# Bio-inspired Layered Clustering Scheme for Self-adaptive Control in Wireless Sensor Networks

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*Abstract*—**In the future, wireless sensor networks (WSNs) are expected to play an important part in our everyday life. Sensor nodes are becoming more and more miniaturized, equipped with radio transceivers, and deployed in large quantities. However, due to their limitations in computational and communication capabilities, clustering techniques are usually applied for energy conservation, where designated nodes known as cluster heads collect data from their nearby cluster members and route the data in a multi-hop manner towards a the required final destination, known as a sink. However, as the number and heterogeneity of nodes increases, a distributed control becomes a necessary requirement. In this paper, we discuss the dynamics in the interactions among a multi-layered self-adaptive clustering protocol for WSNs, separated in clustering and routing layers. Each layer operates independently and utilizes a biologically-inspired adaptation scheme allowing the layers to interact and adapt to environmental changes effectively and in a self-organized manner.**

## I. Introduction

We are currently striving towards a new generation information network society, enriched by an ambient infrastructure, which permits ubiquitous network connectivity and service provisioning based on users' preferences [1]. To satisfy the wide range of service requirements, new paradigms and system architectures are needed that can accommodate often conflicting objectives among each service in a self-organizing and self-adaptive manner.

Traditional network architectures are devised in a hierarchical manner, with local interactions and physical communications taking place on lower layers, while higher layers are involved in routing, or handling end-to-end and application related connections. The interactions among each layer takes place through the service protocol interfaces of the OSI layers, such as between MAC and IP layers. In the future, we expect more isolated types of cross-layered architecture design [2], where networks behave in a self-organized manner. This involves the hierarchical distinction between different services operating on different logical layers on the same devices. These layers operate independently for a specific task and interact and self-organize among each other to offer the desired services to the end users. However, sensor nodes are known to be rather frail in terms of limited radio transmission power, computational capabilities, as well as limited lifetime since they are powered by limited power sources such as batteries. Especially in such a scenario, it is essential that nodes cooperate and self-organize to maximize the network operation lifetime, and are additionally able to adapt to changing environmental conditions, and adapt to good solutions. This paper focuses on the application of data gathering and routing in a wireless sensor network (WSN).

In [3], Dressler discusses approaches based on biological mechanisms for self-organized operation of WSNs [4]. Since many robust features can be found in biological systems [5], in the recent past there is a growing number of proposals based on dynamic mechanisms inspired by biological methods for designing network architectures and their interactions [6]–[8].

What is attractive about a bio-inspired approach is that they are highly robust and can recover quickly without a centralized mechanism. Biological systems are versatile and can adapt to environmental changes. Similarly if we have networks which are prone to constant environmental changes, adaptability becomes an important aspect of a system. Furthermore this should be done in a self-organized way, so as to minimize single-point of failure and also support efficient functionality in large-scale ad hoc networks.

In this paper we study the dynamics of a two-layered wireless sensor network adopting the biologically-inspired attractor selection concept [9] found in the dynamics of gene expression of cells. In particular, we consider a WSN scenario that consists of a layered clustering scheme where on the lower layer, the sensor nodes dynamically select their cluster heads using attractor selection, allowing the system to quickly recover from environmental changes by adaptively selecting a new cluster head. Furthermore, on a higher logical layer data must be forwarded from each cluster to the sink. In this case, routing is also performed by attractor selection and new paths are selected if old ones become unsuitable due to energy depletion or bad correlation of data. We will propose a scheme which uses two independent attractor selection schemes for each layer, which have different range of operation and different objective functions.

The layered architecture described allows two independent objectives of the targeted network, namely clustering and routing to function independently, yet affect each other by the use of an activity defining the "goodness" of the current solution, which links the two layers. The network is then able to shift, much like an equilibrium system, to an overall better solution that tries to meet the two independent objectives. This system additionally is able to shift and adapt to variable changes in the two layers, in a self-organized manner. The control is purely distributed and the system is able to self-adapt to physical changes in its environment.

