Adaptive Dynamic Routing Supporting Service Management for Future Internet

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***Abstract*— There is currently much debate in defining what form the Future Internet will take [22, 23, 24]. The current Internet is struggling to meet the needs of an ever-evolving society. This is largely due to the Internet now become a thriving marketplace with services at the core. The range, number and complexity of services are set to increase with an even more dynamic service environment envisioned in the future. However, as these services grow, service composition will become an important feature of the service environment, leading to new challenges in service discovery and composition mechanisms. At the same time, dynamic service environments will also require that the underlying infrastructure networks are flexible enough to handle the changing service landscape. One area this is particularly important is in dynamic routing to deal with highly dynamic and frequent service changes. In this paper, we adopt mechanisms from biology and apply these to the problems identified, resulting in an integrated Bio-inspired service management and dynamic routing solution for Future Internet. We demonstrate how the bio-inspired mechanisms not only improve each problem individually, but through their integration also improve overall network performance. Simulation results are presented to validate the proposed solution.**

Keywords- Bio-inspired networking, service management, dynamic routing

I. INTRODUCTION

Services that can be tailored to meet the user's needs are predicted to be a principle driver of the Future Internet. However, following the Internet's huge increase in popularity in the last 10 years, it is already under significant pressure to meet the current requirements of users. This is largely due to the fact that the original Internet infrastructure was developed for a limited set of services with static traffic behaviour. The Future Internet will be a much more dynamic environment and as such will face numerous challenges. Particularly important is the ability to support efficient and flexible service management in order to meet changing user demands. At the same time we must ensure that infrastructure networks are able to cope with these changes by means of efficient delivery of services through the core networks.

The future will witness large numbers of disparate services, each with different capabilities. While it is important that services are available in large quantities to maximize user choice, service composition will be required in ensuring that appropriate services are available and tailored to the user's needs. However, large quantities of services lead to problems in efficiently discovering the most suitable services for the users, and composing these services efficiently inline with the changing service environment (e.g. ensure the composed service uses the most up-to-date and relevant service versions). While the improvements made in service management will lead to greater user satisfaction, they will also place more pressure on the underlying communication networks. In particular, one aspect of the Internet that will need to be enhanced is routing to support dynamic traffic (resulting from changes at the service layer), and to perform routing in a distributed and dynamic manner [13].

Taking inspiration from biological systems to enhance adaptive and autonomic communications systems has gained tremendous popularity in recent years [5, 6, 7, 9, 14, 15, 16, 17, 18, 19, 20, 21]. At the same time service management and composition [1, 2, 3, 4], along with dynamic routing [10, 11, 12, 13] have become established areas of research. While much attention has been paid to individual systems, an integrated solution for Future Internet is still under investigation. In this paper, we propose a *Bio-inspired Future Internet* solution that addresses each individual problem and integrates these into a single solution. The proposed architecture will include a service management layer that allows services to autonomously compose and evolve to changing user demand, and an infrastructure layer that dynamically routes traffic through the core network infrastructure to efficiently deliver these services. Besides the adaptive nature of the proposed architecture, the aim of our solution is also to ensure a high degree of system autonomy that will minimise human intervention.

The paper is organized as follows: Section 2 presents a high level description of our Bio-inspired Future Internet solution, followed by the service management layer in section 3, and the dynamic routing mechanism in section 4. Section 5 presents a description of the integration of the two layers. Section 6 will demonstrate the validity of the proposed solution through simulation, and lastly section 7 will present the conclusion.

II. BIO-INSPIRED FUTURE INTERNET

Our proposed Bio-inspired Future Internet solution is illustrated in Figure 1. In this paper, we focus only on content-based services, where the Service Management Layer manages these services for the user's applications (e.g. from composed web services to Video on Demand (VoD) for set top boxes in homes). Example functionalities of the Service Management Layer includes composing services to meet user's requirements, or adaptation of service components to suit the access network resources or device capabilities (e.g. filtering of multimedia streams [3]). Our vision of the future is that services will evolve very fast, as developers create new services or upgrade their functionalities. Also, developers should not have to deal with the mechanisms of how these services are composed, evolve or populated to other servers. These processes should be performed autonomously. The diversity of services (and compositions) will also lead to very dynamic traffic behaviour, which is not well suited to current routing approaches. Hence dynamic and adaptive routing will be required at the underlying infrastructure networks.

