BIOMIMETIC MIDDLEWARE FOR WIRELESS SENSOR NETWORKS

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ABSTRACT
An agent based, Biomimetic (biology inspired) Middleware for resource constrained systems such as Wireless Sensor Networks (WSNs) by emulating nature is able to provide infrastructure oriented services that are characterised by such autonomic and autopoietic properties such as: (1) self-organisation, (2) self–shaping, (3) self-monitoring and self-healing. The paper aims at explaining how these fundamental properties if imprinted on executing agents can help in construction of reliable, cooperative and sustainable information ecosystems such as biomimetic middleware. This can occur through application of genetic evolution and immuno-computing paradigms (i.e. selection inhibition, random enabling/inhibiting, preferential attachment, birth, growth and death) .

Keywords: middleware design, autopoietics, biomimetics, resource constrained system

1. INTRODUCTION

Recent developments in software engineering and well sensor networks technology, biological science as advances in the complex systems theory have brought a new perspective on the different aspects of modeling (Bruzzone and Longo 2005), (Effroni et al. 2005), simulation and design of resource constrained systems. Surprisingly, in a relatively short time very strong links have been established between these disciplines resulting in proliferation of various biology inspired (biomimetic) computing models, methodologies and techniques (Keele and Wray 2005), (Kennedy 2006), (Krishnamurthy et al. 2006a), (Krishnamurthy and Murthy 2006b).

Although fundamentals of biomimetics have been adopted in many areas of engineering, the theoretical principles, concept, and characteristics of this new research domain have not yet been well established or clearly defined. Application of biomimetics in design of software systems is not an exception here (Ishida 1997), (Bonabeau et al. 1999), (Dressler and Krüger, 2004). This is can be mainly attributed to interdisciplinary nature of the field. The main thrust of our research into models of BIomimetic Middleware (BIM) systems is to explore how interdisciplinary insights could integrate systems theory, biology and software engineering in order to achieve a beneficial impact on methodology, architecture and engineering of newer generation of infrastructure oriented and sustainable software for Wireless Sensor Networks (Gustavsson and Fredriksson 2003), (Hull 2004).

A traditional approach for modeling and designing software intensive systems puts a strong focus on defining required resources for construction, testing and then operation of the implemented system. Far away from proper engineering practices the traditional approaches are additionally limited by economics, incompleteness of specifications, imprecise system performance information, over-provisioning as well as other factors. In the proposed biomimetic approach, beyond of the analytical concerns for architecture and design of software infrastructure we provide a consideration to the autonomic and autopoietic properties that may be used to improve the resource management of network systems. Biomimetic approaches provide an interesting modelling framework within which we could study the various interactions among the components of a software system, and how these interactions can influence the function and behaviour of the system under consideration. Architectural models and methods of resource and congestion management for dynamic wireless sensor networks (Wan et al. 2003), (Hull et al. 2004), (Wang et al. 2005) are required to synergise subordination, tolerance and conflict (collision) relations among its components (Chaczko, Klempous, Nikodem and Nikodem, 2007). In particular, in our research we study how the biomimetic can improve the architectural qualities of software infrastructure.

In this paper we aim to demonstrate that the structure of WSNs that adheres biomimetic principles can improve aspects of system cooperativity and robustness. In our opinion, the quality of system robustness can be viewed as the system's ability to recognise the problem (self-monitoring) and to know what to do in order to repair the system itself (self-repair). The prime objective is to demonstrate that we could enhance modeling and designing of the software systems (and middleware in particular) using the biomimetic rules and autopoietic (wher autopoietic = *auto – αυτό* in Greek and for self- and *poiesis – ποίησις* in Greek for creation or production) principles. Before we could claim a major methodological breakthrough we have to demonstrate that by applying the biomimetic approach we can obtain distribution and provisioning of resources (in constrained environment) as good (or better) as bio-systems are able to manage. However, it still remains a question if we actually can verify their optimality. Within our work we strive at proving that we are actually able to do it and derive some primitive measure of its optimality. It will be our future work to verify wider aspects of the proposition.