This paper is organized as follows. In Section II we discuss some essential issues on clustering and data gathering in wireless sensor networks. We present an overview of our considered system architecture in Section III-A and propose our layered control mechanism in Section III. In Section IV we show some preliminary numerical results obtained from simulation to show the robustness and adaptability features of our proposal. Finally, Section V summarizes this paper and gives a brief outlook on future work.

## II. Background and Related Work

In this section, we will briefly discuss some background issues and related work on clustering, multi-hop routing in sensor networks.

### *A. General Issues in WSN Operation*

Wireless sensor networks are primarily deployed for environmental monitoring. The nodes are distributed in a physical environment, and arranged in such a way as to sense and report data to a destination, known as a *sink*, usually in a multi-hop manner. The main issue concerned with WSNs is that they are energy-constrained. Generally they are equipped with finite energy sources, such as a battery. It is however possible that these batteries are equipped with solar panels and can be recharged by solar energy. In this paper we consider such a scenario. Since this is the primary problem of WSNs, many energy-efficient techniques have been proposed, aimed at reducing energy consumption as much as possible. Some of these techniques involve hierarchical routing, and clustering and aggregation methods to reduce data size to be transmitted, and hence the energy consumed in communication.

### *B. Clustering in WSN*

In the area of WSN, clustering is a well established method for grouping sensor nodes together in order to avoid excessive energy consumption due to long transmission distances. In clustering, one specific node, referred to as *cluster head* (CH), takes a special role for managing and controlling the other nodes within its range of operation (cluster). This CH collects the sensed data from the cluster members (CM), process it to some extent, e.g., aggregates and fuses this data, and then sends it to the next cluster toward the sink. Furthermore, it is possible for a node to belong to more than one cluster and hence assist in inter-cluster communication and routing of data to the sink. Such nodes are termed *gateway* (GW) nodes.

A well known clustering scheme is the Low-Energy Adaptive Clustering Hierarchy (LEACH) [10]. This is a self-organizing protocol based on randomization in CH election in order to prevent node energy exhaustion, and the metrics considered in this protocol are based on the energy of nodes and the distance of nodes from their CH for the purpose of joining clusters.

Another established multi-hop clustering scheme called the Hybrid-Energy-Efficient Distributed (HEED) clustering approach is proposed in [11]. The aim of HEED is to identify a set of CHs which can cover a whole area. Eventually, each node belongs to only one cluster, which similar to LEACH would not result in the formation of GWs. However, unlike LEACH, HEED is a multi-hop protocol as CHs can route to the sink via other CHs in the network. HEED is also a self-organizing, and distributed protocol. All nodes follow simple rules based on their local environment to make decisions.

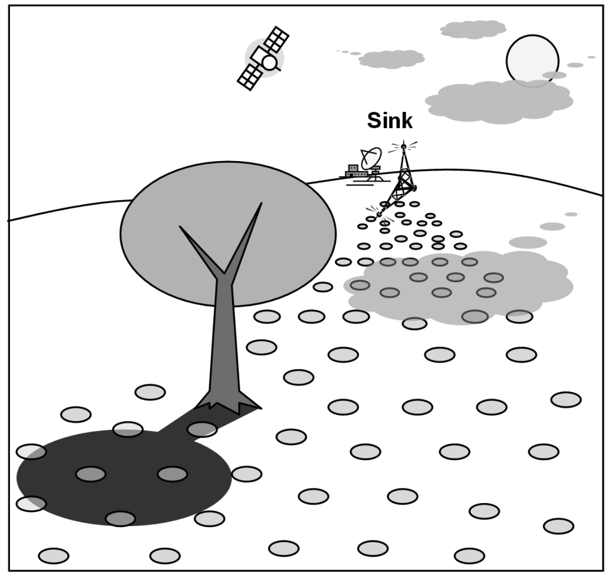


Fig. 1. A field of solar-powered sensor nodes.

