Resilient Bio-Inspired Wireless Sensor Network Based on Genes Regulatory Network

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Abstract—In a Wireless Sensor Network (WSN), nodes have limited energy and low processing capabilities and the network as a whole should act with a strategy that minimizes its energy consumption to maximize its lifetime. This paper presents a research work that aims at introducing a biological inspiration, the Gene Regulatory Network (GRN), to address this problem. We propose a GRN-based controller in each node that is adapted by the Genetic Algorithm to build an auto-organized, robust and adaptive network similar to a biological system. The classical approach to ensure redundancy in the network and make it more robust to failures can be replaced by a simple distributed strategy inspired from robust biological systems. The performed simulation shows that the approach permits to increase the lifetime and the event detection rates of each node.

Index Terms— Wireless Sensor Network (WSN), Gene Regulatory Network, Self-Organization, Biological inspiration, Genetic Algorithm, Lifetime, Efficiency, Robustness.

I. INTRODUCTION

Sensors in Wireless Sensor Networks (WSNs) are constrained entities, with a limited (sometimes non rechargeable) battery and a simple processor. Spreading nodes randomly to cover a geographical space can prove to be a challenging task. Nodes are prone to different types of failures and manually accessing the nodes is not a reliable option. Therefore, the network should apply a fault-resilient, independent and auto-recovering strategy [1].

The sensors' energy and computing constraints have motivated a large part of research in the WSN domain. Optimizing the energy consumption of the sensor is crucial since replacing the battery can be difficult or impossible. Similarly, the modest intelligence provided by the processor does not permit an aggressive computation. Sensing, sampling and transmitting are the main duties of the sensor. These simple tasks do not demand a complicated processing and a central unit is often responsible of the more advanced tasks including network organization, management and maintenance. Previous studies have focused on solutions based on spatial and temporal correlation. In addition, many routing protocols were proposed with the aim of minimizing energy consumption [1] [2].

Attractive characteristics of biological systems such as distribution, evolution, resilience, self-organization and collaborative yet simple behavior are the main reason behind the multidisciplinary trend in computer and optimization problems. Plenty of difficult problems were solved using bio-inspired techniques [3].

In our research, we follow the same trend by introducing the Gene Regulatory Network (GRN) as our biological inspiration. The aim is to address the challenge of autonomous and distributed control in Wireless Sensor Networks (WSN). We base our investigations on the similarity between biological cell networks and WSNs, equally formed of identical simple components. The similarity also covers the limited capabilities and resources and the communication between neighbor cells/nodes. A simple yeast cell placed in different environmental conditions, can illustrate the powerful capacity of Gene Regulatory Network (GRN). Here, “survival” is the keyword, and that's exactly what a GRN inspired controller is supposed to do.

In our analogy, a sensor is a cell in an agglomeration of simple unicellular living organisms, and like a cell, its behavior is driven by its own GRN structure. This GRN controller is common between all the nodes in the network. The aim is to emerge a global optimal behavior at the network level. The optimization process is distributed and dynamic, does not have a central failure point, and does not need to be manually configured at the initialization or during the network lifetime.

The rest of the paper is organized as follows: Section 2 presents an overview of related works inspired from GRNs. Section 3 provides the details of the proposed Wireless Genomic Sensor controller while section 4 gives an overview of the main methods used to implement and adapt the proposed system. Section 5 presents results of the simulation, and shows the advantages of the system. We conclude with section 6 where we summarize the research issues and present some future work.

II. RELATED WORK

Several previous works have proposed artificial systems inspired from biological systems such as Ant Colony, Particle Swarm Optimization, River Formation Dynamics, etc… A complete review of these works can be found in [3] [4]. In the following, the focus is on works inspired from Gene Regulatory Network.

Das et al. (2008) work [5] tackles the issue of optimal coverage in wireless sensor networks. They proposed a GRN model based on differential equations and show that its
A sensor turned off is it works normally, sampling and communicating with its functions at discrete time steps [15] [16].

