Bio-Inspired Methods for Efficient MANET

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Abstract: Mobile Ad-Hoc Networks (MANETs), that do not rely on pre-existing infrastructure and that can adapt rapidly to changes in their environment, are coming into increasingly wide use in military applications. At the same time, the large computing power and memory available today even for small, mobile devices, allows us to build extremely large, sophisticated and complex networks. Such networks, however, and the software controlling them are potentially vulnerable to catastrophic failures because of their size and complexity.

Biological approaches have many of these same characteristics and are potentially subject to the same problems. But in successful organisms, these biological networks do in fact function well so that the organism can survive. In this paper, we present a MANET architecture developed based on several features of bio-inspired approaches, widely observed in biological networks but not ordinarily seen in computer networks. These features allow the network to switch to an alternate mode of operation under stress or attack and then return to the original mode of operation after the problem has been resolved. We explore the potential benefits such architecture has, principally in terms of the ability to survive radical changes in its environment using an illustrative example.

Keywords: Biologically-Inspired Networking, Homeostasis, Survivability, Mobile Ad Hoc Networks

1. Introduction

We focus on the problem of identifying effective and resilient architectures for a Mobile Ad-hoc Network (MANET) or a static wireless sensor networks. Our primary concern is the survivability of a network in the presence of significant change in operation environment, loss of nodes, degradation of the channel and significant variation in the network traffic. By survive we mean that with very high probability the network continues to meet the high level objectives that it has been designed for.
Living organisms are confronted with a similar problem and we therefore look to biology for principles that can be used to define such architectures.

Following are various analogies:-

1) Homeostasis is a basic principle used by organisms to rapidly adapt to changes in their environment and survive. Homeostasis recognizes that there is a desired state that, in normal situations, is maintained. Body temperature is an example of this. But in extraordinary situations, the organism will change its state to deal with an immediate problem. Thus, the organism may change state and raise its temperature outside the ordinary range and create a fever in order to destroy an invading virus. Then, after the emergency has passed, the organism returns to its original state and resumes its normal temperature.
It is important to note two things. First, in order to deal with the emergency in a timely fashion, the organism must change state and change the way it functions rather drastically, not just adjust a few parameters here and there in the current mode of operation. Second, it is critical that the response be controlled. Too large a change in temperature, either upward or downward, would result in death. Similarly, a communication network may have a normal operating mode that makes efficient use of its resources. For example, in a mobile network where the nodes operate on battery power, Conserving power is an important objective and in the normal operating mode the network conserves power. But in an emergency; e.g., when nodes fail, it may be important for the network to reorganize itself quickly and in this case the network may raise the power of the nodes' transmitters in order to rapidly coordinate the nodes during reorganization. Then, when the crisis has been dealt with, the network may return to its normal mode of operation.

2) Specialization: Another basic principle observed in biological networks is specialization: different functions are carried out in significantly different ways. Thus, the circulatory system and the nervous system operate in very different ways. So too, communication networks may have different types of nodes that operate in different ways, each well suited to the tasks the nodes perform. Thus, in a sensor network there are sensor nodes that collect data. At the same time, there may be a different type of node whose primary function is communication and this type of node may have capabilities that are significantly different from the sensor nodes. This leads us to consider a two-tiered network where the nodes in the lower tier are sensors and the nodes in the higher tier are communication nodes. The protocol between the two tiers is comparatively simple when compared with those currently in use in MANETs. At any moment in time, each sensor is associated with only one communication node and all communication to and from that sensor is with this communication node. A protocol exists to associate sensors with communication nodes and thus the network can adapt to changes in topology and congestion. But this adaptation occurs at the rate the network is changing, not at the rate communication is taking place. In general, this will conserve bandwidth and, more importantly, will increase stability by giving the network more control over its reaction to change. In general, the communication nodes are only a small percentage of the nodes in the network and, if they transmit at a higher power, are in closer contact with one another. It is thus possible to have them work in a more coordinated fashion than could be expected if all the nodes of the network were involved in control decisions. Also, additional capability; e.g., computing power, memory and more powerful transmitters, can be given to this relatively small number of nodes without as great an increase in cost as would be incurred if all nodes had these capabilities. In a single tiered network, the loss of a sensor can disrupt communications and the network must adjust to its loss. In a two tiered network, we need only worry about the loss of communication nodes, which may be made more reliable without dramatically increasing the cost of the network. In this paper, we investigate a novel MANET architecture that is resilient to drastic changes in the operation environment.

We first review the homeostasis in biology along with another regulatory mechanism called homeorhesis and compare them.