2. AUTOPOIETICS AND AUTONOMICS

In the autopoietic theory originally proposed by the H. Maturana and F. Varela in 1980 - a living system (biological organism) can be defined as a circular, autocatalytic-like and survival oriented process (Maturana and Varela 1980), (Maturana and Varela, 1987), (Livingston 2006). The theory emphasises aspects of closure of living systems (bio-organisms) thus can be perceived as an adequate alternative for the excessive attention paid to aspects of openness in theory of open systems. The self-* phenomena (where self-* denotes various autonomic attributes such as: self-organisation, self-healing, self-adaptation, self-monitoring, etc.) can be perceived as autopoietic phenomena. Software systems equipped with autonomic properties are capable of performing and managing majority of their operations completely by themselves or only with minimal level of human intervention. Autonomic network systems including autonomic wireless networks by adopting the concepts of autonomics are capable of self-managing all its elements and data communication links. In autonomic scenarios, wireless communication is complex and requires form designers to consider a number of problems related to sensor localisation, clustering, routing, energy management as well as various constraint conditions related to transmission collisions, multipath interference, obstructions that adversely impact the data throughput of high bandwidth communications robustness, reliability and scalability (Loureiro and Ruiz 2007). In order to face the challenges related to implementation of autonomic functions in WSN we propose a model of biomimetic software infrastructure (middleware) system that is characterised by the following fundamental properties:

2.1. Self-organisation

The phenomenon of self organisation is pervasive in natural systems (Eigen and Schuster 1982), (Kauffman 1993), (Eigen and Winkler 1993), (Kauffman 1995), (Bak 1996). It can be defined as a tendency of systems to evolve into a more organised form in the absence of external influence (or pressure) as a response to the system's environment; It can be also perceived as a collective, cooperative and coordinated process in which system's components reach a higher level of organisation while interacting among each other and with the environment. BIM software systems incorporating a colony (ecology) of numerous of components (agents) communicating, interacting (cooperating and competing) among each other and with the environment. Collectively and cooperatively these components can perform various tasks as a team, coordinating their activities to obtain an optimal efficiency. The sum of dynamic behaviour arising due to cooperative (competitive in resource constrained situations) interactions between different parts of the BIM could result in a coherent behaviour of the system as a whole. The system sensitivity relies on capability of middleware services to execute major changes (large amount of elements can be affected) even if the value of an observed (control) parameter is modified by a small volume only. These changes bare resemblance to the phenomenon of a phase shift in the domain of physics, where a local event can result in a global transition (a spontaneous "jump" to state(s) of much greater organisational complexity (Prigogine et al. 1993) in which new properties may dramatically re-emerge. Attributes of the BIM can't be anticipated in advance from the properties of the individual agent interactions. Following the phenomenon of emergence, various observed degrees of freedom originating from a network's parts collapse into a reduced amount of newer components, now with a smaller number of adjustable parameters that are relevant at a global level. Since by principle, the self-organisation properties cannot be predetermined the wireless sensor network system facilitated by middleware evolves to a new configuration or to a qualitatively different level that is compliant with the global system and environmental constraints. The robustness of the self-organising system can be then measured by a rate at which the system in its newer configuration is able to detect and handle its faults.

2.2. Self–shaping

We can define self-shaping it as allometric as scale-invariant, power-law scaling (Mitzenmacher 2003), (Newman 2005), (Clauset 2007), (Grant 2007) property of a system that addresses combined aspects of self-adaptation and self-optimisation. It may be understood as capability of the system to alter or adjust its structure, size and constraints (rates) of metabolic processes according to its varying internal and external surrounding conditions (Bunk 1998), (West & Brown 2005), (West et al. 2007). Shape alterations follow the optimal choice principles by adjusting various parameters in correspondence to the system behaviour (self-optimisation); In resource constrained networks there is a requirement for software infrastructure to be able to self-modify the network shape, adapt to variable levels of available resources and changes in the environment. To promote the system emergent properties such as robustness, survivability or resilience of the BIM, this needs to occur preserving aspects of scale-invariant relations (Dorogovtsev and Mendes 2003) and ego-morphic rules (Chaczko and Resconi 2007). In their work Dorogovtsev and Mendes (2003) argue that this property is fundamental as it ensures presence of all other autopoietic properties (i.e. self-organisation) in the network system.

