Biological Principles for Future Internet Architecture Design

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ABSTRACT

Currently, a large number of activities on Internet redesign are being discussed in the research community. While today's Internet was initially planned as a datagram-oriented communication network among research facilities, it has grown and evolved to accommodate unexpected diversity in services and applications. For the future Internet this trend is anticipated to continue even more. Such developments demand that the architecture of the new-generation Internet be designed in a dynamic, modular, and adaptive way. Features like these can often be observed in biological processes that serve as inspiration for designing new cooperative architectural concepts. Our contribution in this article is twofold. First, unlike previous discussions on biologically inspired network control mechanisms, we do not limit ourselves to a single method, but consider ecosystems and coexisting environments of entities that can cooperate based on biological principles. Second, we illustrate our grand view by not only taking inspiration from biology in the design process, but also sketching a possible way to implement biologically driven control in a future Internet architecture.

INTRODUCTION

The Internet has transformed and changed our lives in many aspects over recent years, where the increase in popular and sophisticated services continues to attract users. However, the current Internet infrastructure, which was built mainly for conservative data traffic usage, is approaching its limit. This has led the research community to investigate solutions toward the future Internet within various project initiatives (e.g., GENI, FIND, AKARI, FIRE) [1]. The motivation for this research development is largely driven by the behavioral changes and needs of users toward the Internet. While the original Internet was designed mainly to allow users to exchange information (mostly to support research and work), today we see highly diverse sets of services, many of which are used daily to enhance our quality of life. These services range from information gathering mechanisms tailored to our personal and societal needs,to support for various social problems, as well as entertainment.

In order to fully support such diverse services, the future Internet will require new architectural and protocol designs. This new architectural design would need to integrate highly intelligent processes to improve their robustness, scalability, efficiency, and reliability. This is particularly crucial because the number of devices in the future is expected to drastically increase. One approach to provide this capability that communications researchers have recently started investigating is through bio-inspired processes [2–4]. Biologically inspired mechanisms have been applied in recent years to diverse types of networks (e.g., sensors, wireless, fixed, services). However, from the viewpoint of the future Internet, current bio-inspired approaches are only a first step toward realizing a fully functional system. The main reason behind this is because most of these bio-inspired solutions have only tackled specific problems for a particular type of network. In order to realize the full potential of bio-inspired solutions for the future Internet, these disparate solutions need to be designed to function in a fully integrated manner.

In this article, we aim at paving the way for this vision to become a reality. We first summarize some of the key requirements of the future Internet, in particular from the core network infrastructure perspective. This is then followed by discussions on relevant properties found in biological processes that enable multiple organisms and systems to coexist in an ecosystem, where our aim is to combine various bio-inspired network control mechanisms within the future Internet. Our proposal is built on two intrinsic properties of biological systems, which includes a fully integrated system of systems within an organism, as well as organisms that can coexist in an ecosystem. The article illustrates how our idea could be augmented with some existing proposed architectures for the future Internet. Lastly, we present our grand vision of future communication networks that are directly driven by biological systems, taking the concept of biologically inspired networking to a new level.

Requirements of the Future Internet

While the future Internet will cover various different types of agendas, we only focus in this article on the core network infrastructure of the Internet. In the future, we can anticipate greater heterogeneity, coexistence, and cooperation among different types of networks. This can range from different content and service distribution networks to virtual networks that all operate over the same physical network. At the same time, communication networks of the future will require emergent properties embedded directly into the networks. This is often dubbed as self-* properties in the literature (self-organization self-management, etc.). In this section we list the requirements expected in our view of the future Internet.

Virtualization and Adaptive Resource Management

A crucial component of communication networks is resource management, and its efficient usage will determine the quality of service (QoS) delivered to end users. Before the Internet gained its current popularity, single network providers usually owned the communication infrastructures. However, this situation is slowly transforming into a new business model, where a distinction between network (infrastructure) providers and service providers is becoming apparent. This is usually referred to as *virtual networks*, where service providers lease the resources they need from network providers and are allowed to have a certain control over usage of these resources. The increased flexibility means that service providers may configure their virtual network according to the services they are offering, while the network provider needs to safeguard the fair usage of the network. However, the dynamics of services may change over short timescales, leading to the need for dynamic resource subscription policies from the network provider. Another crucial requirement of the future Internet is the adaptive usage of resources through efficient routing. One important research agenda is the need for scalable, robust, and distributed routing applicable to large-scale networks. The majority of current routing solutions are based on optimization methods, where prior knowledge of traffic demand exists, and the demand does not change frequently. Performing routing this way is ideal if reconfigurations are only required over long timescales. However, as the number of services increases and evolves at a fast pace, more reactive and intelligent routing mechanisms are required.

