Biologically Inspired, Self Organizing Communication Networks

Yousef E. M. Hamouda and Chris Phillips
Department of Electronic Engineering,
Queen Mary, University of London, UK.
yousef.hamouda@elec.qmul.ac.uk & chris.phillips@elec.qmul.ac.uk

***Abstract*-The rapid exploitation of communication networks in progressively more aspects and their associated complexity have critically driven the desire for autonomic self-organized capabilities to provide scalable adaptive, resilient and emergent behaviour to maintain their operational capability in dynamic situations. The principles of achieving autonomic capabilities are inspired from biological and ecological systems. In this paper, biological behaviour such as migration, replication and death as well as the differentiation and specialization of zygote formation are applied to the communication networks to produce an autonomic self-organizing network architecture.**

I. Introduction

Recently, network systems and information technologies have become integrated into many day-to-day applications. For example, ubiquitous computing is one of the research areas that allow the placement and operation of computerized devices to provide network services everywhere and at any time [1] without explicit user awareness. Generally, the complexity and number of network components, and their overall functional capabilities are rapidly increasing. The increasing complexity of this distributed architecture makes the system more difficult to monitor and manage. However, the overall demands on the communication system becomes difficult to meet using only a small number of nodes, especially in case when these nodes are sensors that have limited resources such as processing power, battery life, buffers, storage and bandwidth [2]. Therefore, researchers have started to explore alternative methods and solutions for operating complex distributed systems that provide scalable and flexible support.

In fact, autonomic communications, autonomic computing, emergent behaviour, swarm intelligence and self-organized networks (SON) are example research areas and technologies that endeavour to hide the complexity whilst providing scalability, reliability, survivability and fault tolerance for modern communication networks [2], [3], [4], [5]. These technologies have been used for designing and implementing protocols and services that appear within different OSI layers starting from data link layer. Some examples of network architectures that fall under the umbrella of these technologies are peer-to-peer overlays, ad hoc networks, sensor networks, wireless mesh networks, ubiquitous computing networks and content distribution services.

Strictly speaking, autonomic communication and autonomic computing have the same goals mentioned above but autonomic communication focuses on network services and resources whilst autonomic computing is more oriented toward software applications and computing recourses [5]. They provide autonomic capabilities and behaviours to the network devices and hosts to cooperatively provide self-governance or self-management of the network. Many possible definitions have been proposed for self-management or self-governance. In [3], the authors survey these definitions and found that these definitions are derived from the definition proposed by Horn in 2001. According to Paul Horn's definition, a self-management system can be described according to eight characteristics, which are self-configuration, self-healing, self-optimization, self-protection, self-awareness, environment-awareness, openness and transparency. Therefore, the self-* property can be used to indicate these elements. Emergent behaviour is the complex result derived from the coordinated actions of a group of individuals, each performing simple tasks or rules, that each individual cannot achieve alone [2]. Similarly, swarm intelligence can be defined as the collective behaviour of simple members arises from their local interactions with the environment [6].

The main principles behind these methodologies are inspired from the ecological and biological phenomena. Swarms of small insects in which each individual performs very simple tasks, are nevertheless capable of producing complex behaviours or actions overall as an emergent behaviour. Colonies of ants or bees, flocks of birds, packs of wolves and school of fish are manifestations of complex natural and social structures that can lead to achieving emergent behaviour autonomously [6]. This paper presents a novel approach to cope with system complexity and to achieve the benefits autonomous operation.

This paper is organized into five sections including this introduction. Section II introduces the main objectives and principles of proposed approach. Section III reviews the related work in this area. Section IV covers the proposed system overview and the used techniques in details. Then, Finally, Section V summarizes the paper and suggests future work.

II. Main Objectives

As mentioned in the introduction, the main challenges to address are: system complexity, scalability, adaptively and survivability. Our approach is to devise a self-organized and autonomous framework that can support emergent behaviour in order to provide services and reach the goals. Within this paper we provide a functional description of the architecture that can be applied to distributed wireless nodes (or sensors) deployed in a dynamically unknown environment. We assume the main goal of these deployed nodes is to work collectively to search for and then track an externally environmental target or possibly multiple targets. After sensing the target, the nodes cooperate to provide predefined services or tasks associated with it.

