accurate results than available in previous simulations.

2.2 BioNeting – Bio-inspired Networking

Besides to classical research area of bioinformatics, the turn to nature for solutions to technological questions has brought us many unforeseen great concepts. This encouraging course seems to hold on for many aspects in technology. Many efforts were made in the area of computer technology employing mechanisms known from biological systems. The most known examples are evolutionary algorithms and the artificial immune system. One application is in network security, e.g. for the search for viruses and worms, where the immune system was used as an inspiration.

In contrast, the focus of our group lays on trying to map mechanisms from cellular and molecular biology to networking architectures. Recently, it was shown that the known approaches to study effects in computer networking, especially methods to analyze the behavior of large scale networks suffer from many presumptions. We try to study this behavior by analyzing the internal functioning of network components as well as their interactions in comparison with cellular systems and the associated intra- and inter-cellular signaling pathways. The main focus of this work is to show the similarities of computer networks and cellular systems [8]. Based on the knowledge about cellular communication, new concepts for the behavior patterns of network nodes can be deduced and the efficiency of individual sub-systems can be increased.

Current Activities: Our current activities focus on signaling pathways in network environments. We are analyzing them in order to build appropriate models and simulations to verify our efforts. This enables us to compare traditional engineering solutions with the bio-inspired methodologies.

3 Biological Information Exchange

In an interdisciplinary team we are about to identify appropriate mechanisms in cell biology and to adapt them to networking technology with the focus on self-organization in mobile ad hoc sensor networks. In a structural comparison of organisms and computer networks it can be seen that both show high similarities. Also, the intercommunication between the systems, the signal transduction pathways, follows the same requirements [8]. Here, a special regulation mechanism is depicted. Its application in networking is described in the next section.

Some organs such as the kidney do play a central role on physiological functions and dysfunctions of the organism. For example a descent of arterial blood pressure below a critical value which will have many negative consequences for the whole body is monitored by a small population of cells in the filtration unit of the kidney [21]. As an answer to this information, these cells produce a protein (renin) which has the function to initiate a cascade of conversions and activations, respectively, of another constitutive but quiescent protein (angiotensinogen) produced by the liver and distributed in several organs. The conversion of this protein to a shorter one (now called angiotensin I) is the first step to form the right answer for solving the initial problem. Further proteins are necessary for the formation of this final answer. The protein ACE (angiotensin converting enzyme) further modulates this protein, angiotensin I by cleaving it into the short and potent protein angiotensin II. This protein represents the final answer which now has many effects on different cells in different organs in order to increase the blood pressure to normal level. On the one hand, angiotensin II stimulates the production of further protein signals in the adrenal gland, which is e.g. a hormone called aldosterone. This protein in turn stimulates the retention of Na$^+$ ions in the kidney which finally has consequences for the blood volume regulation. On the other hand, angiotensin II stimulates the contraction of smooth muscle cells surrounding blood vessels within the kidney. Finally, angiotensin II also activates the production of the hormone vasopressin in the adenohypophysis in the brain which finally plays a role in the blood volume regulation. All these effects enhance the blood pressure in the whole body. The complete procedure is depicted in Fig. 3.

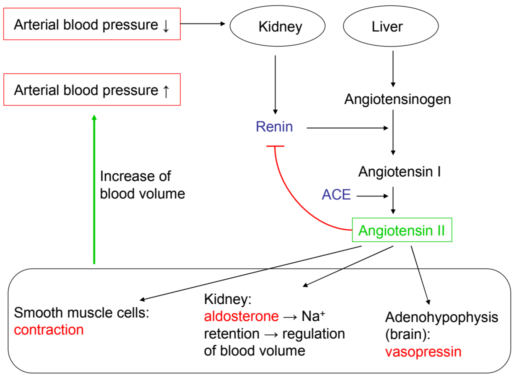


Fig. 3. Overview of the regulation of blood pressure (signaling cascades including a molecular negative feedback mechanism)

Looking at one of the target cells of angiotensin II in the kidney or smooth muscle cells, the protein binds to certain receptors on the cell surface. This binding induces an intracellular signal transduction cascade that finally results in the aforementioned actions to increase the blood pressure. A molecular negative feedback mechanism finishes the whole cellular reaction. If all receptor are bound by angiotensin II, the reaction is blocked which in turn also blocks the primary conversion of angiotensinogen to angiotensin II in the way that the initial renin secretion is blocked. Therefore, this mechanism describes a very effective remote and local control of the blood pressure which plays a central role in the body.

4 Shifting the Paradigms: Feedback Loops

The objective of this paper is to analyze the behavior of communications between nodes in a wireless sensor network over unreliable data paths. The control of activities requires the information exchange between multiple nodes in the network. Such communication is needed for at least two reasons. First, the control information must be transported to the appropriate destination and, secondly, the destination must respond to the request by confirming the instructions. All conventionally designed network protocols for such a function follow the same principles. A transmission of a data packet destined for the particular target is initiated. State information is accumulated at several points in the network until a response packet is received which confirms the transaction. We are looking for a more sophisticated solution for this challenging task. In this paper we describe a novel methodology, which we call feedback loop. We believe that it allows a more convenient operation, especially in low-resource sensor networks.