Energy Efficiency

As the Internet's popularity increases, so has its supporting information and communications technology (ICT) infrastructure. This ranges from increases in data centers to host services, network access technologies, as well as end-user devices. Overall, this has led to a steadily increasing consumption of energy to operate the infrastructure. As the traffic volume in the future is anticipated to increase, this in turn will also lead to a higher amount of energy consumption by networking equipment. A common approach toward saving energy today is switching devices off or putting them into sleep state. However, with the large number of nodes anticipated in the future Internet, this process should be performed in a collaborative manner, while ensuring that end users' requirements are met.

Flexible and Evolvable Infrastructure

A major factor behind the requirement of redesigning the Internet is the fact that the original Internet was designed mainly for accommodating data traffic with stable traffic patterns. However, it is neither feasible nor practical to perform a complete redesign of the Internet each time new requirements, or drastic technological or social changes arise that do not fit the current architecture. Therefore, the design of the future Internet should include a sustainable infrastructure that is able to support evolvability. This should enable new protocols to be introduced with minimal conflict to existing ones. At the same time, the design of architectures and protocols should be made in a modular way, where protocol components can have cross-layer interactions. The evolvability of the future Internet should also allow for a certain degree of openness, where protocols with the same functionalities can be deployed by various entities to suit their own needs; but these protocols must be able to coexist with each other and minimize any possible conflicts. For example, different service providers should be able to deploy their own routing algorithm that best suits their customers' QoS/quality of experience (QoE) requirements.

Service-Oriented Provisioning

A key point that has attracted users to the Internet is the continual development and provisioning of new and more advanced services (rich multimedia content). It is expected that this trend will also continue in the future. Therefore, as a multitude of new services start to flood into the Internet, it is essential that these services are autonomous and capable of exhibiting self-* properties, similar to the requirements for network devices of the future. These properties should allow services to autonomously discover and combine with other services in an efficient and distributed manner. At the same time, deployment of these services should not be restricted to end systems, but may also be embedded into network routers.

This section discussed some of the require-

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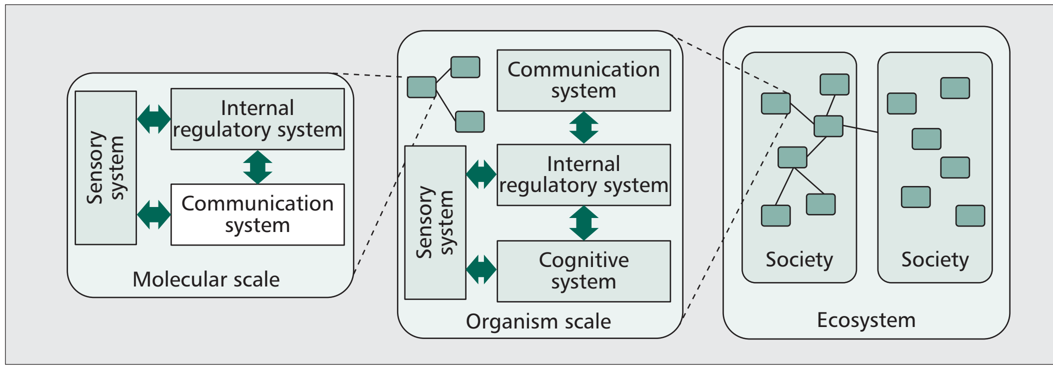

Figure 1. *Hierarchical ecosystem in a biological system.*

ments for designing a sustainable future Internet that is able to handle current and new challenges. Its main features are that the network should support virtual networks and allow each virtual network to adaptively subscribe resources from underlying networks, have self-* properties for managing itself, enable energy efficiency, and support a diverse set of services in a flexible way. Similar characteristics can often be found in biology, and the following section discusses some biological processes that may serve as inspiration to meet these requirements.

Basic Mechanisms of Biological Cooperation

Biological systems have remarkable capabilities of resilience and adaptability. These capabilities are found in various biological organisms, ranging from microorganisms to flocks of animals and even human society. Over billions of years, this resilience and adaptability has evolved to suit the changes of the environment, and for this very reason bio-inspired techniques have provided inspiration for communication network researchers [2–4]. In particular, there are two especially appealing aspects of biological systems that could be beneficial in designing architectures of the future Internet. First, biological systems are always composed of a multitude of protocols that combine various processes to control different elements of an organism. Second, biological systems as a whole exhibit a hierarchical ecosystem structure that allows various organisms and systems to coexist.

Figure 1 illustrates an example of both these aspects, presenting an abstract layered view of internal functionalities within organisms, composed of an internal regulatory system, a cognitive system, a sensory system, and a communication system. In the remainder of this section we describe some key features of this abstract model and its importance in allowing biological systems to coexist in the manner in which they do.