The principle used in this proposal is inspired from the behaviour of the biological zygote or human embryonic stem cell. When the zygote is formed, it comprises a collection of similar stem cells. All the cells of the zygote are equal in terms of behaviours / capabilities. Over time, the zygote cells start to specialize with different functionalities. For example, some of the cells will form the brain; other cells will form the legs and so on, the differentiation being coordinated, at least in part, by the magnitude of exposure to certain chemicals. This logical behaviour is called differentiation or specialization [13]. The same principle will be applied in the proposed communication networks; the network nodes will start equally and then will exhibit some kind of differentiation / specialisation in order to perform certain complex tasks according to the environmental conditions. After a brief summary of relevant related work, given in the next section, we describe the proposed system in more detail.

III. Related Work

A number of researchers have already considered applying biological and ecological principles within communication networks. Good examples are [7], [8] and [9], where a biological-inspired architecture has been introduced to allow network services (agents) to adopt with dynamic network conditions. In this research, the agents are designed as biological entities, which can perform some biological behaviour such as migration, replication, reproduction and death. The agents are executed in a middleware platform that has to be installed on each node in the network. In [10], the concept has been extended to include a platform with biological features as well. Therefore, the platform can migrate, replicate, reproduce and die accordingly to the network conditions. In addition, platforms and agents can cooperate via using symbiotic behaviour in which the network performance can be improved in terms of adaptively and scalability. In [11], a similar concept is applied but with dividing the platform into two parts which are Ecogent Runtime Services (ERS) and Bio platforms. The network services are models by Ecogents that refer to ecological agents. The ERS platform provides the basic functions for the Ecogent such as registration, migration, evolution, and life cycle. On the other hand, the Bio platform can perform the biological behaviour to evolve using genetic algorithms. In [12], swarm intelligence based coordination algorithm for distributed multi-agent agents is used to search for multiple targets and implement some predefined tasks within a minimum time.

Although, other work has been inspired by biological and ecological principles, none of this other research assumes the differentiation / specialisation of node functionalities which is inspired from the biological zygote. Furthermore and to our knowledge, this is the first research to treat the target (described in the next section) as a virtual chemical emitter in which influences to varying degrees the differentiation / specialisation functionalities within the network nodes. Therefore, by applying these principles, communication networks can perform very complex tasks in terms of management and services provisioning. Moreover, unlike the other research in which they address particular network applications, our approach can be generalised to any communication networks technology and protocols including ubiquitous computing, sensor networks, peer-to-peer networks, surveillance applications, battlefield applications, ad hoc routing and media access protocols and so on. The next section describes the system operation in more detail.

IV. Approach Overview

In our approach we assume a potential target can be regarded as a virtual chemical emitter[1]. However, desirable targets in the network can be assigned different diffusion gradient patterns, which are determined by the class of the target, using some form of recognition, not considered further in this paper. These gradient tables held at the sensor nodes determine the influence of the target based on its range from the sensor node. The target gradient patterns can be discrete or continuous functions of the magnitude of its influence versus its distance from the node. Figure 1 shows the system architecture of the proposed solution.

[1] In practice, the target is required to emit no signal. The sensors classify the targets and determine their range to it. Based on the target's class the sensor then uses a chemical diffusion gradient table that determines the magnitude of the target's influence on the sensor node, if any.