2.3. Self-adaptation

The self-adaptation property can be seen as a capability of a system to modify/alter or adjust its internal structure or/and behaviour according to varying conditions in its surrounding.

2.4. Self-healing

The self-healing is to be perceived as a capability that allows to automatically detect, localise, diagnose and heal (repair) failures (faults and errors); The process of self-healing is adaptive, fault-tolerant and inter-dependent with the mechanism of self-monitoring.

2.5. Robustness

Robustness is also known as the fault tolerance can be seen as a capability of the system to resist or tolerate noise, disturbances, faults, stress, modification in system architecture (structure and behaviour) or changes in external ecosystem without causing negative effects on system's functions and without having long lasting effects on its structural composition and dynamics;

2.6. Cooperativeness

Characteristics of cooperativeness is to perceived as a system's capability to stimulate collective and cooperative interactions among its components. Components can perform various tasks in teams, coordinating their activities to obtain an optimal efficiency. In reality, there are various degrees of cooperation/competitive (in resource constrained situations) behaviour at place. The sum of dynamic behaviour arising from cooperative interactions between different parts of the system could decide about coherent behaviour and robustness of the whole system. Thus robustness of a system can be measured as a rate at which its components (resources) are repaired or replaced against the rate ($\mathbf{R}_s = dC_r/dC_f$) they disappear.

2.7. Resilience

The property of resilience can seen as capability to absorb and even utilise (frequently with advantageous results) noise, disturbances and changes that attain them, in order to sustain and persist without any qualitative changes in the architecture of the system.

BIM for resource constrained systems need to be flexible to change and resistant to damage or faults; the systems should be able to self-modify their past behaviour and adapt to newly allocated tasks, changes in levels of available resources or changes in environment. BIMs based WSN are robust as they are able to tolerate failures, non-cooperative behaviour or conflict (collision) relation among its components. We should be able to include software functions that apply genetic mutation and reproduction to seed autonomic and autopoietic properties in WSN.

3. ALLOMETRY AND SOFTWARE DESIGN

In order for BIM software system infrastructure to support management of the WSN according to varying levels of available resources, tasks and changes in the environment we need to model, design and then implement the self-shaping (i.e. self modification of the network topology) function requirement. It is suggested that this new type of the system property can be ensured if we follow allometric laws that are often pertinent to living systems (McMahon and Bonner 1983), (Calder 1984), (Niklas 1994), (Darveau 2002), Gillooly and Allen 2007). Typical examples of common allometric laws are:

- **Murray's law** can be observed in sections of human and animal vascular systems (LaBarbera 1990). To a degree it is also satisfied in plants. Durand (2006) argues that application of Murray's law could be very useful in performance analysis and optimisation of networked systems such as transportation infrastructure or electric power grids. In recent times, the principles of optimisation analysis and resource management of WSNs has also been a topic of an intense debate (Das et al. 2004, Hull et al. 2004.). In our work we aim to demonstrate that, we can better characterise the structure of sensor networks that can with some limitations satisfy the global optimisation of communication networks by applying the Murray's law principle. We take into account the Euclidean geometry agreeing that the optimisation has to be achieved within constraints of the classic geometry. Originally Murray's law referred to the radii (R_i) of mammalian blood vessels, since then many researchers have indicated that the exponent λ is ~3 in the following equation:

$$R_k^{\lambda} - R_{k+1,1}^{\lambda} + R_{k+1,2}^{\lambda} + \cdots + R_{k+1,\eta}^{\lambda}, \qquad (1)$$

  A more general form of Murray's law is demonstrated in Fig. 1.