Internal Regulatory Systems

In order for biological systems to maintain stability and survive through age, there is a need for self-regulation to balance the system and maintain constant conditions in the face of external and internal perturbations. One example of this self-regulation process found in organisms is homeostasis. There are a number of different homeostasis processes ranging from thermoregulation to blood glucose regulation. Homeostasis requires the integration of information from different parts of the body, as well as the analysis and forecast of resources. Another example of an internal regulatory system within an organism is the immune system, which is able to fend off non-self invader cells. These biological mechanisms can serve as good inspiration in the design of self-management and self-regulation in communication networks since they operate efficiently, and are robust without centralized control.

Biological Sensory Systems

Organisms possess a number of sophisticated sensory systems to maintain internal balance. These systems receive their external inputs from sensors and propagate the stimulus through a complex hierarchical network to various components within an organism. Examples of sensory systems are the central and peripheral nervous systems in the human body. Another example is the lateral line, which is a sensing organ found in aquatic organisms. Sensory systems interconnected through the nervous system or lateral line provide a medium for coordinating and transmitting signals between various parts of the body. Insight on where to locate processing units within a communication network can be gained from observing the structure of the nervous system (e.g., the location of ganglia serving as hubs between the peripheral and central nervous systems).

Biological Communication and Signaling

A key property of biological systems is the ability for entities to communicate and signal between each other. This form of signaling can come in various forms, ranging from speech to chemical signaling. Signaling is required for synchronization between organisms. At the microorganism level, reaction-diffusion describes the concept of morphogenesis, the process where chemicals are released and diffused between cells during tissue development to explain patterns of stripes or spots on animal coats. Another example is quorum sensing, which is when cells signal among each other and cooperate in the face of environmental changes. All of these processes are cooperative, and different entities communicate in a fully distributed way among each other. In most cases the organism is unaware of the emergent outcome of synchronization in the whole system.

Societies are formed between various organisms through such signaling and communication processes. They are the very foundation that allows organisms to function collectively and exhibit various self-* mechanisms in order to coordinate various tasks. During migration, flocks of birds use signaling between members in the pack to rotate the leader of the flock to balance energy expenditure of each bird due to wind resistance. Social insects, such as ants and bees, show a high degree of cooperation, and perform division of labor and self-organization while foraging [5].

INTERACTING POPULATION DYNAMICS

Population models, such as predator-prey interactions, competition, and symbiosis, describe the interactions between different species while coexisting within a common space or ecosystem. In predator-prey, the predators are the dominant of two interacting species and feed on the prey. On the other hand, symbiosis occurs when both species coexist and mutually benefit in their growth, while under competition both populations mutually inhibit each other. The population dynamics in the ecosystem determines whether the system is able to maintain balance among competing species. Attaining balanced coexistence among heterogeneous populations (networks, services) in a common ecosystem is one of the goals of our proposal.

FUTURE INTERNET ARCHITECTURE

In this section we discuss how we could possibly map the biological mechanisms of the previous section to example architectures that have been proposed for the core infrastructure of the future Internet. These architectures are the Services Integration, Control, and Optimization (SILO) architecture [1] and Information Transfer Data Services (ITDS) [1], although other architectures can also be treated in a similar way. Our aim is to use an ecosystem model, as shown in Fig. 1, as a basis to ensure that biological processes can simultaneously coexist with the other processes that are involved in its environment.

EXTENSION OF THE SILO ARCHITECTURE

The aim of the SILO architecture is to create a modularized architecture for the future Internet that can:
- Create building blocks from fine-grained services
- Allow these building blocks to be combined in order to support complex communication tasks
- Allow cross-layer interactions between different services

Based on these aspects, the aim is to allow the application layer to select the most appropriate services to support its needs. A positive aspect of the SILO architecture is its ability to create modular architectures based on the capabilities and resources of the end devices. For example, in resource constrained device such as sensors, only vital services are embedded directly into the device to ensure minimum energy consumption, while other services are loaded on demand.

For these reasons, SILO is very suitable for our proposed bio-inspired future Internet architecture, where each biological process can represent a SILO service. Similar to the SILO solution, the processes invoked by the biological mechanisms depend on rules and constraints that govern the relationship between the processes. Therefore, each biological process will have a description that includes:
1. The specific function it performs (e.g., routing)
2. The key requirements of those functionalities from external parameters (e.g., measurements)
3. The interfaces that are compatible with other processes

In the case of 1, this allows applications to determine the appropriate biological process that meets its requirements in the deployed environment. Such characteristics include overhead of the protocols and delay incurred when the process is applied to a specific topology. At the same time, parameters are defined for each of these processes to maintain behavioral constraints, which could be applied through policies.