There are other recent work aiming at energy-efficient solutions to clustering in WSNs include [12]–[18]. In particular, [19] proposes a clustering scheme which is based on data correlation. In this approach, nodes are grouped into clusters based on the similarity of data of the nodes. However, the clustering scheme does not take into account energy as a metric in clustering, which is a significant metric in a WSN. In [20], a routing protocol is used which switches transmission power based on the volume of data to be sent. This approach considers flat routing in contrast to hierarchical routing offered by clustering.

## III. Proposed Layered Control Method

In this section we present our proposed layered control method as sketched in Fig. 2. The method operates by each node following the dynamics of a nonlinear differential equation independently on both layers. The dynamic model is based on the attractor selection mechanism which will be described in the following subsection.

### *A. Overview of System Architecture*

We consider the following scenario as shown in Fig. 1. Sensor nodes are widely deployed in a monitoring area to gather some information on the environment, e.g., temperature, rainfall, or seismic activity. This data should then be transferred to a remotely located sink in a multi-hop manner. We assume that there is only a limited discrete set of integer values to send. Each node has a cache to store data it had previously

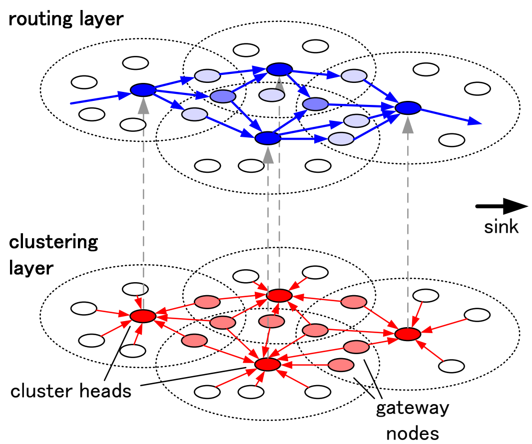


Fig. 2. Illustration of the proposed two-layered WSN control scheme.

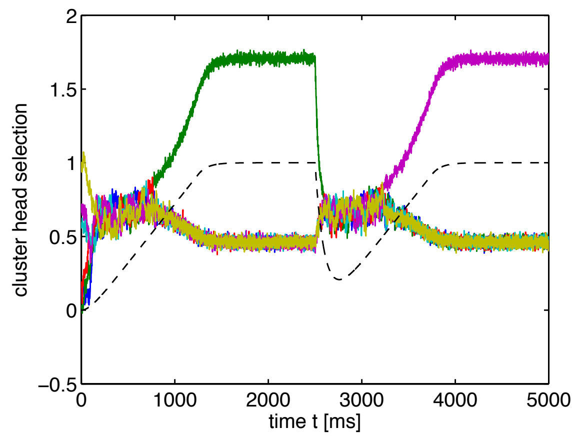


Fig. 3. Attractor selection with varying activity dynamics.

collected or forwarded. Since each transmission of data results in energy consumption, only differences to past values are incrementally sent. In the scenario, sensors are assumed to be equipped with solar powered cells. We also note that the environment is subject to temporal obstruction by shadows of objects in and nearby the field such as trees, buildings etc, and clouds which cover the sun. This effect temporarily changes the rate of charging of the cell. This, however does not mean that the current node needs to be compromised in terms of goodness. Hence such temporal factors will need to be taken into account when considering the protocol.

### *B. Biologically Inspired Control Mechanism*

The concept is based on adaptive-response by attractor selection (ARAS) in [21]. In this model the notion of attractor selection is defined by a function $f$, an activity $0 \leq \alpha \leq 1$, and noise term $\eta$. The principal equation of the dynamics of state $x$ is given by the following stochastic differential equation:

$$\frac{dx}{dt} = f(x)\,\alpha + \eta \tag{1}$$

The function defines the attractors. Attractors are the potential stable solutions of the system. The activity defines how suitable the current (found) solution is and increases as the solution becomes better, and gets smaller when the solution is not suitable. Hence as the activity becomes smaller, the noise term dominates and allows random selection to take place until a better solution is found (in which case activity will grow again) and the solution converges to the newly found attractor. Fig. 3 demonstrates the effect of attractor selection in relation to activity dynamics. In this figure, the activity is initially low, and so a random walk phase is initiated to find a good solution. There is no real preference at this stage. As time passes, this random search obtains better results and the activity becomes higher. At around the time of 1000 ms, the selection becomes deterministic and this pushes one value to high and the rest low. A good solution is hence chosen.