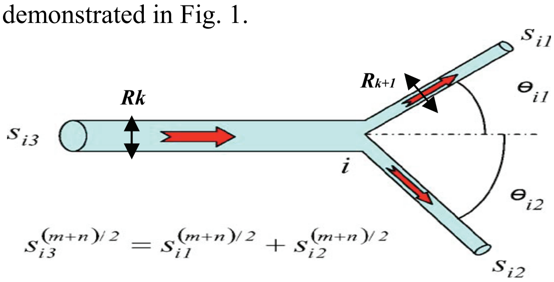

  Figure 1: The Relation Between Cross-Sectional Areas of Adjoining Channels in Minimal Resistance Networks (Durand 2006).

- **Kleiber's law** (Kleiber 1932), although somewhat controversial the law postulates the proportionality between organismic metabolic rate q_0 and body mass M raised to the power 3/4 defined as follows:

$$q_o \sim M^{3/4}, \qquad (2)$$

He and Chen (2003) estimated that the power exponent is to be set respectively 1/2, 2/3, 3/4 for 1- dimensional, 2-dimensional and 3-dimensional organisms thus reconciling the 3/4 (Kleiber's law) and the 2/3 (Rubner law) values for power exponent in the lawand generalising the law which can then be defined as:

$$qo \sim M^{d/d+1}, \qquad (3)$$

where d is the dimensionality, qo the metabolic rate and M is the mass of the organism (He & Chen, 2003). Drawing from the fractal cell geometry concepts He and Zhang (2004) brought about a controversial idea that the fractal dimension analysis of the exponents leads to a 4/5 allometric scaling law for the human brain thus concluding a 5th dimension of life. Application of Kleiber's law finds many followers and opponents (Bejan, 2002), (Kozlowski et al. 2003), (Kozlowski and Konarzewski, 2004), (Makarieva at al. 2005), (Chaui-Berlinck, 2006), (West and Brown 2005), (Brown, West and Enquist 2005), (Phillips 2006), (West et al. 2007), (Enquist et al. 2007) of the metabolic theory of ecology which predicts that there is a strong relationship between metabolic rates and body size, mass and even temperature in all biological organisms; beginning from unicellular bacteria and finishing on plants and animals. This occurs over 27 orders of magnitude, based on the laws of geometry and physics of networks.

- **The Square-Cube law** is commonly applied in engineering design. Drawn from the mathematics of proportion is a principle that states that resources consumed can be measured in 3 or more different dimensions (and regarded as a volume). First demonstrated in 1638 by Galileo's *Two New Sciences*. It states that: "*When an object undergoes a proportional increase in size, its new volume is proportional to the cube of the multiplier and its new surface area is proportional to the square of the multiplie"*. This can be expressed as:

$$v_2 = v_1 (l_2/l_1)^3, \qquad (4)$$

where v_1 is the original volume, v_2 is the new volume, ℓ_1 is the original length and ℓ_2 is the new length. It is worth to note that it doesn't matter which length is actually used.

$$A_2 = A_1 (l_2/l_1)^3, \qquad (5)$$

where A_1 is the original surface area and A_2 is the new surface area. For example, if a cube solid with a side length of 1m were doubled its size, its volume would be 8 m^3 and its surface area would be 24 m^2. This principle applies to geometry of all solids. The law would be relatively easily enforced if applied in 3D topology of networks or translated into other WSN network measures.