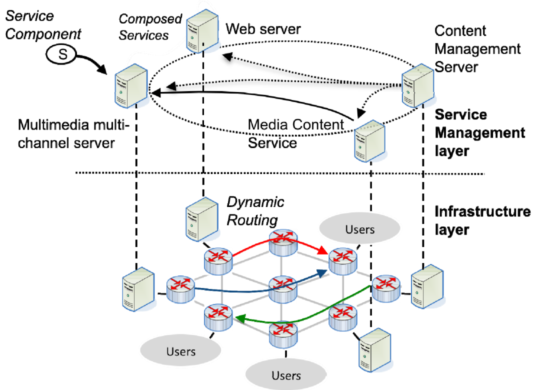

Figure 1. Proposed architecture

Our objective is to create a bio-inspired solution that meets the objectives of the individual layers illustrated in Figure 1. and ensure that the co-existence of the two layers will lead to improved scalability, efficiency, adaptability, and robustness [8]. Different Bio-inspired solutions have been applied to each layer of the proposed architecture, where a combination of mechanisms from *Biological lifecycle* and *Chemotaxis* are applied to the Service Management Layer, and *Chemotaxis* mechanism is applied to dynamic routing at the Infrastructure Layer. The following sections will describe how each of these techniques will contribute to each layer.

III. SERVICE MANAGEMENT LAYER

This section describes the mappings of bio-inspired techniques to service management, as well as mechanisms of creating composed *Service Groups* (*SGs*). The application of Biological lifecycle mechanisms will enable a more efficient service management process. The approach builds on the previous work of Autonomous Agents supporting self-organising services (referred to as *Service Agents (SA)*) [2], where added functionalities include mechanisms for SAs to coordinate and form SGs. The composed groups will evolve and change as services evolve and user demand changes. This provides service developers/providers with a degree of autonomy, as services can be deployed onto an server where the biological service lifecycle then takes over, ensuring 'fitter' (more useful) services thrive and weaker ones do not.

A. Service Agents Biological Lifecycle

The SAs reside on a node known as the *Application Server* (*AS*) and contain service content that support specific user applications. The SAs are analogous to biological entities (e.g. bees, bacteria), where these biological entities share a common behaviour throughout their lifecycle. The migration, replication and death behaviour of the agent is represented as x. Each SA carries a set of factors (v_i), a weight (w_i) associated with the factor, and a threshold (θ_x) that governs the behaviour of the agent. In the event of any changes in the environment, the behaviour x is invoked when $\sum v_i w_i > \theta_x$.

Migration: The SAs are able to perform migration by moving between different ASs. The movement is driven by the load on the current AS platform (AS_i). In the event that load on AS_i increases over a certain threshold, the SA will start to investigate the load of neighbouring AS_j for migration.

Energy Management: Each agent contains energy and is able to manage this energy throughout its life. When the SA resides on an AS, it expends energy for using the ASs resources (e.g. CPU, memory). At the same time, as the SA serves requests as part of a service group, it is able to gain energy for its contribution. Therefore, if a SA is part of many groups, it is able to gain large quantities of energy as its popularity increases.

Replication: SAs are also able to replicate themselves when the number of requests for that particular agent is high. This is due to the fact that each SA is only able to support a certain number of users. The SA will consider the number of requests it receives over a period of time, and if greater than the set threshold and the agent contains sufficient energy to replicate, the agent will begin replication.

Death: In the event that the SA gains less energy (e.g. SA becomes less popular) compared to the energy expended on the AS, the agent will die off. Through this process, SAs are able to live and die depending on the popularity of the service, which creates an evolving environment for services.

Service gradient search: Due to the large number of ASs, an efficient distributed search technique is required. When a query is transmitted it should be attracted towards the AS holding the particular SA. We use simple *Diffusion* of service advertisements to the ASs in close proximity, which creates a gradient field that will attract the queries towards the AS holding the SA. We assume that each AS platform contains a directory of SAs within its vicinity, where a hop count value is maintained for each SA.

Initially, when placed on an AS, the SA has a certain amount of energy it can use to propagate the hop count. As the agent diffuses this value to the neighbouring ASs, the agent details and hop count will be entered into the directory (Figure 2). As each AS receives the diffused hop count value, it will reduce the hop count value and continue to diffuse this to its neighbouring ASs. The process will continue until the hop count reaches zero. To find a SA, a query is diffused into the environment. When this query reaches an AS, the AS searches neighbouring ASs to find the service entry with the highest hop count. This process continues until the query reaches the AS containing the actual service agent. Therefore, by migrating from AS to AS through a higher hop count value, the query will get attracted to the SA. An example of this is presented in Figure 2, where a query for SA_3 approached AS_5 which passes this to AS_6 since AS_6 contains a higher hop count value for SA_3. If an AS has no entry for an SA, the query is passed to the next AS randomly, resulting in a random walk. The process is based on micro-organism motility, where a chemical gradient formed in an environment is sensed by the micro-organism to migrate towards the source (also known as chemotaxis [6]).