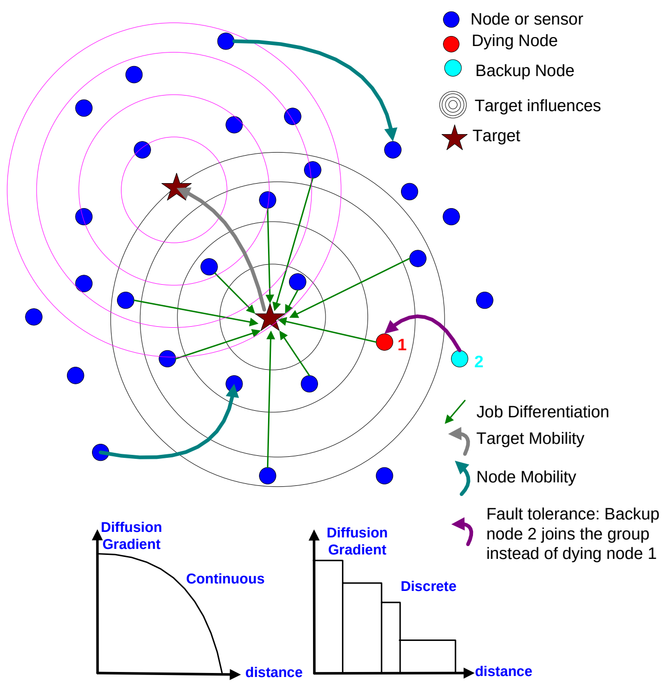

Fig. 1. Proposed System Architecture

Initially, all the wireless nodes assume to be equally in terms of functionality and effectiveness. When a target comes into range of a node or group of nodes, the nodes around the desired target will be influenced to different degrees based on their range from the target.

As shown in the Figure 1, the target is treated as if it emits a virtual chemical that influences nodes in the affected area to a degree that is determined by their proximity to the target. Nodes within this region of influence organise themselves into a group. This group cooperatively provides the required services and the network management functions according to the strength of the sensed chemical. Therefore, this scenario is similar to the differentiation / specialisation principle found in the biological zygotes. In the same figure, discrete and continuous diffusion gradients versus the distance from the node are also shown. The target and/or the nodes can migrate from point to point. Thus, seamless service provisioning has to be addressed in this approach. Fault tolerance has to be considered in case of node or software failures. Target classes are supported in our approach. Therefore, different targets can have dissimilar influence strengths, although they may be located equal distances from a node. A simple illustration is given in Figure 2.

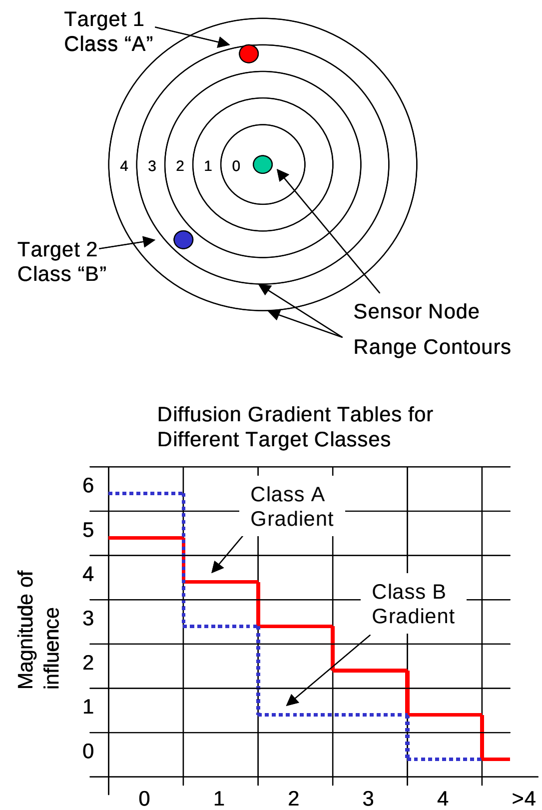

Fig. 2. Relationship between Range, Target Class and Resulting Influence upon a Sensor Node

In this case two targets are within the vicinity of a sensor node. From the diffusion gradient table for Class "A" type targets, Target 1 has an influence strength of 2 as it is at range 3. Target 2 is also at range 3. However, from its diffusion characteristic it will be assigned an influence strength of 1. Therefore in this instance the node will be influenced to a greater degree by Target 1[2].

