Slime Mold Inspired Coordinations for Wireless Sensor and Actor Networks *

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ABSTRACT

We adapt the tubular network formation behavior of slime mold to design coordination protocols for wireless sensor and actor networks.

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General Terms: Algorithms, Design, Experimentation, Performance, Reliability.

1. INTRODUCTION

In wireless sensor and actor networks (WSAN), a large number of sensor nodes obtain information which must be transmitted reliability to any of several actor nodes in an energy efficient and timely manner [1]. In particular, actor-actor coordination selects the actor which each sensor is associated with; sensor-actor coordination finds the optimal means of sending and receiving information between an actor and its sensors.

Given a deployment of actors and sensors, the problem is to design a coordination protocol that connects all the sensors to the actors. Efficiency requires data being able to travel from a sensor to an actor in a small number of hops. Robustness requires either that multiple paths exist between any sensor-actor pair or that broken links are quickly repaired by the creation of alternative routes. While these design requirements suggest that a centralized approach is the best way to create such a network, biological systems solve similar problems without any global coordination or global information. One such self-assembled biological system is the nutrient distribution network generated by the slime mold *physarum polycephalum*. We propose adapting the tubular network formation behavior of slime mold to perform coordination. Specifically, the slime mold behavior does not require location information, but adds redundancy to routing paths to better meet reliability constraints.

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Physarum polycephalum is a slime mold organism with multiple nuclei and a relatively short life cycle on the order of a week. This form of fungi is *plasmodial* meaning that it grows from a spore into a multinuclear mass of plasmodium. Considerable research has focused on observed behavioral manifestations, surveyed in [2], including search for food, avoid danger, and determine the shortest paths through mazes under certain circumstances. Nutrients are distributed through the plasmodium via a dynamic, self-assembled network of tubes. Not all these tubes are equal, but rather there is a hierarchy of tube widths corresponding to a complex resource distribution network. Large tubes connect pairs of food sources within the plasmodium while small tubes bifurcate from the larger tubes and distribute nutrients throughout the protoplasm.

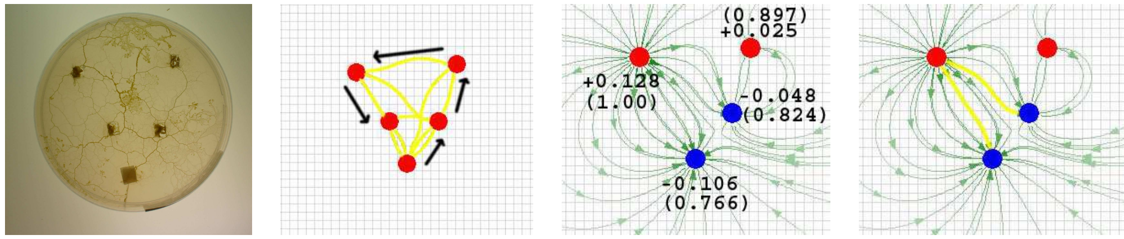
Experimental observations have shown that slime mold will connect nutrient sources into a variety of final configurations including Steiner minimal trees, minimum spanning trees and other more redundant structures. Often, the tubes of a slime mold will be arranged in a geometry that balances efficiency (keeping the total tube length short) and robustness (having multiple paths in case of a tube being severed). These observations are entirely consistent with an algorithm lacking complete global information.

2. A HIGH LEVEL MODEL USING SINGULAR POTENTIALS

Through laboratory experiments, we found out that, as shown in Figure 1, the large scale tube formations could be reproduced using *singular potentials* corresponding to estimates of the nutrient content available at each food source. In these laboratory experiments, *physarum polycephalum* is grown in petri dishes on agar. Nutrient sources consisting of blended oats in gelatin are placed at points of interest on the agar to study slime mold network self-assembly. We found that one CC of nutrient blend would be consumed in two days. Assuming a constant consumption rate, they estimated the amount of nutrient present to follow a linear profile. Using this information, we tested the following Physarum Polycephalum Singular Potential algorithm.