We believe that the notion of attractor selection is an effective way to establish an adaptive system, where any perturbations or events influence the system's current equilibrium state and eventually direct it to a stable attractor, i.e. a new equilibrium state. The main idea is to induce inherent adaptability and resilience in a network rather than pure optimization which traditional methods seek to achieve. While the original attractor selection model maximizes a single activity, a WSN needs to achieve multiple objectives at the same time, e.g. selecting highest energy nodes as *cluster heads* (CHs) and at the same time route aggregated data to high energy *gateways* (GWs) towards the sink over the clustered WSN. Furthermore, when such a system is subjected to unexpected changes, e.g. node failure/destruction, the system is able to reliably recover itself in a self-organized manner. We now introduce the layered attractor model which allows independent objectives to balance each other in order to meet an emergent purpose such as those that occur in biological systems [22].

### *C. Dynamics of the Clustering Layer*

The clustering formation mechanism follows that of conventional methods, as in [10], [11]. At regular reclustering intervals $T_c$, each node $n_i$ sets a backoff timer $t_i$, which is based on its state in a state vector, described next. Once this timer expires, the node $n_i$ will broadcast a *cluster head claim* (CHC) message and sets its status as CH. However, if prior to the expiration of its own backoff timer, node $n_i$ receives a CHC from another node, it instantly cancels its own timer and joins the other cluster as cluster member. If a node is member of several clusters, it acts as a GW node between these clusters. Gateway nodes play an important role in the routing layer that will be described in Section III-D. Since we assume that the network has a sufficiently high relative node density in comparison to transmission range, we expect that the majority of nodes will be GW nodes and only few nodes will have a unique cluster membership.

The method we propose for clustering is as follows. At each reclustering interval $T_c$, each node $n_i$ exchanges its residual energy $e_{i,0}$ with its neighboring nodes, which are all normalized over the maximum battery energy $e_{max}$. Through this exchange phase, node $n_i$ is notified of all its active neighboring $M_i$ nodes, which it stores in a state vector $\vec{x}_i$, which includes a nodes own's state and the state of its own neighbors. Each node then calculates the activity using the variance of energy within its locality (1-hop neighbors), and also the feedback activity from the routing layer of the current node to the sink. This is given by

$$\alpha_i = R\,A_i + (1-R)\sum_{j=0}^{M_i}(e_{i,j} - e_{ave})^2, \qquad (2)$$

where $\alpha_i$ is the clustering activity of node $n_i$, $e_{ave}$ represents the average energy of $n_i$'s neighbors, $n$ is the number of neighbors within the cluster, and $A_i$ is the routing activity of the network, which will be discussed next. $R$ is the coefficient of the significance or effect of the routing layer on the clustering layer. In order to perform a selection, each node $n_i$ continuously applies the dynamic system as in [21]. Node $n_i$ then sets off a backoff timer, where the backoff timer for CH election of node $n_i$ is given by

$$t_i = t_{max}\sqrt{1 - x_{i,0}}, \qquad (3)$$

where $t_{max}$ is the maximum waiting time for CH election. As described earlier, a node whose timer expires, broadcasts a CHC to its neighbors and elects itself as a CH. Nodes which receive the CHC message will $select$ themselves as CMs.