The SILO architecture currently uses a control agent that determines the services to be composed together. In a similar fashion, a control agent can determine the most appropriate biological process to support the type of application. Figure 2 illustrates an example of the bio-inspired SILO architecture and its application to a virtual network above a physical network. The figure also illustrates the protocol stack and the different processes fitting into the stack. The paths along the virtual network are selected using a noise-driven internal regulatory mechanism known as attractor-selection, an internal regulation system found in E. coli cells [6]. The underlying network uses the reaction-diffusion mechanism for signaling between the nodes, and the routing process is based on chemotaxis [7], which is a motility mechanism used by microorganisms to attract a gradient found in an environment. Also similar to the original SILO services, each process is equipped with "knobs" to allow external tuning of parameters.

The layered protocol shows how the different processes in the routing and overlay path layers interact with each other. The attractor-selection mechanism is defined through a number of states and is driven by noise. Internal regulation changes the state due to external influences; that is, this internal regulation controls the bandwidth resource for the virtual path. Once a certain threshold is exceeded, attractor-selection interacts with the underlying network, which uses chemotaxis to discover new routes. The chemotaxis mechanism is a distributed routing mechanism that selects the path node by node from the source to the destination following the highest gradient. The gradient is formed through the node-to-node interaction of the reaction-diffusion process [7].

An example of the interaction between two bio-inspired control mechanisms is shown in Fig. 3. The figure shows how paths are discovered

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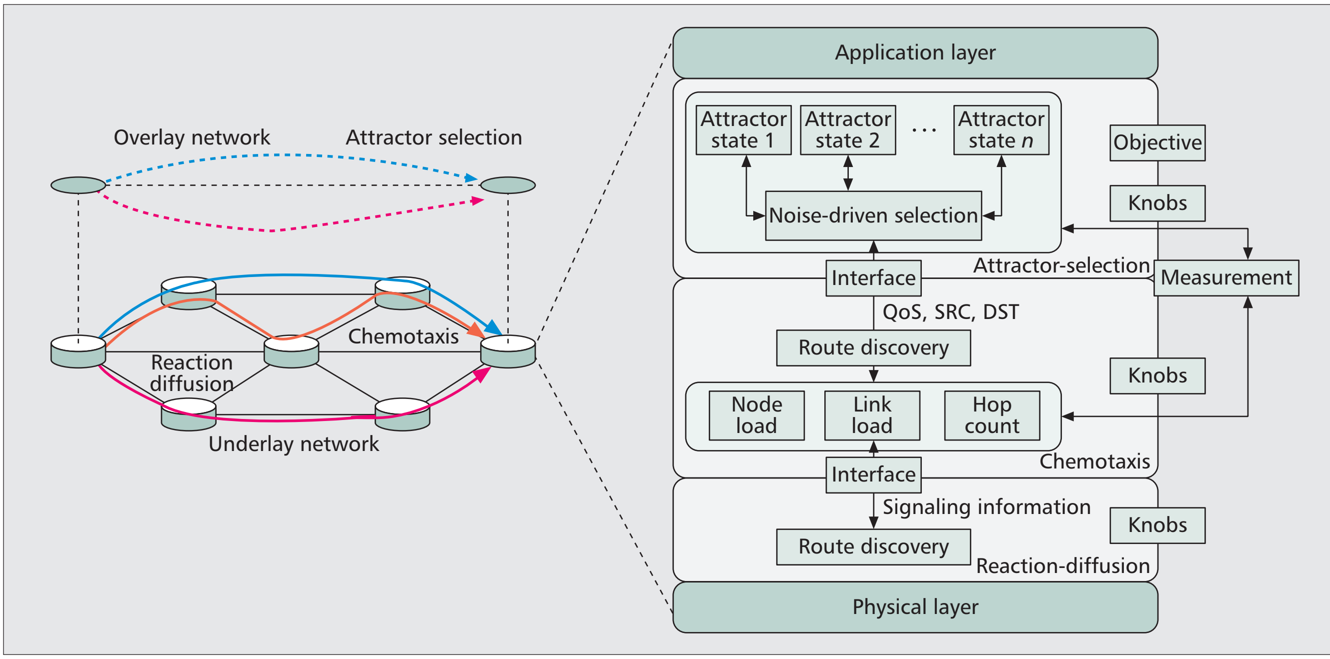

Figure 2. *Bio-inspired SILO architecture.*

through the gradients using the chemotaxis model for both the primary and secondary paths. Initially, attractor-selection determines the overlay path 1 (red line) to be chosen. Since the QoS requirements are fulfilled, the system remains in a stable state and is kept at the dynamic attractor for path 1 despite small fluctuations. At time step $t = 400$ congestion occurs, leading to the path becoming unstable, which in turn decreases the QoS of the overlay layer. The path is then switched from path 1 to path 2 (blue line), which offers greater stability, and at time step $t = 600$ the system becomes stable again. This simple example shows how different dynamic biologically inspired control schemes can symbiotically cooperate in reacting to congestion and changes of traffic conditions at various timescales. Coming back to our ecosystem model presented in Fig. 1, we can see that the different biological mechanisms are applied at the molecular level (attractor-selection and chemotaxis), and are able to coexist within an organism.

