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Biologically Inspired Networking and Sensing

Algorithms and Architectures

Pietro Lio & Dinesh Verma

Biologically Inspired Networking and Sensing:

Algorithms and Architectures

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Preface

Computer communication networks have transformed human civilization, and enabled information to be shared across the globe at the speed of a mouse-click. They have transformed the way society functions, and their effects can be seen in all aspects of our life. This transformation can truly be called a miracle.

In spite of their far-reaching impact, the computer networks that provide the foundation of the World Wide Web and the Internet have many limitations. The networks were not designed to accommodate mobile users, they are extremely vulnerable to security threats, they break relatively easily, requiring extensive manual labor to resolve many of these disruptions, and have very limited ability to respond to changing conditions like huge swings in their workloads.

Researchers in the networking area are continuously striving to find ways to improve the attributes of computer communication networks and find ways to address the limitations. These new explorations are gradually helping to address the weaknesses of the network infrastructure. The investigations to improve the network include incremental improvements to the extant protocols and systems, as well as fundamentally different ways to looking at the networks.

Some of the researchers exploring a fundamentally different way to resolve the limitations of modern day networks have been looking towards biological systems for inspiration. This has results in an exciting new area of biologically inspired computer networks. Such networks are designed and developed using principles that are commonly found in natural and biological systems.

This book provides a current snapshot of some of those research activities. By bringing together the research activities from a variety of institutes around the globe, we hope to provide a good coverage of the various approaches that are being explored to improve the networking paradigms.

COMPARING BIOLOGICAL AND COMPUTER NETWORKS

The impetus to draw inspiration from biological networks comes from the fundamental observation that biological systems just do a better job at many functions than the best designed electronic computers and computer networks.

Perhaps the most obvious example of a domain where biological networks have an advantage is the human immune system. The immune system is able to react to attacks from a variety of viruses and bacteria, including those that it may have never encountered before. It is able to identify the intruders, and take action against them in a very effective manner. Even though the number and varieties of the viruses and bacteria keep on multiplying due to mutations and natural evolution, the immune system is able to manage these variations with relative ease. In stark contrast, computer networks have a very difficult time identifying malware, intrusions, and other attacks, and struggle to cope up with the new security threats that keep on surfacing all the time. In some instances, the security mechanisms become a nuisance rather than a useful feature.

Another unique area where biological systems have an advantage is in their ability to adjust themselves in the face of a changing external environment. When the external temperature is hot, the body sweats to cool itself down, and when the external temperature is low, the body shivers to restore and gain some heat. Not counting some extreme situations, the human body (and many other biological systems) is able to adapt to an amazing degree. On the other hand, the computer networks of today are rarely able to cope with a dynamically changing workload, and their ability to deal with extreme external changes is very limited.

There are some aspects of networking in which current computer networks outperform biological networks, e.g. the fidelity and speed at which information can be communicated in electronic networks is much more reliable and higher-speed than biological networks. The goal of biologically inspired networks is not to belittle those advantages, but to explore those aspects that can be made better by drawing inspiration from biology.

Some of the recent advances made in improving the design of networks using biologically inspired paradigms are compiled in this book. The next section explains the structure of the book and the content of the different chapters.

STRUCTURE OF THE BOOK

This book consists of thirteen chapters which provide a good overview of the current state of the art in biologically inspired computer networks. For organizational purposes, the work is divided into three different categories.

The first category consists of chapters that are proposing new architectures for computer networks that are based on biologically inspired techniques. These chapters include description of work that is trying to develop a new paradigm for computer communications.

The first chapter *A Networking Paradigm Inspired by Cell Communication Mechanisms* describes molecular communications - a new paradigm for networking in which information is encoded to and decoded from molecules, rather than electrons or electromagnetic waves. This paradigm is being used to explore new models for nano-networking and in synthetic biology. The chapter provides an overview of the current state of the art, and the models used in the current state of the art for molecular communications.

The second chapter, *Organic Network Control: Turning Standard Protocols into Evolving Systems* presents a new architecture that allows for automatic adaptation of protocol parameters in dynamically changing environment. It is based on an observer-controller paradigm and uses evolutionary algorithms for adaptation. The chapter provides some examples where such protocols can be used, and also surveys the current state of the art in the area.

The third chapter *Robust Network Services with Distributed Code Rewriting* looks at a way to design distributed software systems that are based on continuous replication of a code base. They use the concept of *quines* – a piece of software that prints its own code, and leverage *quines* to create a system that dynamically rewrites itself in a regulated manner simultaneously exploiting competition as well as cooperation.

The fourth chapter *Neural Networks in Cognitive Science – An Introduction* provides an overview of an architecture for cognitive modeling that leverages neural networks. It is an instance of biologically inspired neural networks being used in various domains and applications.

The fifth and final chapter in this section, *The Dendritic Cell Algorithm for Intrusion Detection* is a new architecture to perform the security functions in computer networks. It uses an algorithm modelled after the body's immunity functions, and provides a new approach to detect anomalies in network traffic.