The situation is more complex when a number of nodes are within the vicinity of target(s). The nodes have the ability to communicate with each other and possess the ability to specialise in order to provide a better overall service or capability. They are therefore able to coordinate their actions. Consequently, the strength of the target's influence sensed by the group around the target can determine the specialization and differentiations of the possibly tasks and functionalities provided from each node. This group operates cooperatively to provide services or apply special tasks on the sensed target. As a result, this approach can eventually lead to an emergent behaviour, which is the achievement of the complex result of

[2] To cope with a multitude of potential targets in the vicinity of a node, one approach is to use fuzzy logic to determine the resultant behaviour as it provides a workable means of state space reduction from which simple fuzzy rules can be applied. However, this aspect of the work is not considered further here.

(i.e. a service provisioning) from the collective assembly of simple functionalities provided by the individual nodes.

The group affected from the target can be classified as helper node(s) and the main node. Each group has one main node, which is influenced the strongest by the target. Therefore, the main node is usually the nearest node from the target[3]. On the other hand, the helper node(s) are nodes that are affected to some lesser degrees by the target's influence. A group can contain many helper nodes depending on the dispersion and strength of the target's diffusion gradient.

Biological behaviour principles including migration, replication, reproduction and death can be applied for both hardware and software perspectives. However another key aspect of our system is the ability to cope with mobility of either the targets or the sensor nodes.

When a target is in range of a group of nodes for some time, we assume that learning mechanisms within and between the nodes may permit improved service delivery, typically by adapting the service mechanism based on trial and error and monitoring the resultant performance from which experience can be gained. It would be disappointing if this experience were to be lost when a target moves to a new location away from the nodes hitherto providing the service.

Therefore in case of target mobility, we consider the migration of the experience gleaned between the original service delivery nodes. The new group can resume the operations from the last point in which the old group finished dealing with the target. Prediction of the target next position can be exploited to proactively deal with target mobility. Therefore, the overall performance and response time of providing the services can be improved.

In case of node mobility, two possible scenarios can be assumed in terms of hardware or service functionality movement. Firstly, the nodes themselves can move from position to another to cope for example with environment coverage. In this case, if the node is one of a group member, it has to handover its responsibilities to another node to guarantee the seamless of providing the services. The prediction principle used in the case of target mobility can be also applied in this case. This is described in more detail later in Section IV.E. Secondly, the nodes can assume they are fixed in their positions but the software programs and data residing in the nodes can migrate from node to another based on the environment conditions.

As an example of this form of migration, consider the case where the network infrastructure and nodes are providing a form of terminal virtualisation to the nomadic target. This service may use CPU processing, buffering storage of different nodes. However, as the target moves, its proximity to these service components could well increase to a point where the service delivery is compromised. In order to improve system performance it may therefore be appropriate to move virtualisation resources to nodes which will be closer to the target's predicted position in order to keep transmission latency within certain bounds.

Appling the biological behaviours on the nodes such as differentiation, migration, replication, reproduction and death in both hardware and software point of views can improve the overall performance of the systems including adaptively, survivability, fault tolerance, scalability and load balancing. Basically, for very simple scenarios, the following functional steps can be followed to achieve the goal of the proposed system:

A. Location Awareness

The network nodes have to locate the target. Therefore, target position and distance from the nodes that are affected by it have to be known to allow the system to differentiate the tasks provided by the nodes. One approach could be to employ Ultra WideBand (UWB) pulses. Nodes could send UWB pulses to allocate the targets based on the radar principles to determine the distance of the target from the nodes.

We assume that the nodes can sense the strength of the target's influence and then can consult a table that provides a mapping between the strength of it and predefined distances. This is used to differentiate the tasks that each node will assume in consultation with the main node.

B. Identification and Classification

In this stage, targets can be classified into different classed based on the sensed influence from the different nodes around the target. Methods that exist include the use of cameras and image recognition software or Radio-frequency identification (RFID) tags on the targets. The latter case provides a ready means of classifying the targets as well as their range; however, it is only possible if the target has hitherto been labelled.