Figure 4 shows how the concept of modularity and openness can be realized within the bio-inspired future Internet. Two routing mechanisms (ant-based routing [5] and chemotaxis) have been applied to the underlying networks. Each routing algorithm consumes a certain quantity of resources, but both mechanisms can symbiotically coexist in the network, supporting the requirement of openness. The most ideal routing mechanism may depend on different objectives (e.g., scalability, timeliness for route discovery, reaction to dynamics, energy of signaling overhead). Therefore, through the symbiotic requirements, various new protocols can be updated and added.

Extension of the ITDS Architecture

Another example is the bio-inspired ITDS, which focuses on service provisioning as a key requirement. The aim of ITDS is to have transfer of information in the underlying network rather than just raw data as is currently done. This proposal is realized through sets of services that are embedded into the routers to perform application-based processing. This is far from the traditional approach, which only allows end hosts to have service intelligence while the underlying network is used for forwarding packets. Whereas the original ITDS only handles the application layer requirements, we extend this by allowing embedded processes into the network layer as well. This in turn allows the network to be highly adaptive and support evolving services.

An example of bio-inspired ITDS and its corresponding protocol stack are shown in Fig. 5. In this figure we show a combination of two services on two virtualized planes, the security and multimedia planes. On the security plane we have a reliability function that works in sequence with the privacy function, where the reliability function is based on an immune system mechanism. At the multimedia plane, we consider a codec service that works in conjunction with a caching service that can extract data to serve various end users. We assume that each of these services is able to migrate from node to node. Since one of the objectives of the future Internet is energy efficiency, we also have an embedded service that measures energy output within a node. Cooperative signaling is also performed between the nodes to permit certain nodes to be switched off while others take the burden of the traffic to minimize overall energy consumption. Cooperative signaling is performed using the quorum sensing process, and the energy efficiency service is based on the internal thermoregulation process of an organism. When we map this back to the ecosystem model of Fig. 1, we can see that this example expands further from the example used for bio-inspired SILO. In this example, our bio-inspired processes in the underlying network are based on mechanisms found at

