Efficient and Scalable Communication in Autonomous Networking using Bio-inspired Mechanisms – An Overview

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Autonomous networking is a challenging research area. Systems, in this case networks, are composed of many independent entities that perform a predefined task. The behavior of the global system is a result of the interaction of all the autonomous entities. The programming paradigms shift to the development of just these small entities. Self-organization is the solution for managing such environments. In this paper we demonstrate the possibilities which evolve by the application of cell biology for computer networking. With the focus on autonomous networking, the combination with methodologies known from swarm intelligence is evaluated. We show the capabilities of this combination and derive destinations and goals for self-organization in communication networks showing a more efficient and scalable behavior.

1 Introduction

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 swarm intelligence, evolutionary or genetic algorithms, and the artificial immune system. The adapted mechanisms find application in computer networking for example in the areas of network security [7, 15], pervasive computing [11, 27], and sensor networks [21, 23].

Organic computing, which is a new term covering the bio-inspired mechanisms in engineering and computer science related fields, is attempting to build high-scalable architectures, which are self-organizing, self-maintaining, and self-healing [6, 14]. In the fields of computer networking, methods known from swarm intelligence are employed. Mechanisms known from ant colonies and swarms of bees build the basis for cooperative tasks [22, 25]. Issues of self-organization are directly addressable using such mechanisms.

In contrast, the focus of our group lays on trying to map the cellular and molecular biology to networking architectures [11, 12, 20]. 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 there interactions in comparison with cellular systems and the associated intra and extra cellular signaling pathways.

The main focus of this work is to show the similarities of computer networks and cellular systems. Based on the knowledge about cellular metabolism, new concepts for the behavior patterns of routers, monitor systems, and firewalls can be deduced and the efficiency of individual sub-systems can be increased. Focusing on examples of hot topics in the computer society, i.e. network security, potential solutions motivated by cellular behavior are currently studied and, hopefully, will soon bring new results in these areas. In combination with efforts known from swarm intelligence, most self-organization issues can be addressed. Cell biology based mechanisms build new communication paradigms and ant colonies are adapted to group formation. Doing this, we must keep in mind that the deeper the parallels between biology and technology, the more important it is to map the corresponding elements correctly. Algorithms known from swarm intelligence are employed for clustering and group formation issues. This is a necessary basis for further bio-inspired communications.

The rest of the paper is organized as follows. In section 2, an overview to the state of the art in bio-inspired networking is provided. This builds the basis for further studies discussed in section 3. The combination with swarm intelligence is detailed in section 4. New destinations and goals are shown in section 4 and some conclusions summarize the paper.

2 Bio-inspired Networking – State of the Art

Since billions of years, nature worked out organisms that adapted perfectly to environmental changes. Survival of the fittest is the primary selection mechanisms. Research on self-organization started in the 1960ies and combination of nature and self-organizing technical systems was first introduced by Eigen [13]. Reviews of current research on biological self-organization can be found in [4, 14].

The development in the area of bio-inspired engineering is relying basically on the artificial immune system, swarm intelligence, evolutionary (genetic) algorithms, and cell and molecular biology based approaches. The immune system of mammals builds the basis for research on the artificial immune system. The reaction of the immune system, even to unknown attacks, is a high-adaptive process. Therefore, it seems obvious to apply the same mechanisms for self-organization and self-healing operations in computer networks [16, 19].

The behavior of large groups of interacting small insects such as ants and bees builds the basis for field of swarm intelligence. Simple and unrelated autonomously working individuals are considered to compose complex cooperative tasks. Similar actions are required in various areas of engineering and computer science and should build a basis for building self-organizing systems [3, 18]. A main focus lies on the formation of groups or clusters.

Evolutionary (genetic) algorithms are self-manipulating mechanisms. The evolution in nature is the basis for such methodologies. In particular, there are multiple ways for organisms to learn. A natural selection process (survival of the fittest) is going on letting only the optimal prepared organisms to survive and to reproduce. Changes appear for example by mutations. An overview to evolutionary algorithms is provided for example in [2, 6].

An emerging research area looks for cell and molecular biology based approaches. All organisms are built in the same way. They are composed of organs, which consist of tissues and finally of cells. This structure is very similar to computer networks, which is also true for the signaling pathways. Therefore, research on methods in cell and molecular biology promises high potentials for computer networking in general and adaptive sensor networks and network security in particular [10, 11, 12, 20].