The next section of the book consists of chapters that are focused on resource optimization in computer networks. Any computer network operates under an environment of constrained resources such as bandwidth, power, and computation capacity at nodes. In different types of networks, different resources are the bottlenecks which need to be optimized. In the context of military or satellite networks, bandwidth is usually the bottleneck. In the context of commercial wireless sensor networks, battery power becomes the most constrained resource, while for high speed optical networks, the computation and switching capacity at intervening electronics is the bottleneck resource. Therefore, new approaches that allow optimal use of scarce resources are valuable to explore in all types of computer networks.

The first chapter in this section, *TCP Symbiosis: Bio-Inspired Congestion Control Mechanism for TCP* looks at ways to improve the congestion control scheme used in the widely deployed TCP protocol using biologically inspired techniques. The authors use concepts borrowed from biophysics, such as the Lotka-Volterra competition model, to improve the congestion control behavior, and show that the new biologically inspired approach has better stability and scalability characteristics than the prevailing congestion control schemes.

The second chapter in this section, *From Local Growth to Global Optimization in Insect Built Networks* discusses how insect colonies optimize themselves in a completely distributed and decentralized manner. They provide an in-depth analysis of the local behaviors of insects that leads to an eventual overall optimization of the global network in the colony.

The next chapter, *Network Energy Driven Wireless Sensor Networks* examines the subject of managing energy in wireless sensor networks. The approach proposed is that of scavenging energy available from unwanted radio frequency waves, a model inspired by the behavior of emperor penguins. In networks where energy is at a premium, such harvesting approaches can provide significant value.

The final chapter in this section, *Congestion Control in Wireless Sensor Networks Based on the Lotka Volterra Competition Model* provides an alternative approach to congestion control in wireless sensor networks. The Lotka Volterra model is a mathematical model that characterizes the population of different species in an ecosystem. The model, when applied to the task of managing bandwidth resources and congestion during communication, provides an interesting paradigm to manage scarce resources.

The third section of this book looks at the task of routing in computer networks. Routing is the process by which packets emanating from a source in the computer network are eventually delivered to their destination for unicast communication, or to multiple destinations in the case of multicast communications. The routing protocols for traditional networks like the Internet have become standardized and well-established, specially for the paradigm of unicast or point-to-point communications. There is still a lot of room for routing innovation in other types of communication paradigms such as multicast or unicast. Furthermore, as new types of computer networks emerge, e.g. mobile ad-hoc networks, disruption tolerant networks, or nano-scale molecular networks, each with their own specific idiosyncrasies, new types of routing protocols need to be investigated for them.

The first chapter in this section, *Autonomously Evolving Communication Protocols: The Case of Multi-Hop Broadcast* looks at the routing needs of broadcast networks which are relevant in tactical military environments, wild-life monitoring, and other instances of mobile ad-hoc networking. They propose an alternative approach for routing using autonomous machine intelligence built upon on-line evolutionary approaches such as natural selection and genetic programming. Creating a genetic programming language and a selection mechanism for multi-hop broadcast protocols allows them to create a system that outperforms traditional networks under some conditions.

The next chapter, *Application of Genetic Algorithms for Optimization of Anycast Routing in Delay and Disruption Tolerant Networks* provides another algorithm based on genetic programming, with the difference being the type of networks that are targeted. This chapter looks at the routing problem in disruption tolerant networks.

The third chapter in this section, *Data Highways: An Activator–Inhibitor–Based Approach for Autonomic Data Dissemination in Ad Hoc Wireless Networks* uses the paradigm used in cell morphogenesis to create paths for information dissemination in ad-hoc networks. The concept provides a completely decentralized approach to establishing paths that lead to data sinks, a peculiar behavior that is commonly found in ad-hoc sensor networks.

The last chapter in this section, *Scented Node Protocol for MANET Routing* provides an approach based on modified ant colony algorithms to create effective routes in mobile ad-hoc networks.

Taken together, the thirteen chapters in this book provide a current snap-shot of network research drawing its inspiration from biological systems.

WHO IS THE BOOK FOR?

This book is intended for researchers in the academia, industry, and governments who want to understand the issues in networking, and obtain an overview of the recent advances in the field of networking that are inspired by biological systems. This book will introduce some new advances in networking. Researchers in the field of communication networks, performance modeling and distributed computing will find the chapters in this book to be of particular relevance.

WHO IS THE BOOK NOT FOR?

This book is not intended for a biologist or a researcher who is new to the principles of computer communications network. It does not provide a tutorial or introduction to the design of current computer networks, a topic that can take several books on its own. It also does not deal with incremental advances to existing deployed networks. Most of the ideas covered in this book will require a radical change in the networking infrastructure to implement.

This book is a compendium of research papers and surveys. As such, it is not a comprehensive introduction to the subject of biologically inspired communication networks. It is instead targeted for researchers who already have some understanding of the area and are looking for focused, detailed research papers on specific aspects of it.