We address these issues by studying the mechanisms in nature from a microscopic point of view, i.e. studying the behavior in cellular environments, precisely the signaling pathways and self-organizing methodologies, and try to adapt the lessons learnt to sensor networks. In the previous section, a molecular negative feedback mechanism was described. This kind of feedback loop seems adequate for application in wireless sensor networks with unreliable communication channels. Furthermore, it must be possible to adapt this procedure to work in other environments as well.

The paradigms for data transport in sensor networks are already changing. A new methodology, called directed diffusion, was introduced [14]. Directed diffusion has some novel features: data-centric dissemination, reinforcement-based adaptation to the empirically best path, and in-network data aggregation and caching. These features can enable highly energy-efficient and robust dissemination in dynamic sensor networks, while at the same time minimizing the per-node configuration that is characteristic of today's networks [11].

Similar changes are expected for the control information flow which we are focusing on. A typical heterogeneous sensor network is shown in Fig. 4. Dedicated sensor nodes have attached sensing facilities or antennas for remote communication. To activate a particular task, e.g. gathering of sensor

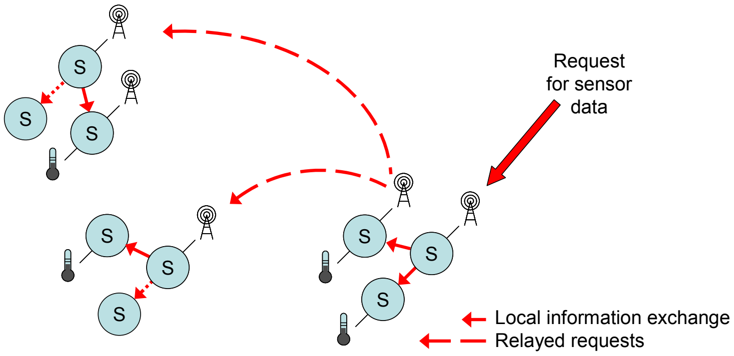


Fig. 4. Transmission of information within a typical sensor network. Sensor nodes can operate sensing facilities, depicted by an attached thermometer, and remote communication facilities, depicted by an attached antenna

data, the necessary commands must be transmitted to all nodes with sensing facilities. This task can be split into several sub-jobs. First, neighborhood relationships need to be created to inform nodes about available resources in the network. Secondly, appropriate routing mechanisms have to be applied for the transport of the control information.

As learnt from biology, we propose a diffuse communication principle. A message to be sent is given a priority. This priority depicts the importance of the particular task to achieve. Based on this priority, the message is sent to a percentage of the direct neighbors and an even lower percentage of remotely accessible nodes. This process is repeated until the desired job is confirmed running or the job is globally canceled. Therefore, a randomness factor is applied to the dispersion of information or, in particular, to the distribution of tasks [9].

So far, the scalability of this communication paradigm is still questionable. This issue is addressed by the feedback loop mechanism. Methods other than the same communication path should be embedded into the communication paradigm. Especially in sensor networks, there are many other alternatives to find out whether a requested task was started or not. Examples are the utilization of sensing capabilities allowing the sensor nodes to obtain information about the environment and the incorporation of feedback information into network internal data transmissions such as neighborhood discovery or clustering. Thus, a protocol designed for control information transport within a mobile ad hoc sensor network can include extremely asymmetric information pathways to obtain a high efficient data dissemination.

5 Experimental Work

In our lab we reproduced the depicted scenario using Mica2 motes. All the motes are running TinyOS, which allows a fast and effective prototyping of communication protocols and mechanisms. We established a multi-hop scenario using several motes in which we can test various protocols. To induce a variable loss probability and also to vary the reliability of the complete system, we can move the sensor motes around and turn single nodes off for a while. We are testing the feedback loop mechanism for transferring sensor data with different emphasis to a gateway system where event specific action can be initiated, e.g. for synchronization or retransmission. We are comparing the feedback mechanism with traditional communication protocols.

The experiments gave us the confidence that our approach points to the right direction. Further tests will provide us more information about the resource requirements, i.e. the number of packets sent through the network until the effect was acknowledged.

6 Conclusions

In conclusion it can be said that we were able to construct a novel communication methodology for transmission of control information in wireless sensor networks. Unreliable data paths and time variations of the reliability affect the traditional network protocols and lead to unnecessarily high transmission overhead or impractical communication. Feedback loops, as proposed in this paper, shift the classical communication paradigms by employing techniques adapted from cell biology. Additionally, an importance factor is applied for the overall reliability of a particular transmission. Especially in low-resource sensor networks, this allows a far more efficient utilization of available resources and leads to a higher quality of the global system. Bio-inspired networking architectures will help addressing multiple issues of self-organization and adaptation to environmental changes. Thus we enable an emergent behavior of a global system consisting of multiple, possibly heterogeneous, autonomously working nodes. In the context of wireless sensor networks, we were able to work out more efficient algorithms. During the first experiments, it was shown that protocols designed with our feedback loop are functional and even lead to resource savings such as in power consumption.

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