Quorum Sensing Digital Simulations for the Emergence of Scalable and Cooperative Artificial Networks

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ABSTRACT

This article proposes digital simulations of a bacterial communication system termed quorum sensing, and investigates the design of artificial networks build on the behavior of bacteria societies that tweet using quorum sensing signals. To this end, this article proposes a cell-based model that uses a “bottom-up” agent-based model coupled with ordinary differential equations, and develops the abstraction of intracellular dynamics as a basis underlying cooperative artificial network formation. Results show the emergence of self-sustainable behaviors thanks to the proposed model of metabolism that permits bacteria to grow, reproduce, interact, and coordinate at the population level to exhibit near-perfect bioluminescence behaviors. Moreover, the evolution of cooperation in the subsequent artificial network leads to the emergence of non-predicted coercive strategies. Coercion has been shown to be beneficial to share common interests between variants of cooperators leading the entire population of cells to be networked.

KEYWORDS
Agent-Based Modeling, Autonomous Behavior, Bioluminescence, Cell-to-Cell Communication, Coercion, Cooperation, Distributed Control, Gene Expression, Metabolism, Self-Regulation

INTRODUCTION

The simulation and design of biological mechanisms of self-regulation has been shown to provide insights through engineering digital artefacts that display self-organized, scalable and robust features which is one of the key purposes of the artificial life research. One of the self-organizing mechanisms of biological systems is that their units have the ability to communicate to help to fulfill their goals. For instance, there is a growing realization that the robustness of biological systems is often derived from collective population-level behaviors that extend beyond individual cells (Gorochowski, 2016). In the context of unicellular organisms, bacteria were for a long time thought to be independent unicellular organisms, until 1979, when bacterial colonies of Gram-negative bacteria such as Vibrio-fischeri

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and Vibrio-harveyi were shown to be able to perform a collective light-emitting behavior (Bassler, 1999). Traditionally, this phenomenon is known as Quorum Sensing (QS), and happens when the cellular density reaches a certain threshold. Indeed, bacteria cells can communicate with each other by producing, realizing, and taking up diffusible signaling molecules known as “autoinducers”. When the autoinducer binds to the target genetic receptor in a receiving cell, this results in the production of more signaling molecules. At high cell densities, this process causes the triggering of specific phenotypic responses such as bioluminescence or biofilm formation.

Communication is a widespread phenomenon in natural organisms and is fundamental to any kind of coordinated, parallel and distributed processes in human designed systems. The design and simulation of cellular communications has been explored by the artificial life community in two backgrounds: multicellular (Doursat, Sayama, & Michel, 2013; Stanley & Miikkulainen, 2003) and unicellular organisms. However, cell signaling in unicellular organisms is less studied. Indeed, there are fewer works on cell signaling in unicellular cell signaling.

We believe that the unicellular approach, provides several intrinsic beneficial properties, e.g. all the organisms are autonomous and share a single distributed communication system (QS). In addition, despite their sizes, single celled organisms such as bacteria have computational and evolutionary autonomous capabilities for self-replication and self-organization (Majumdar & Mondal, 2016). Moreover, an improved understanding of unicellular signaling by QS has numerous scientific benefits (Beckmann & Mckinley, 2009) and may provide insight into the evolution of multicellularity itself. Indeed, compared to a cell from a multicellular organism, a bacterial cell is a mobile and autonomous entity that can grow and act independently at an individual level, and coordinate its behavior with other cells at a population level to exhibit coordinated features previously recognized as specific to multicellular organisms, e.g. shape formation (Pascalie et al., 2016).

The potential of QS then resides in the simplicity of its general concept that gives rise to complex behaviors. But it should be noted that, although QS is simple in its fundamental principles, the QS mechanism is complex in its biological details. Although we have a good understanding of intracellular mechanisms, there remains considerable challenges.

We believe that abstracting the complex interactions of cell-to-cell communication into a representation will enrich our understanding of complex bacterial societies and may provide insights for alternative design techniques.

Thus, this paper proposes a multiagent computational model of QS, and investigates the potential of the link that can be established between QS and artificial communication networks. Specifically, the model uses a bottom-up agent-based approach and proposes a cell-based model coupled with Ordinary Differential Equations (ODEs) that abstract the intracellular dynamics of a bacterium cell such as a model of growth, a model of communication, a model of light-production, and a model of metabolism.

Our model is tested in a set of experiments (Djizzar, Fernandez Perez, Djedi, & Duthen, n.d.) where we evaluate the communication capabilities of bacterial colonies, their self-organized bioluminescence behavior, and their sustainable abilities to cooperatively form artificial communication networks. Results show evolution of cooperation and emergence of coercive strategies.

Our bacterial-inspired networks could be potentially used for the emergence of robust and autonomous network topologies that can address issues such as mobility or energy, which are key factors for the development of new self-organizing networks (Aziz, Sekercioglu, Fitzpatrick, & Ivanovich, 2013; Dressler & Akan, 2010).

The rest of this paper is organized as follows. Section 2 presents the related works and the problem statement. Our cellular model and their main parts, explicitly: growth, quorum sensing, metabolism and light-production, are detailed in Section 3. The proposed artificial communication network model is presented in section 4. Simulations results are evaluated and discussed in section 5 and 6. Section 7 outlines the model parameters and Section 9 concludes the paper.
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