C. Specialization and Differentiation

Based on the measured distances between the affected nodes and the target, the group that provides the tasks to the target can be defined. Therefore, the tasks can be differentiated based on the measured distances. As mentioned above, the main node is usually the nearest node to the target and it will typically provide the majority of the service

[3] There is scope to introduce a main node election process to determine which one is selected. A key example is where a number of targets are close to a certain node. Under these circumstances, in order to better partition the overall workload it may be sensible for different nodes to assume "main node" status for each target.

functionality or at least its management, while the other helper nodes will assist the main node according to the influence strength received from the target.

D. Functionality Provisioning

Each node in the group will start providing of its special functionalities based on the above calculated rules of influence under the guidance of the main node. The main node is able to ensure that the specialisation is achieved efficiently without conflicts or unnecessary duplication of functionality. Conflicts can arise if two or more helper nodes are the same distance from the target and wish to assume the same role. Under certain conditions the main node may wish to steer the differentiation process so that the specialisation is coordinated. Each helper node informs the main node of its intended role and for the main node to send a confirmation or instructions to the contrary can readily achieve this[4].

E. Target Hand-Over

Due to the movement of the node(s) and/or the target there needs to be a mechanism in place to provide a coordinated handover of functional responsibilities. We achieve this primarily through the control of the main node. When helper node(s) range from the target exceeds a value greater than for which their existing responsibilities are appropriate, they inform the main node. A similar condition arises if the target gets closer to a helper node or a node that has hitherto not been influenced by it. These nodes inform the main node of their situation. This can be done using a localised broadcast[5]. The main node then determines if itself or any of the existing nodes are in danger of moving to a distance from the target that is in conflict with their service delivery responsibilities. If this is the case the main node may well instruct a helper node to transfer learnt state information to an alternative helper node that is to assume the same role. It is also possible that the main node may sense that a different node is likely to wish to become the new main node due to its existing or forthcoming proximity to the target. In its localised broadcast the existing main node could prevent it taking on this role. However, an alternative outcome is for the existing main node to relinquish responsibility to the new node and pass over "intelligence" information that may enable the new node to perform its duties more effectively straight away. By using movement prediction, the existing main node can try to ensure that any handover of functional responsibilities is carried out seamlessly.

F. Packet Routing and Communication

The phase exists if the service role involves permitting communication to and from the target. Many approaches can be adopted in this stage. One-hop routing can be done if all the nodes in the group and the target are in the same radio coverage area. Helper nodes can send their packets to the main node and then the main node forward the packets to the target. Another approach is to send the data packets directly from the nodes within range of the target directly to the target. On the other hand, multi hop routing can be done if the nodes inside the group are not in the same radio range.

G. Other Behaviours

Node can perform other biological behaviour such as replication, reproduction and death. In hardware perspective, death can be done for example, due to battery life exhaustion, or, sudden software or hardware crashes. Therefore, hardware fault tolerance and reliability can be assumed. From a software perspective, death of the software can be achieved due to the absence of the targets around a perpendicular node. The replication and reproduction can be achieved for software perspective to evolve and adapt the software functionalities based on the environment conditions.

V. Conclusion And Future Work

This paper has introduced challenges facing current and future autonomic communication networks. The motivation for using autonomic self-organized networks is presented to cope with the complexity of networks. Differentiation and specialization principles are applied to the proposed system to allow a group of nodes to cooperatively achieve tasks and goals according to the diffusion gradient of the desired targets. The proposed solution is drawn from the biological principles found in zygote formation as well as other biological behaviours including migration, reproduction and death.

Future work is now focusing on implementation aspect of the system such as the control plane signalling between nodes. A simulation model of the proposed system architecture is also being developed to assess its performance

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[4] Of course situations could exist where the "helper" node attempts to find the main node and can't as there is actually no node closer to the target than itself. Under these circumstances the node should do nothing, as the target is too far away to warrant further action (until it moves closer to a node).

[5] One challenge here is to determine if the target entering a node's circle of influence is one which is already under the supervision of a main node or a "fresh" target that has so far not been identified. To differentiate between these cases without RFID tags becomes a significant point of interest. It is possible that features of the target, such as its trajectory, could be used to infer whether it is the same as an existing classified one or not. However this aspect of the system operation is not considered further in this paper.

relative to more traditional wireless sensor network architectures.

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