- The proportionality between breathing and heart beating times t and body mass M raised to the power 1/4:

$$t \sim M^{1/4}, \qquad (6)$$

- Mass transfer contact area A and body mass M:

$$A \sim M^{7/8}, \qquad (7)$$

- The proportionality between the optimal cruising speed V_{opt} of flying bodies (insects, birds, airplanes) and body mass M in *kg* raised to the power 1 / 6:

$$V_{opt} \sim 30.M^{1/6} m.s^{-1}, \qquad (8)$$

4. CONSTRUCTAL THEORY AND LIMITS OF SELF-SHAPING

We are aware that biomimetic approach has serious limitations. Stringently applied biological and allometric rules may also pose threats to the design and construction of software infrastructure systems. It is a fact that millions of years of biology have proven to be very successful. However, there are good reasons to believe that abrogating these laws for artificially (human) created systems would likewise cause sadden system instabilities and even a complete (unrecoverable) failure (death). After all as a rule biological systems die.

In constructal theory defined in 1996 (Bejan 2000, 2002, 2006), (Reis et al. 2004) its author Adrian Bejan postulated that: *"For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it ..."*. In its essence, the constructal principle states that every system is destined to remain imperfect, however the constructal principle generates the perfect form, here understood as the least imperfect all forms possible. According to the theory, the best that we could do when designing and implementing software based systems is to optimally distribute the imperfections among components of the system. Presumably such optimal distribution of imperfection among components of the system will determine the final shape or topology of the distributed system under study. The limits of self-shaping can arise from agent/node traffic trajectories and a structures of strange attractors that may indicate that changes triggered by a given value of a parameter might contribute to an undesired phase shift (transition) and thus consequently impact the system's stability (the system can become chaotic). There are several techniques discussed by Frazier and Kockelman (2004) as well as Ramasubramanian and Sriramm (2002) that can be used to predict which self-shaping transitions may result in the system to become chaotic. In our simulation environment we aim to detect such undesired self-shaping scenarios. The most commonly known is *the largest Lyapunov exponent* technique that can help to predict a chaotic behaviour in the system. The value of the largest Lyapunov exponent is a measure of the rate of nearby trajectories convergence/divergence in each dimension. As the system reshapes (evolves), the sum of a series of attractor values will diverge or converge. If the largest Lyapunov exponent exceeds zero then the system is to become chaotic. To find the largest Lyapunov exponent (Frazier and Kockelman 2004), we can apply the following function:

$$\lambda_{max} = \frac{1}{N\Delta t}\sum_{t=0}^{N-1}\ln\left(\frac{|s(t+\Delta t)-s'(t+\Delta t)|}{|s(t)-s'(t)|}\right) \qquad (8)$$

Theoretically, with Δt increases, the exponent value converges to its true value. In reality, this may not be always the case as the noise and finite number of data sets determine the range of exponent values. The second technique that may be used to test for chaotic tendencies in the system is the Fractal Dimension Indicator method. For chaotic systems the indicator value will be simply a non-integer. In his work Abarbanel (1996) indicated that there are many kinds of fractal dimensions, but the most practical one is the correlation dimension. Another technique (Frazier, Kockelman, 2004) to test for the presence of chaos uses the Fourier power spectrum function. For periodic data, the system characteristic frequencies of the power spectrum will spike while for the rest of frequencies it will be close to zero. For chaotic data, the spectrum will be broadband and have a broad peak.

5. EXPERIMENTATION

In our simulation experiments we attempt to test the concepts of Bejan constructal theory and verify if the underlying principles can be effectively applied in construction of BIM for a constrained resource system such as WSN. As a guide the Table 1 list analogies between constructal theory and software engineering (architectural design). Following the constructal approach for distributing the "imperfection" in the system, it suggested to seed the more resistive regime (policies) at the smallest scale of the network

At this stage various experimentation has been conducted using the originally developed Matlab based 3D WSN simulator designed for the purpose to test mechanisms of self-organisation and allometric self-shaping. The simulator was designed to handle various stressful conditions in WSN networks. Initial tests of allometric self-organisation in WSNs that follows the Murray's law when forming the 3-dimensional lattice demonstrate favourable patterns of energy usage (see Figure 2, Figure 3, Figure 4 and Figure 5).