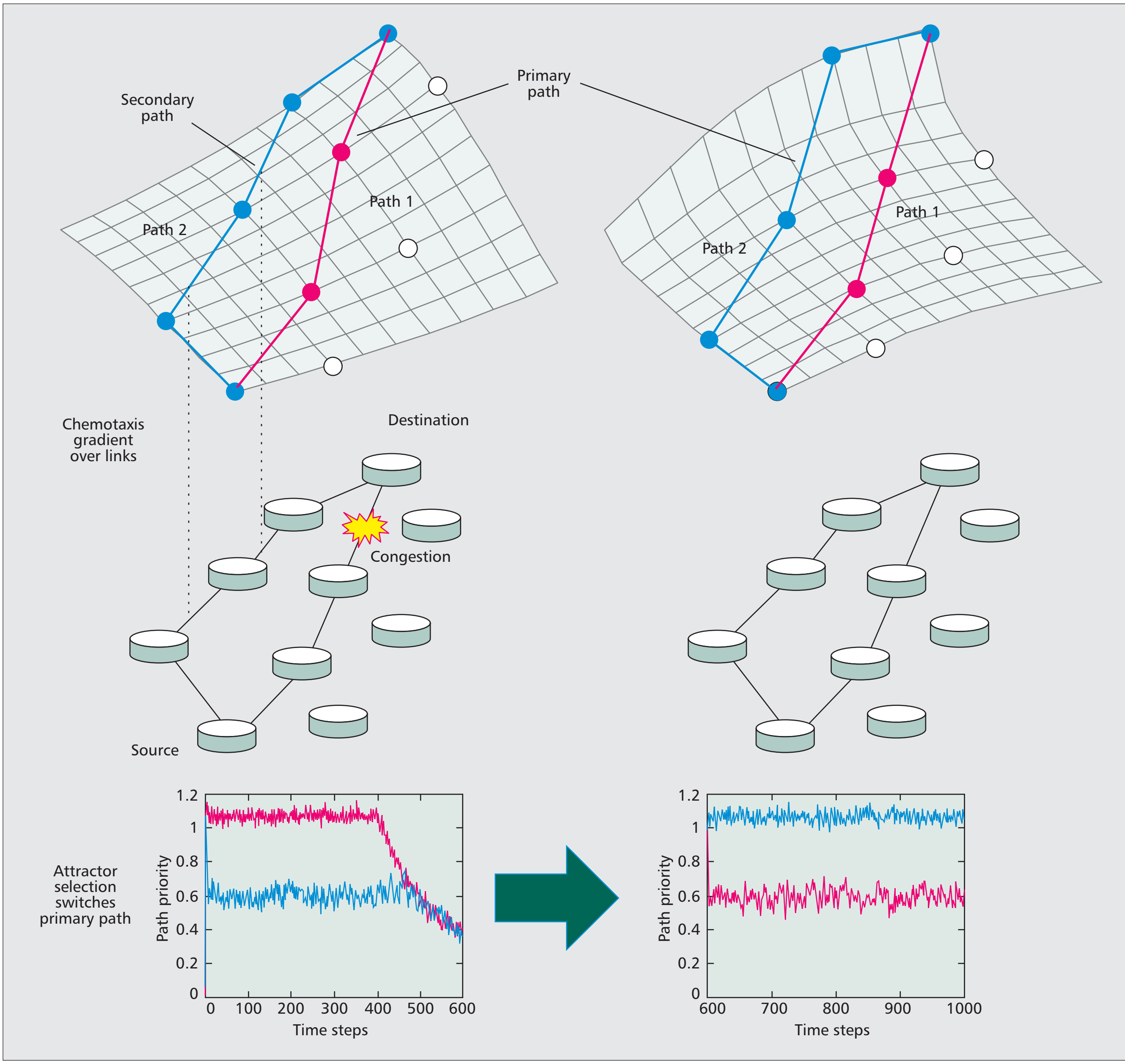

Figure 3. *Illustration of cooperative adaptation between attractor-selection and chemotaxis gradient-based routing.*

the molecular level, while the processes used to manage the security and multimedia plane, as well as their interactions, are based on internal regulatory system of an organism. So the example shows how processes at the microorganism level can coexist with processes at the organism level, representing a virtual network operating over a physical network.

Biologically-Driven Future Networks

While biologically inspired mechanisms have provided increased capability and adaptability for communication networks, a major challenge is understanding a biological process and developing an appropriate algorithm. At the same time, most bio-inspired algorithm designers use refined biological processes that omit various hidden functionalities, where these functionalities may solve foreseeable future problems.

Therefore, a viable alternative to the current approaches is to allow systems to be directly driven by biological systems — or as we term it *biologically driven* future networks — bypassing the step of using artificial bio-inspired algorithms. An example of our proposed concept is illustrated in Fig. 6. In this example a cell may represent a virtualized overlay network, and in the event of changes in the overlay network environment, this triggers feedback into the cell culture. This feedback may lead to mitosis, where the output from the mitosis process can be filtered back to the overlay to reconfigure the overlay network into two virtual networks. This vision may be one possible solution toward the development of network devices for the future

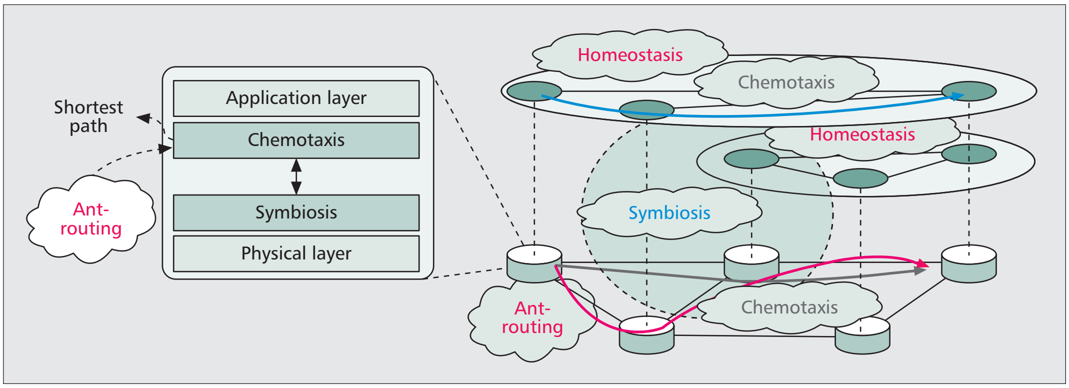

Figure 4. *Illustration of evolvable protocol for SILO architecture.*

Internet, particularly to cope with increased and unknown complexities. As shown in the figure, a biological culture of microorganisms could directly drive the behavior of the underlying network, and when a change is experienced in the physical network, a feedback process could manually be injected to change the environment of the biological culture. From a practical perspective, we need to limit this vision to the use of microorganisms. In essence, this allows us to harness and directly exploit communication processes at the nano/molecular scale of biological systems [8] to control communication systems. Directly using biological systems for various systems has been investigated previously. For example, in [9] slime mould was used to design the Greater Tokyo railway network, while in [10] slime mould was again used to design the U.S. road networks. However, we believe that a similar concept could also be extended to the real-time management of communication networks. Through this approach, a new methodology of tackling problems in future networks can be devised with the concept of biological software/hardware co-design (where biological cultures could be interfaced to software and hardware systems). A major benefit would be that there is no requirement for defining a complex protocol and designing countermeasures for all possible kinds of communication network scenarios.