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Chapter 1
A Networking Paradigm Inspired by Cell Communication Mechanisms

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ABSTRACT

This chapter provides a brief review of molecular communication, a networking paradigm inspired by cell communication mechanisms. In molecular communication, information is encoded to and decoded from molecules, rather than electrons or electromagnetic waves. Molecular communication provides bio-compatible and energy-efficient solutions with massive parallelization at the nano-to-micro scale; it is expected to play a key role in a multitude of domains including health, the environment, and ICT (Information Communication Technology). Models and methods of molecular communication are also reviewed, and research challenges that need to be addressed for further advancement of the molecular communication paradigm are discussed.

INTRODUCTION

Molecular communication is an emerging technology that exploits biological materials or living matter to enable communication among biological nanomachines (or nanomachines in short) (Hiyama, 2005). Nanomachines are small-scale devices that exist in nature or are artificially synthesized from biological materials. Some examples of nanomachines found in nature are biological cells, molecular motors that produce mechanical work (e.g. myosin), and biochemical molecules, complexes, and circuits that are capable of processing chemical signals. Examples of artificially synthesized nanomachines include synthetic molecules, genetically engineered cells,

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artificial cells, and bio-silicon hybrid devices that are programmed to produce intended biochemical reactions.

In molecular communication, information is encoded to and decoded from molecules, rather than electrons or electromagnetic waves. Since nanomachines are made of biological materials and not amenable to traditional communication means (i.e., electrons or electromagnetic waves), molecular communication provides mechanisms for nanomachines to communicate by propagating molecules that represent information. Molecular communication allows networking of nanomachines and potentially enables new applications in various domains including health (e.g., nanomedicine and tissue engineering), the environment (e.g., monitoring and quality control), ICT (Information Communication Technology)(e.g., implantable biological sensors and actuator networks), and military situations (e.g., biochemical sensing).

Molecular communication exhibits unique features that are not commonly found in telecommunication technology as it currently stands. The distinctive features of molecular communication compared to current telecommunication technology are highlighted in Table 1.

- Communication components: Molecular communication allows networking of nanomachines while telecommunication is to communicate using silicon-based electric devices. Nanomachines in molecular communication are nano-to-micro scale devices that exist in biological systems or are artificially synthesized from biological materials.
- Signal types: Molecular communication uses chemical signals to communicate information, unlike telecommunication technology which uses electrical or optical signals. Using signal molecules as carriers of information opens up new possibilities in ICT. For instance, signal molecules carry physical properties that encode a high density of information. Also, signal molecules may carry some functionality. For example, a DNA sequence that codes some biological functions can be transmitted to a receiver nanomachine which acquires new functionality (e.g., a functional protein) as a result of gene expression.
- Communication speed and range: The speed and range of molecular communication are extremely slow and strictly limited compared to existing telecommunication technology. The speed and range of molecular communication vary depending on the communication mechanisms used. The fastest and longest range communication is achieved through neural signaling which propagates electro-chemical signals (i.e., action potentials) at 100 m/sec over several meters, while the free diffusion of molecules based on Brownian motion is extremely slow and contained within a limited range.
- Communication media: In molecular communication, chemical signals propagate in

Table 1. Molecular communication and telecommunication

Communication	Telecommunication	Molecular Communication
Communication components	Electronic devices	Bio-nanomachines
Signal types	Optical/electrical signals	Chemical signals
Communication speed	Speed of light (3×10^8m/s)	Extremely slow
Communication range	m ~ km	nm ~ μm
Communication media	Air or cables	Aqueous

an aqueous environment, while electrical signals in telecommunication (or electromagnetic waves) propagate through a metallic cable (or in air). In molecular communication, a communication medium normally contains thermal noise which influences significantly how signal molecules propagate in the communication medium. In addition, a communication medium contains other molecules which may react with signal molecules, affecting the communication performance.

- Other features: Biocompatibility is another unique feature of molecular communication. Since molecular communication uses communication mechanisms derived from biological systems, it can directly interact with our cells, tissues and organs. Molecular communication also operates with chemical energy, unlike telecommunication which requires electric energy and power sources. Chemical energy in molecular communication may be supplied by the environment where the molecular communication operates. For example, molecular communication systems deployed in a human body may harvest energy from the human body, requiring no external energy sources. Furthermore, molecular communication may be energy efficient with low heat dissipation. For example, molecular motors, transport mechanisms found in biological cells, convert ATP energy to mechanical work at nearly 100 percent efficiency.

MOLECULAR COMMUNICATION

Figure 1 depicts a basic form of molecular communication. In this paradigm, the sender and receiver nanomachines communicate by propagating signal molecules via a communication channel. The sender and receiver often represent a group of molecular mechanisms performing n-to-n communication. The signal molecules are transmitted by a sender (or senders) of communication, propagated through the communication channel, and received by the recipient(s) of communication. The communication channel provides a mechanism for signal molecules to propagate while it typically contains noise sources such as thermal noise and other molecules that interfere with the propagation of signal molecules.

Figure 1. Molecular communication