### *D. Dynamics of the Routing Layer*

The routing layer determines the best path to the sink. Here attractor selection takes place, where the candidate nodes for selection are GWs from the CH's point of view and CHs from the GWs point of view, which lead towards the sink. The routing depends heavily on routing to nodes closer to the sink. For this purpose the sink broadcasts a *hopcount-to-sink* (HoTS). Nodes are first initialized with their relative distance in terms of number of hops from the sink. This is to assist in the routing phase, so that routing of data is towards the sink. A longer path consumes more network energy, induces delay, and causes more data accumulation as it traverses more CHs than necessary. The HoTS initialization phase proceeds as follows: The sink sends a HoTS message to its one-hop neighbors, containing a HoTS value of 0. The neighbors of the sink will immediately set their local HoTS to 1 and broadcast a HoTS message of value of 1 to their own neighbors. HoTS messages eventually propagate to the whole network. Each node will set its local HoTS as the minimum among all the HoTS messages received plus one.

Let's consider a discrete set of values that sensors can sense in a network. Nodes sense data, store and forward only when their values change from previously reported values. Likewise CHs also forward only changes in data of their CMs from previous reports. This also happens with GWs, however GWs also overhear from their lower clusters and only forward values of their higher clusters to their lower cluster, if they have not previously heard the same value from their lower cluster.

In such a scenario, switching to a new GW will cause the new GW to forward values which have already been sent previously, as its cache is empty. This consequently uses up more node energy in transmitting the unnecessary and repeated data. Hence we wish to reduce this "switching" effect as much as possible by adapting the previous node for routing, unless the node starts to have a low energy value. Furthermore, switching introduces a delay in data transmission: since CH1 has to wait until the sleeping GW which needs to be newly appointed wakes up and hears a *GW appointed* (GWA) message. Also, the previously appointed GW will go to sleep upon hearing the new appointed message.

The dynamics of the routing layer selection work the same way as the clustering layer as laid out in [21]. Each CH makes a selection from a vector of lowest HoTS GWs $\vec{y}_i$ and receives a feedback activity based on the selection of GW. The GWs also make a selection if they have several CHs towards the sink in the same way as the CH does the selection. Adaptation takes place when a selection of a GW or CH is a good selection for consecutive rounds of selection. In the scenario of Fig. 1, a good selection may correspond to a node which has stored large amount of previous data, while having high charging rate due to direct access to sunlight and high residual energy. Once a good path is chosen, temporal obstruction, such as a cloud patch, will not cause a change in selection. However, if the obstruction is prolonged, or the environment changes more definitely, the system is forced to make a new selection.

The routing layer activity is based on routing data to the next best node towards the sink and is as follows:

$$A_i = \frac{e_j\,dq_j\,D_j}{e_{max}\,dq_{max}\,D_{max}}, \qquad (4)$$

where $A_i$ is the activity of selecting the current GW node $j$, reflecting its suitability for routing, the rate of charging of a sensor node $dq/dt$, the total size of the cached data $D_j$ for caching *new* data, and $D_{max}$ is the maximum cache size.

### *E. Interaction Between Layers*

Although the two layers are functioning independently, they ultimately have an interdependent outcome which results from activity feedback of one layer into the other layer. This is described in Fig. 4. In the figure, each process of information gathering as done during the message exchange phase, activity calculation, and selection occur on both levels of routing and clustering, independently. However, in this scenario the feedback from the routing layer is fed back into the clustering layer, and hence this affects the activity and selection in the clustering layer. The advantage of this is a mere equilibrium that can be reached where two independent objectives are met by interdependent interaction. The consequence is that both the clustering and routing, carrying independent goals affect each other continuously.

## IV. SIMULATIONS

Simulations are performed in MATLAB to demonstrate the interdependent effect of the two clustering and routing layers,

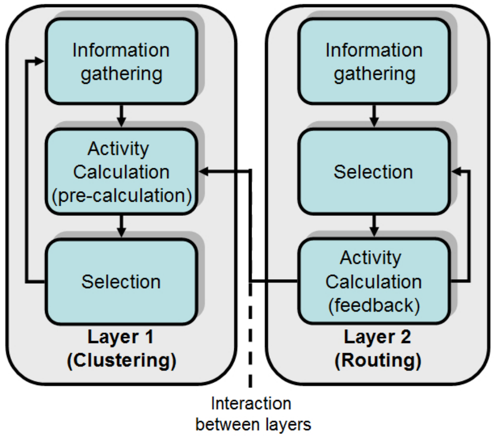


Fig. 4. Interaction between the routing and clustering layers using activity.

