Bio-inspired networking – the basis for efficient communication in sensor and actor networks

Falko Dressler

Autonomic Networking Group
Computer Networks and Communication Systems
University of Erlangen-Nuremberg, Germany
dressler@informatik.uni-erlangen.de

Abstract. Recent approaches in the domain of bio-inspired networking enabled further scalability and efficiency in communication and coordination in massively distributed systems. Sensor and Actor Networks (SANETs) represent a specific class of such environments in which classical communication protocols often fail due to scalability problems. This presentation outlines biological communication techniques, which are known as cellular signaling pathways. We show the adaptation of these principles to the world of SANETs at the example of our rule-based control system for network-centric communication and data processing. This system is able to perform data pre-processing such as data aggregation or fusion as well as data-centric communication based on rules that are distributed throughout the entire network. First simulation results demonstrate that this system is able to outperform classical routing approaches in specific SANET scenarios.

Keywords. sensor and actor networks, self-organization, bio-inspired networking, rules-based sensor network, cellular signaling

1 Introduction

In this presentation, we depict a system for network-centric operation in Sensor and Actor Networks (SANETs) that we named Rule-based Sensor Network (RSN). This system is the result from recent studies in the context of *bio-inspired networking* – precisely, in the context of cellular signaling cascades. In the following, we summarize the requirements in the domain of massively distributed systems and introduce the biological background. Then, we present RSN in detail and conclude with two first application scenarios.

Whereas other application domains exist, we concentrate on SANETs [1]. Starting with the first domain, we can identify *scalability* and *energy efficiency* as the most challenging characteristics. Self-organizing algorithms have been developed relying for example on clustering and aggregation techniques to improve scalability and network lifetime [2]. In SANETs, *coordination* aspects need to be solved for sensor-actor coordination as well as for actor-actor coordination [3].

This includes additional communication constraints for network-wide coordination or, at least, local decision taking strategies that lead to an emergent behavior on a higher abstraction layer. Additionally, *real-time constraints* need to be considered as demanded by feedback control in sensor-actor coordination. Some of these challenging requirements are addressed by RSN. This approach basically provides the building blocks for developing network-centric operation and control techniques needed in massively distributed systems such as SANETs.

In the last few years, bio-inspired networking has become a new trend for addressing yet unsolved problems by adapting solutions known in nature [4]. Whereas a broad range of techniques and methods have been studied (e.g., the artificial immune system, swarm intelligence, and evolutionary algorithms), we focus in this paper on a rather new domain, the adaptation of communication and coordination techniques from cellular signaling. Figure 1 (left) sketches the principles of cellular information exchange. Information particles, e.g. proteins, are received by a cell according to the specific binding to a locally expressed receptor (or even a set of receptors) [5]. The activation of the receptor initiates a signaling cascade in which new proteins are created or activated and, finally, a cellular response can be observed, which represents the *specific reaction* of the cell according to the received information. Thus, cellular processes are regulated by interactions between various types of molecules, e.g. proteins. A key challenge for biology in the 21st century is to understand the structure and the dynamics of the complex intercellular web of interactions that contribute to the structure and function of a living cell [6].

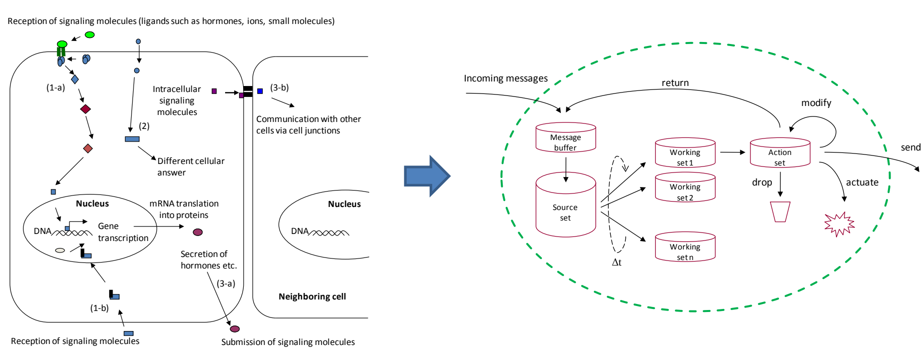

Fig. 1. Cellular signaling (left) adapted to network-centric operation in SANETs (right)

2 Rule-based Sensor Network (RSN)

Inspired by the capabilities of cellular signaling, i.e. the specific reaction to received information and the possibility to build signaling networks defining complex reaction pattern, we developed a rule-based programming system for application in SANETs as depicted in Figure 1 (right). The primary design goals were a small footprint to enable the application of RSN on small embedded systems, easily transferable code, flexibility, and scalability for network-wide operations (basically, RSN provides the tools and concepts but the specific application needs to be designed properly as well). The rule-system greatly helps in designing distributed algorithms for use in self-organizing massively distributed systems. Additionally, RSN was inspired by early rule-based systems that have been developed in the context of active networking solutions [7].

The key objectives motivating the development of RSN were improved scalability and real-time support for operation in SANETs. RSN is based on the following three design objectives:

– *Data-centric communication* – Each message carries all necessary information to allow data specific handling and processing without further knowledge, e.g. about the network topology.
– *Specific reaction on received data* – A rule-based programming scheme is used to describe specific actions to be taken after the reception of particular information fragments.
– *Simple local behavior control* – We do not intend to control the overall system but focus on the operation of the individual node instead. Simple state machines have been designed, which control each node (being either sensor or actor).

These goals are achieved by using a simple rule system that enables the node to process received messages and to initiate adequate state and message specific operations. Thus, all received messages are stored in a buffer (source set). Periodically, after a configurable timeout Δt, all messages in the source set are processed by the instructions defined by the rules. Every rule has the form `if CONDITION then { ACTION }` as depicted in Figure 2. Each rule specifically selects messages from the source set to apply the corresponding action. Details about the actions and further RSN parameters are described in the following.

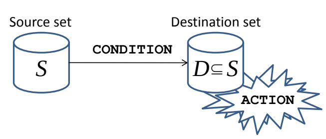

Fig. 2. Each rule selects a number of messages form the source set (`CONDITION`) and applies a (set of) actions to the selected messages (`ACTION`)

The main advantages of RSN are the small footprint of rules and the simple local programming of nodes – making self-organization possible even in large scale sensor and actor networks. In particular, this system allows the quick and heterogeneous reprogramming of (individual) nodes. Therefore, network-centric optimization of the placement of computational intensive rules becomes possible – some concepts can be adapted from the database community: the data stream query optimization problem. Our future work in the context of RSN includes further evaluation of aggregation techniques, the implementation on sensor nodes for "real world" experiments, and intensified investigations of reprogramming techniques.

Currently, we implemented RSN in form of a C++ library. This library contains all functionality that is necessary to process RSN statements. RSN statements are formulated in a flexible script language. We integrated the RSN library into the OMNeT++ simulation framework in order to execute intensive tests and experiments with different algorithms for data aggregation, probabilistic data communication, and distributed actuation control.

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