Table1: Software Engineering vs Constructal Theory

Software Engineering	**Constructal Concept**
Architectural view, composition	Flow architecture (geometry, structure)
Evolving component, process	Change of structure
System Requirements	Global objective/ constraints
Load balanced architecture	Equilibrium flow architecture
Object or component relation	Fundamental relation
Evolving architectures/components	Non-equilibrium architectures
Removal of design constraints	Increased freedom to morph
Maximisation of data flow in ports	Maximization of flow access

The relations between sensor nodes cross-sectional areas of adjoining links emulate minimal resistance networks according to the generalised Murray's law. On other hand, simulation results of k-Means clustering of WSNs with randomly seeded nodes indicate excessive loss of field energy (Figure 4) and after routing a higher drop-out rate of cluster heads (CH);

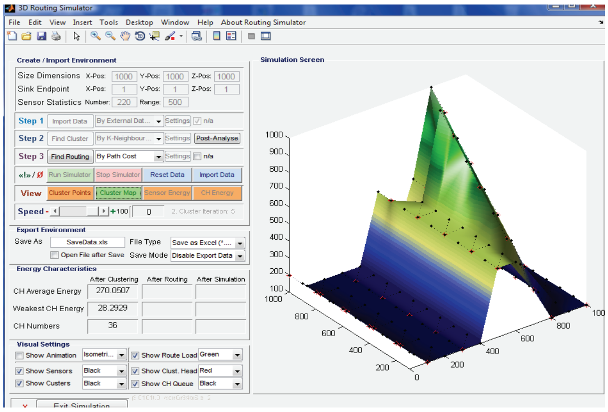

Figure 2: 3D WSN Simulator Testing the Energy Left in The Field After the Process of Clustering (by k-Neighbourhood) in the WSN Organised as a Lattice Structure of 220 Nodes

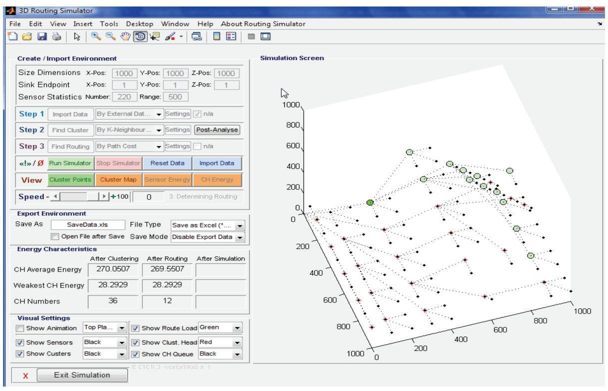

Figure 3: 3D WSN Simulator: Top View of the Lattice Topology After Routing

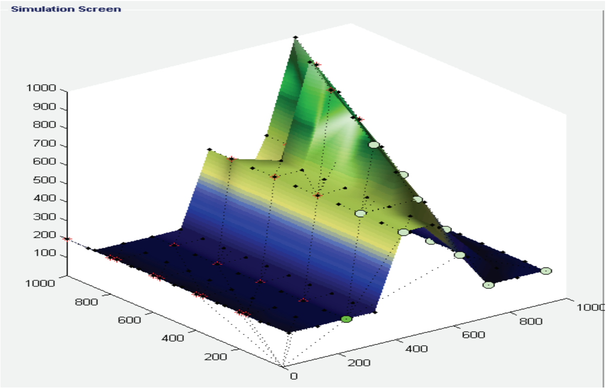

Figure 3: Top View of the Lattice Topology. The Result of Simulation that Tested the Usage of Energy in the WSN when Using the Path-cost Routing Algorithm. White Circles Depict (Energy) Healthy Cluster Heads.