A similar approach to our work is presented by Markham and Trigoni (2010) [6] [7]. Using a discrete model of GRN (called dGRN), the authors propose an embedded controller that offers every sensor the ability to regulate its sampling rate (and therefore energy saving) based on its data and its neighbors’ behavior and shared information. They particularly emphasize the use of the genetic algorithm which permits them to automate the dGRN controller design. The controller structure is adapted to an application where sensors have to track a mobile target, without the interference of an intelligent human designer.

Similarly, Taylor’s "Biosys" [8] shows how a GRN inspired controller can be used to configure submarines robots. These robots are distributed moving machines aiming to achieve a distributed task. As for artificial existence, the work of Knabe et al. use GRN controllers to build biological clocks that respond to periodic environmental stimuli [9]. Quick et al. (2003) propose a GRN based real time controllers, coupled to the environment and embedded in artificial organisms [10].

Preliminary work of Ghosh et al. presented in [11], proposes the use of the attractor theory in GRN to achieve a fault-tolerant WSN routing.

III. WIRELESS GENOMIC SENSOR

Cell information is encoded in the DNA, and its behavior is encoded by the genes interaction at the cell or at the multicellular level. Gene activation and their rate of transcription depend on many factors, including the regulatory proteins effect at its input and sometimes the protein level of expression at its output [12].

At any given time, Gene regulatory network of a living organism should optimize the cell behavior to make it survive its environment conditions. Similarly, our aim is to offer every sensor the ability to choose the most adapted behavior to its environment. This is biologically known as phenotypic plasticity [13].

We use the Random Boolean Network (RBN) as a representation of the Gene Regulatory Network. The model uses an oriented graph where genes and their products are represented by nodes and edges represent the influence of the regulation between these nodes [14]. States are binary and the temporal evolution of the system is supposed to happen synchronously in a periodical manner using regulation functions at discrete time steps [15] [16].

A sensor has two states: ON and OFF. If the sensor is ON, it works normally, sampling and communicating with its environment in normal time periods. A node turned off is judged non vital at the current instant, and doesn't make part of the functional network. The sensor will enter the “sleep” mode which will help reserve its energy. Its energy consumption will be considered negligible. These states are not static, a sensor can change its state based on its environment and the role it can play in this environment. If a sensor can't add any significant contribution to its environment, it's better to keep it in the "sleep" mode. A "sleeping" sensor has periodical distant wake ups, where its own WGS controller can update its information and decide whether to switch ON or not.

Two types of influence can be found in a regulatory network: (1) internal, measuring proteins concentrations inside the cell. Proteins produced as an expression of certain genes will positively or negatively influence the expression of other genes and (2) external, as a result of environment conditions and of the concentration of migrant proteins, coming from other cells.

We consider simplified WGS genome representation as a sequence of Ng genes. Each gene has one activation site (formed of two proteins) and one output protein (its concentration reflects the gene expression level). Each gene is therefore representing a simple law, having proteins concentrations as inputs and outputs. Table 1 resumes the proteins used in the controller.

### IV. IMPLEMENTATION OF THE WGS

#### A. Scenario

In order for the problem to be concrete, we introduce here a scenario of usage. The same scenario will be used to test the proposed system. A square area of dimensions (L x L) is covered with N wireless sensors in a random and uniform way. Every node is characterized by two radiuses: (1) coverage radius R (indicating the circle where the sensor can detect events) and (2) Transmission radius RT. We will use the following numerical values in the network simulation: L=16 units, N=50, R=3 units and RT=6 units (fig. 1).

Events occur randomly over the square space. At every time step, the probability of an event occurring is 0.1, its duration follows a normal law (mean= 7s and standard deviation = 4s.).

\[ P_{\text{Failure}} \] is the probability that a sensor fails. In our simulation, N=30 and \( P_{\text{Failure}}=0.1 \) which means that three sensors will stop working, each at a random time chosen between 0 and Tmax (maximum network lifetime).

In a functional network, a large part of the initial square zone should contain sensors able to detect the events occurring in the remaining coverage space and transmit gathered
information to a gateway node constantly fed by a power source.

Fig. 1. Geometric representation of the random coverage of 30 sensors of radius 3 u. over a 16 u. x 16 u. square space.