Optimization in general and routing aspects are also in the focus of bio-inspired networking. Swarm intelligence builds the basis for this kind of work as shown by Di Cargo and Dorigo [8, 9]. The group of Suda has built a middleware, called the bio-networking platform [28, 30], to investigate in multiple biological inspired technologies. Optimizations and application in various research areas such as pervasive computing [27] and security [26] have been worked out. In the area of sensor networks, first attempts to study the behavior of swarms of insects, typically ants and bees, and to adapt the discoveries to build more efficient sensor networks are in progress. For example, Kadrovach [17] and the group of Osadiciw [23, 24, 25] are working in this area. Liang provided an approach for redundancy allocation [22] applicable in autonomous systems environments. Bio-inspired robots, which use biological mechanisms for flight control and localization, were developed for example by Chahl and Thakoor [5, 29].

All these examples demonstrate that there is already work on bio-inspired mechanisms in the fields of communication networks.

3 Cell Biology as the Key for Computer Networking

In this section we focus on cell biology as a key for computer networking. We first show structural similarities followed by some information about the signaling pathways within single cells and between tissues. Based on obvious similarities, high potentials of this analysis are worked out which will lead to paradigms and algorithms showing a higher efficiency in computer networking.

3.1 Structural Comparison of Organisms and Computer Networks

The sector of cell and molecular biology is analyzing the basic behavior of organisms from a microscopic point of view. All the cells are acting in a predefined manner, controlled by the DNA. In summary it can be said, that cells are the smallest entities in a profoundly self-organizing system comparable to autonomous systems in computer science.

In Fig 1, a structural comparison of organisms and computer networks is shown. It can be seen that both show high similarities. This organization of an organism is a highly regulated process from the single cell up to complex organs of the body. The hierarchy in the organism is very high. Every process, e.g. movement, metabolism, communication, etc. is organized by interactions of several organs. Organs represent an assembly of one or more tissues, which fulfill a common function. One tissue is build by different cell types. One cell type consists of identical cells, which are associated and communicate with each other to fulfill a common function within the tissue.

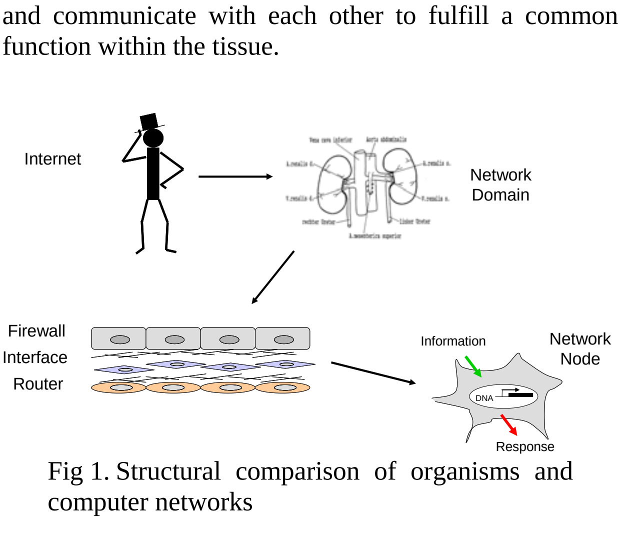

Fig 1. Structural comparison of organisms and computer networks

The organization in computer networks is quite similar. An internet consists of network domains, (sub-)networks, and network nodes, respectively. The network nodes fulfill specific tasks that finally lead to a common behavior of the network. Examples are the storage the aggregation, and the forwarding of data.

3.2 Cellular information exchange and adaptation to network security

The focus of this section is to examine the information exchange in cellular environments and to extract the issues in computer networks that can be addressed by the utilization of these mechanisms [11, 12, 20].

Similar to the structure, the intercommunication within both systems is comparable. Information exchange between cells, called signaling pathways, follows the same requirements as between network nodes. A message is sent to a destination and transferred, possibly using multiple hops, to this target.

From a local point of view, the information transfer works as follows. A specific signal reaches only cells in the neighborhood. The signal induces a signaling cascade in each target cell resulting in a very specific answer which vice versa affects neighboring cells. This process is depicted in Fig 2. A cell is shown with a single receptor that is able to receive a very specific signal and to activate a signaling cascade which finally forms the cellular response.