1. Initialize the plasmodium at one or more food source.

2. The plasmoidium would them stream toward a randomly selected food source that had not yet been discovered at a fixed rate during while the food that had already been discovered would decay linearly as discussed.



(a) (b) (c) (d)

Figure 1: (a) A laboratory slime mold experiment. (b) One possible solution using the singular potential algorithm. Other solutions are possible corresponding to different orderings in how food is discovered. In this case, the order chosen was the order in which the plasmodium discovered the food in the laboratory experiment, but all other factors including amount of food remaining at each source point, ψ and the resulting network paths, were computed based on the prescribed ordering. One of the incremental moves is shown in (c) and (d). In (c), the nodes, their relative nutrient values and the singular potential are shown. In (d), new paths are created following the minimum field lines.

3. When the plasmodium reaches a new food source, the new food source is connected to the existing network by following the minimum path of the mean field.

$$\psi = \sum_{n=1}^{N} (f_n - \bar{f}) \ln(|\vec{x} - \vec{x_i}|^2), \qquad (1)$$

   where N is the number of discovered food sources, f_n is the amount of nutrient remaining at the n^{th} food source and $\bar{f}$ is the mean of the f_n's.

4. Return to 2.

This algorithm has a number of attractive properties for our purposes. It uses global information amongst discovered food sources via ψ, but it acquires new food sources incrementally using local interactions. The use of singular potentials is connected directly to electrostatic potentials and fluid streamlines. If these nodal values represented charge instead of nutrient content, ψ would present electric field lines. If the nodal values represented fluid sources and sinks with the specified mass fluxes rather than nutrient values, ψ would be the streamfunction and lines of constant ψ would correspond to material paths of the fluid flow.

3. COORDINATION ALGORITHMS

Under sensor-actor coordination, we propose an algorithm to address the problem of finding optimal one-to-many or many-to-one routing paths which meet the desired efficiency and reliability constraints. This is a difficult problem in networks with a very large amount of nodes, since traditional routing protocols do not scale well. Currently, the only viable routing algorithms for these applications are location-based which have various drawbacks. Using the slime mold model as the basis for our algorithm, we will translate the singular potential algorithm into the networking protocol domain. The problem then is as previously discussed, to create an optimal tube network connecting the slime mold to all food sources. The optimal tubes then are used as the basis for all routing decisions in the desired direction.

To translate the slime mold algorithm from the microbiological domain to the network protocol domain, we must identify nutrient demands with networking demands. In this case, we propose to map the nutrient content in each food source to networking capability at each actor and sensor. Specifically, we define the "data flux capability" (or, capability, for short), corresponding to the food source's nutritional value in the slime mold problem, to be the available (unused) bandwidth departing the actor or sensor. The capability is computed as the node's uplink bandwidth, if connected, minus the actual flux of data entering the node. For an actor, which is always "connected" as long as it functions normally, the uplink bandwidth signifies the data consuming power, and the data flux capability thus represents the available processing potential. An actor's capability should never be negative, since it should not be asked to handle more than it can by design. For a sensor, the initial uplink bandwidth is zero, before it's connected to the network to be able to upload its gathered data. Once a sensor gets connected, it can also serve as the "relaying sink" for other sensors until all of its uplink bandwidth is occupied.

Our preliminary algorithm works as follows. Initially, when there are no connections among sensors and actors, there is plenty of unused departing bandwidth and no data flowing into the actor, so the actor has a large positive data flux capability. For sensors within the transmission range of the actor, some might have negative capabilities if they are collecting data in and still not connected to any actor. By applying the singular potential algorithm to compute the resulting field, we then connect the actor to sensors within its range by following the shortest field lines as in the slime mold problem. Note that the bidirectional links between the actor and sensors are usually asymmetric. Thus sensors within the transmission range of an actor might need multiple hops to reach the actor. Upon the reaching of each new node, we update the data flux capability at every node currently in the network, and connect the new node based on the computed field. We then repeat this process until no new nodes are found, or all actors' processing power are consumed.

4. REFERENCES

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