We then identify several key features of homeostasis that are applicable to MANETs for our design. Based on this observation, we present a homeostatic MANET architecture that consists of various factors and components:

Adaptive to the varying environmental circumstances can be considered as:

- Firefly synchronization
- Resilient to failures by internal or external factors
- Human Immune system
- Complex behaviors on basis of limited set of basic rules
- Ant colony optimization
- Able to learn and evolve itself under new conditions
- Hyper mutation in immune system

Current and Future Challenges in Networking and their analogous biological principles.

1) Highly Dynamic Architectures

- Node behaviors and demand
- Highly dynamic link qualities
- Varying load
- Mobile ad hoc networks
- Real-time tracking of mobile target
- Dynamic spectrum access

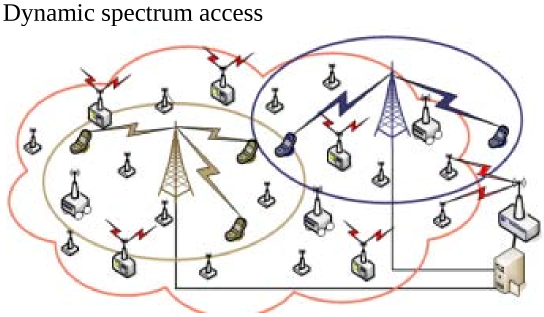


Figure 1: Highly dynamic architectures

Biological Principles

- Artificial Immune System
- Activator-inhibitor systems

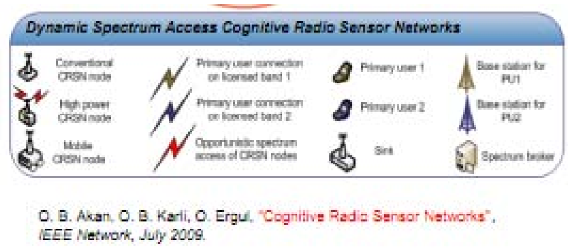


Figure 2: Artificial Immune Systems

(2) Large Networks

- Number of devices
- eBay data warehouse > 10,000 networked machines for processing about 25 Petabytes/day
- Service space
- Traffic load incurred
- Larger search space for optimal route

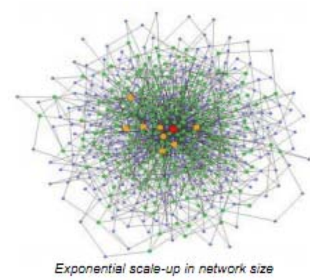


Figure 3: Large Networks

Biological Principles

- Ant Colony Optimization (ACO) techniques
- Epidemic spreading: transmission mechanisms of viruses

Figure 4: Ant Colony

(3) Mismatch between increase in demand and supply

- Set of available services
- Bandwidth capacity
- Network lifetime
- Scarcity of resources vary with network:
- Power, processing in WSN
- Spectrum in CRN
- Capacity and size in nano-networks.

Biological Principles

- Foraging processes in ant colonies
- Cellular signaling networks

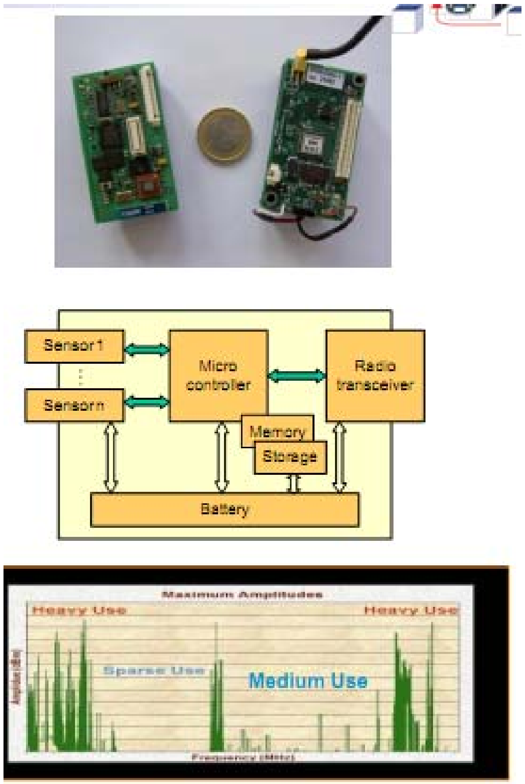


Figure 5: Increasing demand and supply

(4) With increased network scales centralized control unpractical

- Nodes/links/paths may die out
- Some networks are infrastructure-less
- MANET, WSN, Wireless Mesh Networks
- Unattended autonomous operation required
- Self-organization, self-evolution, survivability