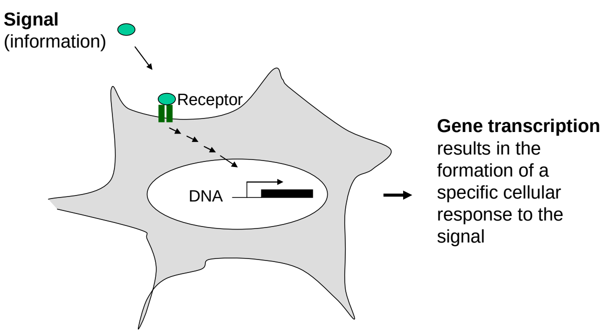

Fig 2. Local information exchange in the cellular environment

Similar mechanisms are present in networking environments. Looking on network security solutions, monitoring probes gather information about the ongoing traffic in the network. The collected data will be sent to an attached intrusion detection system for further processing. Finally, corresponding firewall systems are configured with rules concerning the actual behavior in the network. Similar mechanisms can be deduced from pervasive computing environments or sensor networks. General issues to address in such a network are:

- Adaptive group formation
- Optimized task allocation
- Efficient group communication
- Data aggregation and filtering
- Reliability and redundancy

The remote information exchange works analogue. As depicted in Fig 3, proteins are used as information particles between cells. A signal can be released into the blood stream, a medium which carries it to distant cells and induces an answer in these cells which then passes on the information or can activate helper cells (e.g. the immune system). The interesting property of this transmission is that the information itself addresses the destination. Only cells with a very specific receptor are able to receive the information, i.e. the protein binds at the receptor.

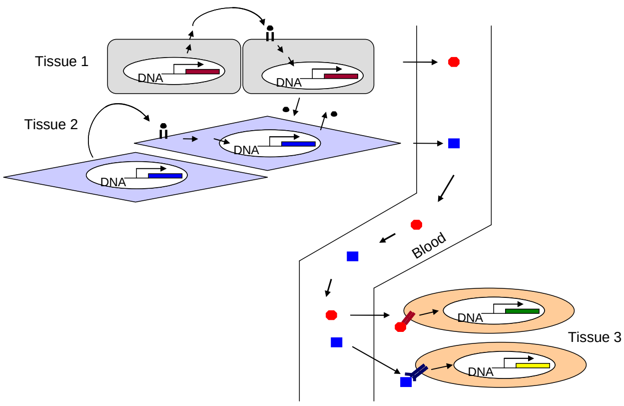

Fig 3. Remote information exchange between cells and tissues

In this scenario, the corresponding issues in computer networking are for example:

- Localization of significant relays, helpers, or cooperation partners
- Semantics of transmitted messages
- Cooperation across domain borders
- Internetworking of different technologies
- Authentication and authorization

The lessons to learn from biology are the efficient and, above all, the very specific response to a problem, the shortening of information pathways, and the possibility of directing each problem to the adequate helper component. Therefore, the adaptation of mechanisms from cell and molecular biology promises to enable a more efficient information exchange. Additionally, issues of task allocation and group communication are directly addressed by the introduced capabilities.

4 Application of Swarm Intelligence

The studies on the behavior of swarms of bees and ant colonies have already shown high potentials solving issues in the areas of group formation and self-organization [9, 22, 23].

Some of the communication aspects, e.g. localization of resources, signaling of control information, and others can be directly addressed by the methodologies known from cell biology as described above. Others need further assistance. The most challenging issue is the adaptive formation of groups of nodes, so called clusters. Communication mechanisms provided by intercellular signaling pathways typically rely on the formation of clusters.

Groups can be organized using various parameters such as similar properties, localization information, and other relationships. Swarm intelligence and collective behavior are key solutions for such questions [1]. The clustering of entities using ant system like algorithms leads to interesting solutions that obviously are the basis for further interactions as depicted in section 3. An example is shown in Fig 4. This figure represents an initial configuration with a random, uniform distribution of nodes.

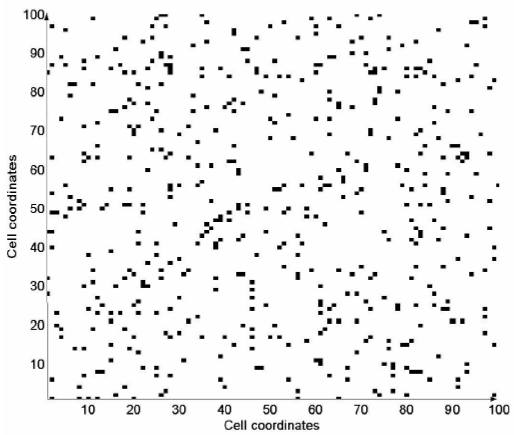

Fig 4. Clustering. Initial random distribution of nodes

Algorithms of swarm intelligence, i.e. collective ants, can be used to form clusters of nodes. In this example, only binary information is used to identify the relationship of nodes. Nevertheless, this algorithm can be enhanced to work in more sophisticated environments with multiple properties for an efficient clustering. A final state is shown in Fig 5.