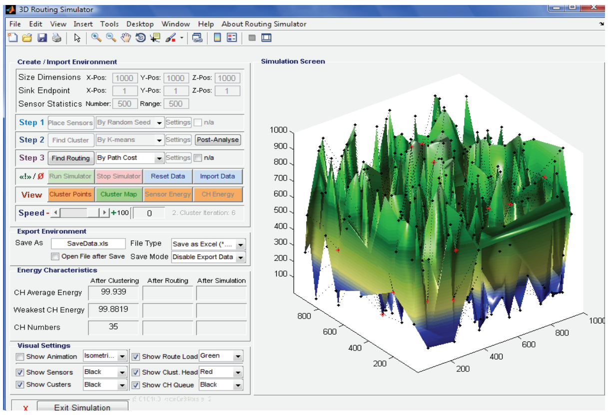

Figure 4: Isometric View of the Randomly Seeded WSN.

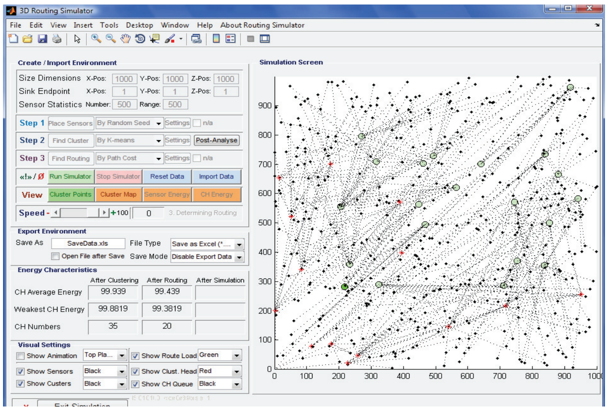

Figure 5: Top View of the Randomly Seeded WSN After Routing. Only 20 CH Left from the Original 35 Clusters.

6. CONCLUSION

In this paper we have presented the important properties of a Bio-Inspired Middleware model for a resource constrained (WSN) system. Thorough analysis and simulation of such models is required to assess suitability of the approach and a better understanding how the suggested autopoietic properties, principles and rules could help in design and construction of new generation of robust and collaborative Multi-Agent Systems (MAS) (Gorton 2007). The main point is to seed and promote the autonomic and evolving computational properties (abilities) of a WSN system at the local-level and preserve emergence of robustness at the global-level when the system undergoes a major transitional phase(s) change. In order to quantitatively improve BIM model and understand the implications, we are required to study the spatial structure of attractors and the spatio-temporal mappings, cooperative relations, binding energies, agent trajectories and structures of attractors in context of applied biomimetic rules and principles. The spatio-temporal mappings can provide a useful tool to monitor and possibly adjust stochastic properties, relations, connectivity and cooperative relations as well as the interacting agents behaviour in WSN. Simulation of binding energies, agent/data traffic trajectories and structures of attractors can provide information about required parameter values that trigger a change and final impact of phase shifts (transitions) caused by these parameters. Presented simulations can help in establishing whether agent/node movements or traffic trajectory is directed by a positive value of Lyapunov exponent that befalls onto a selected attractor. The technique discussed by Frazier and Kockelman (2004) as well as Ramasubramanian and Sriramm (2002) can help to predict if the system has tendency to become unstable (chaotic behaviour). Similarly to biological systems - the software intensive, real-time network systems such as resource constrained WSN are dynamic in spatio-temporal terms. Various characteristic parameters in these systems are changing with time, thus full understanding of both qualitative and quantitative properties of a BIM using limited capabilities for varying time and topology parameters in simulations is proven to be difficult and unrealistic. These issues need to be realised before dealing with implementations of real systems.

Our study of complex adaptive systems is in its in intermediate phase, so far we can confirm that biomimetic functions based on genetic, immuno-computing and swarm algorithms incorporated in middleware or network management services have important roles to play in the architectural design and optimisation of software-based, resource constrained systems such as WSN systems (Das, Banerjee, Roy 2004). Furthermore, it is expected that our work on MAS-based, biology-inspired frameworks and application solutions would ultimately lead us to design and development of more reliable and flexible systems.

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