Biological Principles

- Epidemic spreading mechanisms
- Insect colonies
- Synchronization of fireflies
- Artificial immune system

(5) Heterogeneity and asymmetry

- Node types and capabilities
- Link capacities
- Network characteristics
- RFID devices to mobile vehicles
- Sensor & actor networks
- Different mobility patterns in VANET

Biological Principles

- Homeostatic system
- Nervous, Endocrine, Immune systems
- Insect colonies composed of heterogeneous individuals

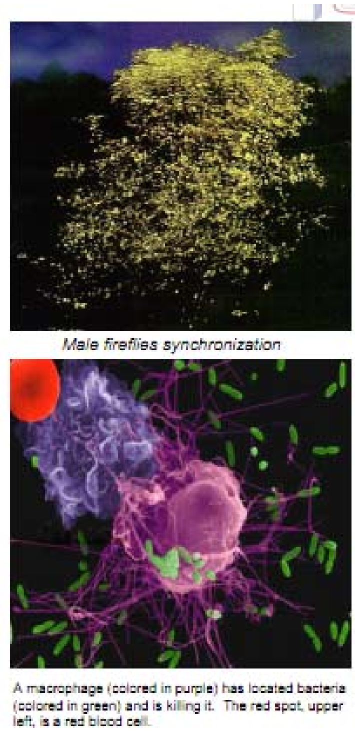


Figure 6: Centralized control unpractical

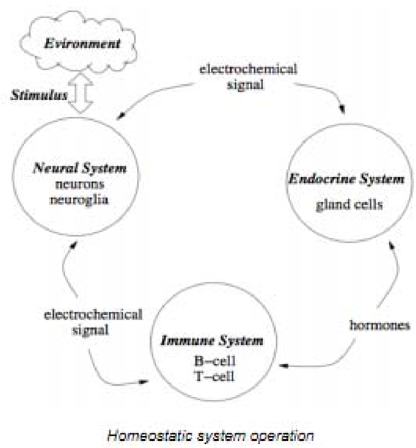


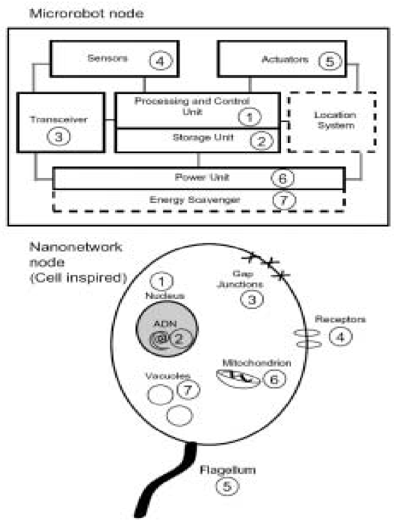
Figure 7: Homeostatic system

(6) NEMS & MEMS Devices

- Antenna size
- Channel limitations
- Different rules of physics
- Nanonetworks RF & acoustic inapplicable:

Biological Principles

- Living cells:
- Sense the environment
- Receive external signals
- Perform at nano-scale
- Cellular signaling networks



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2. Summary and Discussion

This paper presented a homeostatic MANET architecture that can survive critical failures, attack, or drastic change in workload by switching its mode of operation to an alternative mode and recover when the critical situation is over. The proposed architecture is feasible and practical. We reviewed several possible approaches to implement the proposed architecture, and presented an illustrative example in a wireless sensor network application, where sensor nodes can coordinate among themselves to reach far when a nearby communication node has failed, and therefore they cannot communicate to the destination otherwise.

While we believe this paper provided a good starting point for building a resilient MANET, there are a couple of issues that require further research. Firstly, when the event monitoring process is distributed, if the network undergoes multiple different critical situations then the decision making process has to be more sophisticated. For example, depending on the increasing threat level, progressively more robust security mechanism may need to be applied. In this case, it is possible that one part of network reports that the network requires a medium level of protection, while another part of the network requires for a high level of protection. In this case the network security level may be first upgraded to medium then later to high. Alternatively, if an in-network processing is supported then these messages may be merged during propagation and a decision can be made when the more critical event reaches the decision maker.

Another issue is related to supporting the communication between the homeostatic control modules, e.g. between event monitors and a decision maker. Obviously, the communication between these modules should be treated high priority. In certain cases, it may make sense to dedicate an out-of-band communication channel for this purpose. But it may not be ideal in terms of resource efficiency or such an external communication band may not be available. At the same time, we do not want to treat these control communications as same as regular traffic so that control packets may be dropped when the buffer is full. Because the utility of control traffic is highest when the network is under duress, it is important to provide a mechanism to secure their delivery in timely manner while allowing them to share resource.

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