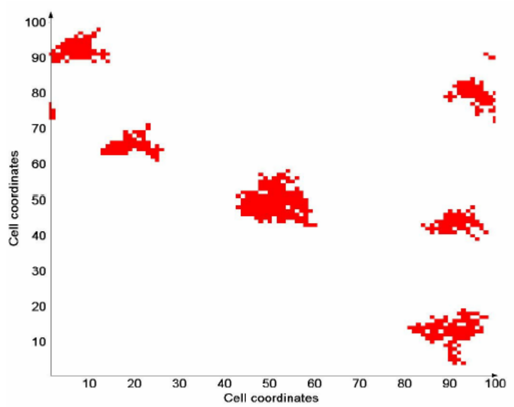

Fig 5. Cluster formation after running the algorithm some 10.000 steps [1]

After the successful group formation, other mechanisms can be applied for an efficient communication whether between individual systems (end-to-end, unicast), between all group members (group multicast), or between systems assigned a particular function (anycast).

5 Destinations and Goals

The objective of this paper is to provide information about mechanisms that allow us to build self-organizing network infrastructures. The key properties are efficiency and scalability. In order to address these issues, some bio-inspired mechanisms have been worked out: communication paradigms following the mechanisms in cell biology and clustering or group formation based on algorithms known from swarm intelligence. The primary destinations are discussed which point to novel solutions for various network environments employing the mentioned mechanisms.

Identification of properties

Instead of having a network administrator configuring individual systems and their properties, dynamic algorithms are required for self-organizing issues. In the past, such mechanisms were provided for identifying individual nodes based on an individual property, e.g. routing protocols are in some manner self-configuring by identifying neighboring nodes. Nevertheless, the final goal is to put new nodes into an existing network without any preconfigured knowledge. The properties of the nodes can be described in some common way. Bio-inspired communication mechanisms learnt from inter-cellular signaling pathways provides the appropriate mechanisms.

Localization of nodes

For some reasons, the position of special nodes must be detectable. In communication networks, typical examples are the localization of dedicated gateway nodes or the allocation of resources in mobile sensor networks. Swarm intelligence based clustering in combination with bio-inspired communications allows a fast and adaptive localization of resources even in unreliable network environments.

Group communication

One of the key features in autonomous systems is an efficient communication paradigm which connects multiple interacting nodes. This paradigm is called group communication. Research on such issues started with developments of IP multicast and is ongoing work in peer-to-peer networks. In most protocols, the management and maintenance of the group is the limiting factor in terms of scalability. Often, especially in pervasive environments or in sensor networks, group communication mechanisms are required which do not rely on the prior formation and maintenance of groups. Such communication paradigms can be derivated from cell biology. Here, fuzzy communication mechanisms are successfully employed showing a very high efficiency and specificity.

Task allocation

Modern task allocation mechanisms are related to distributed systems research. Nevertheless, many efforts were made using bio-inspired engineering approaches for better utilization of the global system. Interestingly, this is possible employing the discussed methodologies known from swarm intelligence in combination with new communication paradigms. The problem of task allocation can be reduced to the identification of available resources and group communication between related nodes.

Further work in the described destinations on application scenarios for bio-inspired networking methodologies is still required. Progress is currently driven by two factors. First, the analysis of biological mechanisms is looking for areas offering new paradigm and concepts which can be transferred to computer science related field. One example is the described application of cellular and molecular biology for communication networks. Secondly, some of the natural processes are still unknown or need further research in non-engineering field. We have to look constantly for emerging new achievements in science and adapt the changes to our algorithms.

6 Conclusions

We outlined biological inspired mechanisms for efficient and scalable communication in autonomous networking. Self-organization issues are promising to be the key answer to build large and complex systems fulfilling different tasks out of many simple independent autonomous entities. Such systems can be found quite often in computer networking. Network security, pervasive computing environments, and sensor networks are only single examples. All these systems require similar operations as their basis mechanisms:

- group formation
- adaptive communication
- resource localization and management

Mechanisms known from cell biology for the identification of resources and efficient inter-node communication in combination with swarm intelligence based approaches for adaptive group formation are adequate solutions for the depicted problems. In summary it can be said, that further developments of communication principles will have to rely on the elaborated methodologies in bio-inspired research.

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