B. Energetic Considerations

Sensor energy consumption has two causes: (1) the sampling and processing in measurement mode and (2) the radio communication (transmitting/receiving). In order to have real values, we base our calculation on wireless temperature sensor, Monnit WIT™.

C. Routing

We choose the Ad-Hoc DSR (Dynamic Source Routing) protocol to simulate routing, the cost being the energy consumption over the chosen route. Sensors energy levels are updated according to the selected route to the gateway.

D. Genetic Algorithm

Based on genetic roots and natural selection concepts, the genetic algorithm is a part of evolutionary algorithms family. These algorithms are mainly used to find and optimize a solution that is difficult to get by classic means. Put in simple words, the genetic algorithm starts with an initial population of solutions, and optimizes it through generations, a term used to characterize sequential iterations of the algorithm, where populations are replaced with new “more adapted” generation of children in the next iteration. Children are issued through “crossover” of the most “fitted” parents [17]. In the current case, a simulation is run over the whole network. The tested controller is implemented on each node and the nodes are left to interact in the conditions of the test and the fitness function is deduced from the network performance in terms of coverage and lifetime. Table II shows the genetic algorithm parameters. The WGS controller has Ng genes, each having the following structure: [Influence type (amplifier, inhibitor) of protein 1, Input protein 1, Influence type of protein 2, Input protein 2, Output protein, Output function type (on or off by default)].

V. RESULTS

In this section, we provide results of the simulation implemented in Matlab. We compare our solution to a redundancy based one where the number of sensors initially put in the field is greater than the required number in order to get a satisfactory initial coverage rate. This approach uses redundancy to resolve the problem of sensors failures.

In the conditions of the test, we get the following results:

A. First life cycle:

A sensor having 270 joules of initial energy is estimated to function during 3600 s. Figure 3 (blue line) shows an average initial coverage rate of ~ 93%, associated with an average of 25
sensors turned on (50% of the nodes) during the first life cycle of the network that has a duration of 3600 s.

The coverage rate drops around t=3600s (fig.3), this is associated with a collective drain of energy among sensors that were turned on initially. This can be seen in fig.2 where the number of sensors turned on falls at the same time. The network becomes quasi-inactive during the time needed to recover from this collective failure.

B. Second life cycle:

After the recovery, the network becomes active for the second time with 14 nodes turned on and a coverage rate of 73%. The second drop appears near $t = 7600$ s and the same recovery behavior described above reappears. Since the sensors left are not enough to have an acceptable coverage rate, we can no longer consider the network functional for a third life cycle.

The recovery from a particular node failure can be seen around $t=2000$ s where two nodes where turned on to recover from the failure of one node. Compared to a normal network (red line in fig.3), the enhancement of the proposed network can be seen using one of two perspectives: coverage rate and life time. While keeping the network functional (average coverage rate of 83% compared to 99%), the GRN controller increases lifetime by 100%.

VI. CONCLUSION AND FUTURE WORK

In this paper, we presented a work inspired from the robustness of gene regulatory network, where we offer the sensor which is a limited and constrained entity, a simple intelligence that is able to derive the sensors network toward an autonomous and distributed behavior that will also increase its lifetime. In brief words, the following characteristics were added to the network: autonomy, self-organization, distributed control, robustness, efficiency and a longer lifetime.

Our WGS: Wireless Genomic Sensor is a GRN based controller. Its structure is proposed automatically by the genetic algorithm, and optimized through the evolution process using a fitness function that reflects the optimal objectives we want to implement in the network: coverage and lifetime.

This is verified by the network ability to recover automatically after individual or collective failures. In addition, the improved network lifetime is twice the lifetime of a network implementing a normal redundancy strategy.

Mobile sensor networks are a possible future direction for this application since mobility is a challenge directly related to the environment. Some recent studies suggest that GRN can be equally beneficial in the routing domain in WSNs. Additionally, we plan to substitute the Random Boolean Network model used in this paper with a scale free network model since new knowledge in the network formation and evolution is pushing toward the latter as a more accurate representation of biological networks in general. Finally, it may be beneficial to compare the current approach to a similar proposition that also suggests the use of autonomous controllers to achieve a higher coverage rate or a longer lifetime.

REFERENCES