However, there are still a number of challenges before such an approach could finally be realized. First, biological systems require a favorable environment in terms of nutrients and temperature to be cultivated, cells may die faster than they reproduce, and they may react differently or uncontrollably, all of which must be catered for. It may also lead to new security challenges. At the same time, synchronization between the biological organism and operations within the physical network will be a challenge, since biological processes at microorganism level can take hours to show some effects. New software and hardware design will also be required, where hardware modules must be able to house the biological culture, and the network conditions must be fed back to the biological environment.

Conclusion

In this article we discuss approaches to support the design of the future Internet architecture by making use of biological mechanisms. A

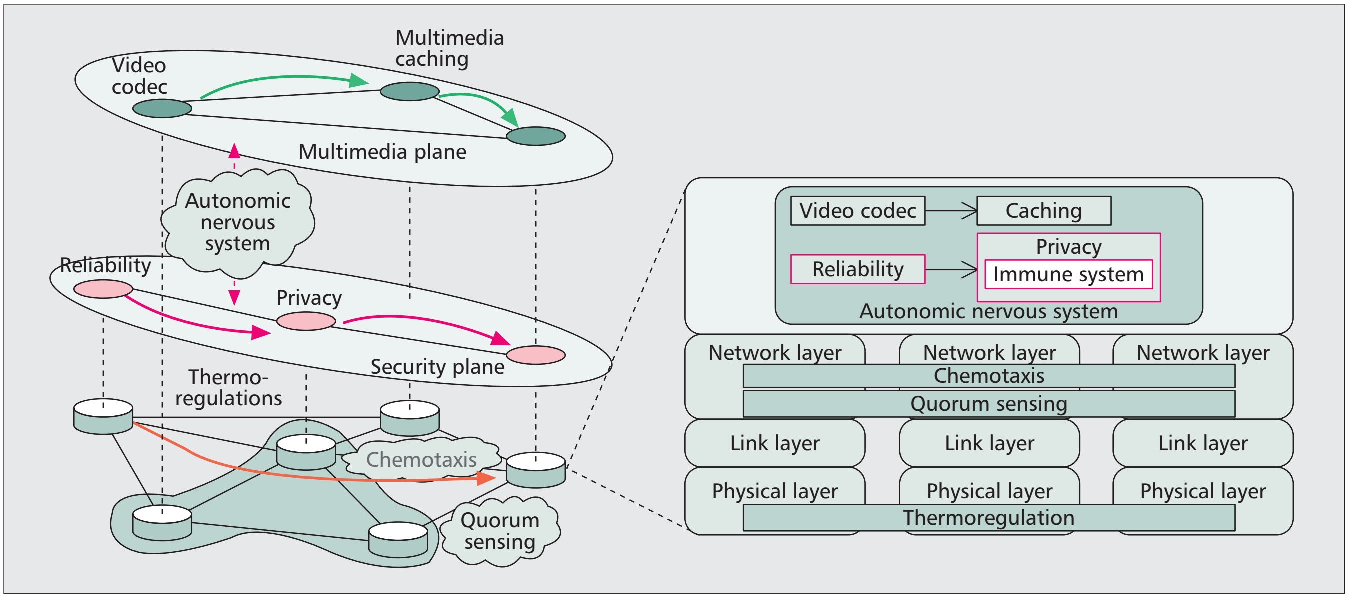

Figure 5. *Bio-inspired ITDS.*

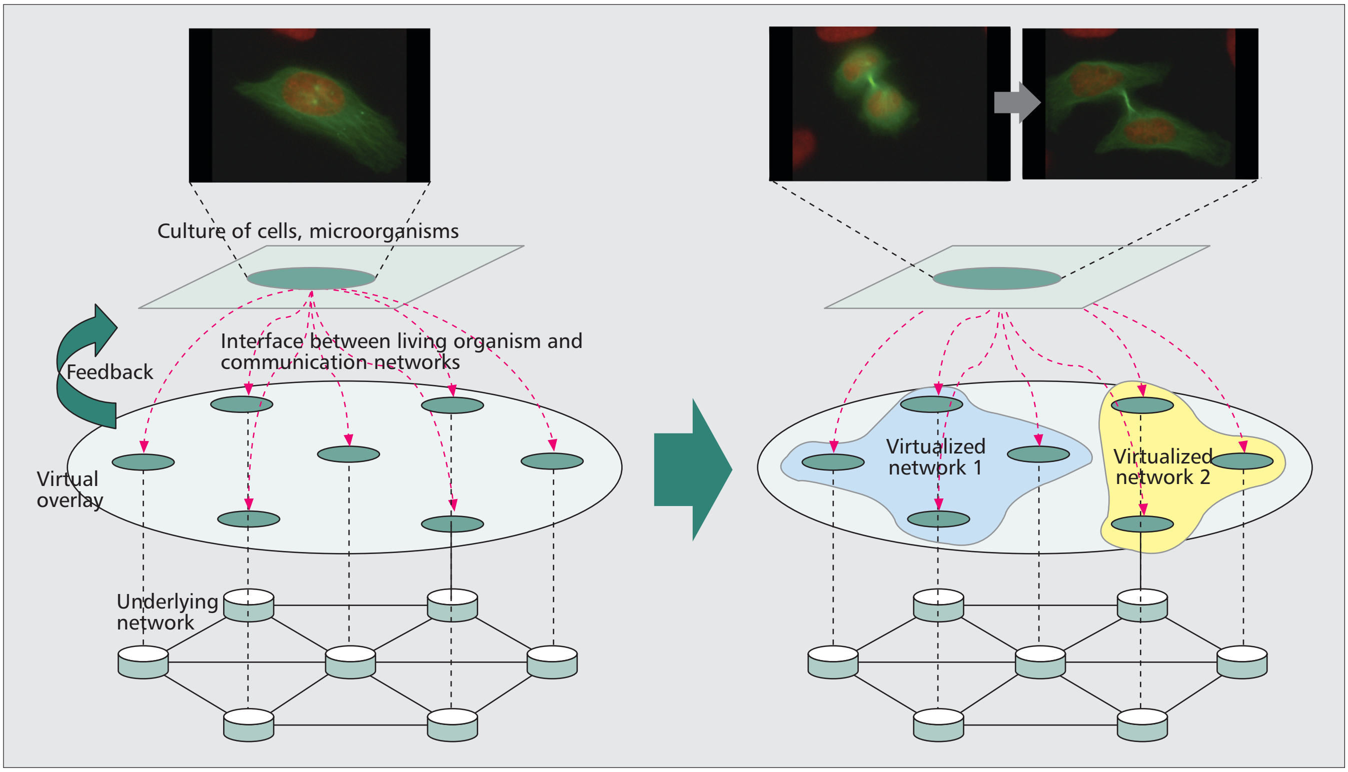

Figure 6. *Biologically driven future networks.*

large number of different bio-inspired methods have previously been proposed for enabling communication networks to exhibit self-* capabilities, where the majority of these solutions has only focused on individual specific mechanisms to solve a particular problem. However, from the future Internet perspective, we need to take a step back to see how these existing bio-inspired solutions can be integrated to meet the many requirements of the future Internet. In this article we outline possible solutions of integrating biologically inspired processes into the future Internet architecture to support this need. Specifically, we illustrate how this could be augmented with two existing architectures proposed for the future Internet, SILO, and ITDS. While applying biologically inspired methods may improve the robustness, adaptability, and evolvability of a new Internet design, our grand vision is communication networks of the future that can be directly driven by biological systems.