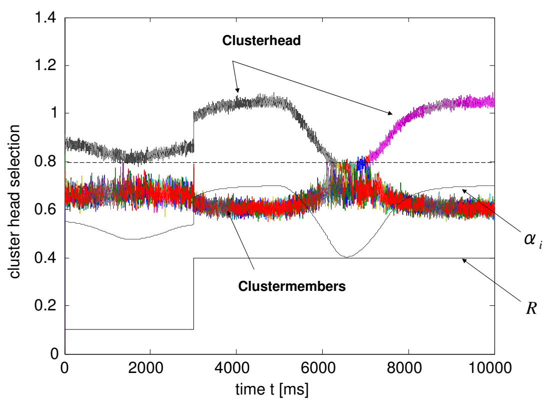


Fig. 5. Attractor selection with varying activity dynamics.

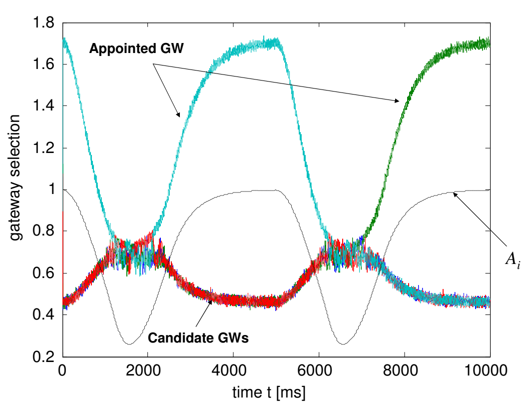


Fig. 6. Attractor selection with varying activity dynamics.

in which attractor selection takes place. This is shown in Fig. 5 and Fig. 6. In Fig. 5, clusters are formed and CH is elected. The activity in the clustering layer also depends on the routing layer, as defined in (2). In the figure, we manually change the value of R from low to high to investigate the degree and effect of routing layer on the clustering layer. In the figure, when R is low, a change in the routing layer does not make a change in the clustering layer, as the clustering activity is not affected by the larger drop of routing activity shown in Fig. 6 between 1000 ms and 2000 ms. At 3500 ms, the effect of R is increased. The activity is again dropped between 5000 ms to 8000 ms. The effect of this has become more significant on the clustering layer, hence this triggers a new reclustering and a new clusterhead is selected at around 7000 ms. This ofcourse defines a new set of GWs and a route will be selected as a result, hence an interdependent relationship takes place.

In the clustering layer, a good solution is preventing one node to be exhausted by always being a CH. Hence the system generally tries to keep the energy variance low within neighbors. In the routing layer, this corresponds to a good GW selection by the CH, and a good CH selection by the GW. Since the activity in the routing layer is based on several metrics. A good solution may be a node which is directly under the sunlight, has cached previous data, and has high residual energy. At around 2500 ms mark, the activity drops. The current solution is no longer satisfactory, and hence a new solution should be discovered. Once again we enter random walk to find a good solution. At around 3500 ms a new good solution is discovered and the system once again converges. This dynamic process continues throughout the life of the sensor network.

## V. Conclusion

In this paper we presented a bio-inspired clustering scheme for WSNs, consisting of two independent layers of clustering and routing, having independent objectives, yet an interdependent outcome. The paper presents the architecture and basic mechanism of the layered clustering and routing protocol. It is believed this system provides a robust, self-organized clustering and routing scheme which adapt effectively to environmental changes. Future work should aim at careful implementation of the system and comparison with other existing models.

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