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References

[1] S. Paul, J. Pan, and R. Jain, "Architectures for the Future Networks and the Next Generation Internet: A Survey," *Comp. Commun.*, vol. 34, no. 1, 15 Jan. 2011, pp. 2–42.

[2] M. Meisel, V. Pappas, and L. Zhang, "A Taxonomy of Biologically Inspired Research in Computer Networking," *Comp. Networks*, vol. 54, no. 6, Apr. 2010, pp. 901–16.

[3] F. Dressler and O. B. Akan, "Bio-Inspired Networking: From Theory to Practice," *IEEE Commun. Mag.*, vol. 48, no. 11, Nov. 2010, pp. 176–83.

[4] P. Lio' and D. Verma, "Biologically Inspired Networking," *IEEE Network*, vol. 24, no. 3, May/June 2010, p. 4.

[5] G. Di Caro and M. Dorigo, "AntNet: Distributed Stigermetic Control for Communication Networks," *J. Artificial Intelligence Research*, vol. 9, 1998, pp. 317–65.

[6] K. Leibnitz, N. Wakamiya, and M. Murata, "Biologically-Inspired Self-Adaptive Multi-Path Routing in Overlay Networks," *Commun. ACM*, vol. 49, no. 3, Mar. 2006, pp. 62–67.

[7] S. Balasubramaniam *et al.*, "Parameterised Gradient Based Routing for the Future Internet," *Proc. IEEE Advanced Information Networking and Application (AINA)*, Bradford, U.K., 2009.

[8] I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A New Communication Paradigm," *Computer Networks*, vol. 52, June 2008, pp. 2260–79.

[9] A. Tero *et al.*, "Rules for Biologically Inspired Adaptive Network Design," *Science*, vol. 327, no. 5964, Jan. 2010, pp. 439–42.

[10] A. Adamatzky, "Physarum Machines: Computers from Slime Mould," *World Scientific Series on Nonlinear Science*, Series A, 2010.

Biographies

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