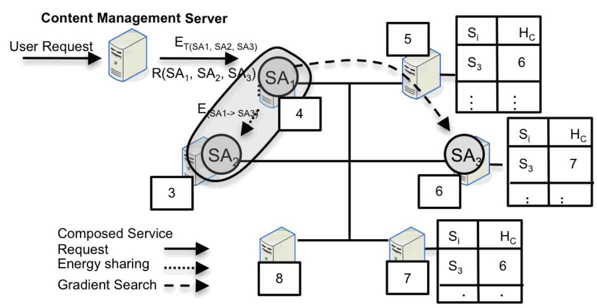

Figure 2. Gradient based query and energy sharing

Each SA entry in the AS directory has a set Time to Live (TTL). After a fixed period of time, the hop count of each SA will get reduced by one. Therefore, the SA will be required to update these entries, using a portion of its energy, to continually emit and update the hop count values. However, this is also dependent on the amount of energy the SA is gaining. In the event that the SA does not gain enough energy, it will only be able to use a small portion of energy for maintaining entries in peer ASs. Therefore, when the service reduces in popularity, the gradient emission will reduce, leading to increased resistance for the search process. This mechanism creates an automated, distributed, evolving process for discovering services, where new services with latest functionality will flood the AS networks, and as services loose popularity, the agents will slowly disappear.

B. *Dynamic Service Composition*

As described earlier, the primary goal of maximizing value to users is through composition of various services. The key towards composing the services is for services to discover other services that can enhance their collective value. Initially a request R_i from a user will be translated to a set of SAs ([SA_1, SA_2…]). The translation process will be performed through a *Content Management Server* (CMS), where the CMS may contain a specific service description solution that relates different services. Once the set of SAs is determined, a query is sent to the closest AS (AS_F) to determine if it holds an SA (SA_{ASF}) from the query. If it does, the SA_{ASF} will be the leader of the group and dispatch parallel queries for other SA in the set (in the event that the first AS does not contain a SA in the set, the AS will send this query to the neighbour and the whole process will repeat). Once all the SAs of the set have been found and are available to join the service group, a reply is sent to the SA_{ASF}, and the composition is formed.

C. *Service Management Evaluation*

In this sub-section, we present evaluation of the service management mechanism. The simulation compares service management incorporating the bio-inspired (SM-B) and the non-bio (SM-NB) case. In SM-NB, services do not have bio-inspired functionalities such as migration, death, replication, or gradient search (search is based on query flooding). The performance evaluation is presented Figure 3. The tests were performed on a 100 node topology to validate the scalability of the solution. Two sets of experiments were performed: the first set evaluated the effects of varying the gradient size and the second set for varying the composition size. The varying gradient size included a minimum gradient size (1 hop), maximum gradient size (maximum hop count between network edges), and half gradient size (half of the maximum size). In our simulation, for both the flooding (SM-NB) and gradient-based search (SM-B), we employed a broadcast search.

With message broadcasting there is a cost incurred in the number of messages used per search. Figure 3(a) shows the average number of messages per search used for both flooding and gradient-based searches across varying gradient sizes. The SM-NB solution consistently requires approximately 1270 messages to discover the best route. For SM-B, the gradient search differs greatly depending on the gradient size. At the minimum gradient, the number of messages is large (1200). This is logical given that, at minimum gradient, the search is limited to one hop of the actual node. As the gradient increases to half, the average number of messages reduces dramatically to 225. At full gradient the number of messages required is 0, since at full gradient the target node is visible to every other node in the network. Figure 3 (a) also shows the blocking rates experienced at varying gradient sizes. For the SM-NB we see that the blocking rates are relatively consistent (0.65 - 0.66). For the SM-B case we can see that the rejection rate is quite high (0.52) for minimum gradient size. However, as the gradient radius increases the blocking probability also decreases. This also resulted in greater replication for the full and half size gradient, and fewer deaths, ultimately leading to a higher number of agents. Figure 3(b) shows the blocking rates for varying composed service sizes. For SM-NB, as the size increases from 2 to 5 services, the blocking rate increases from 0.5 to 0.8. This is due to the fact that as the composition size increases, this in effect increases the number of agent requests. Hence the SAs reach their limit of the number of requests they can serve leading to a large number of requests being rejected. SM-B shows a very small blocking increase (0.06 - 0.14) from 2 to 5 composition size, directly attributed to increased migration (14 – 32733) and replication (1470 – 1777) resulting from the increased agent requests.

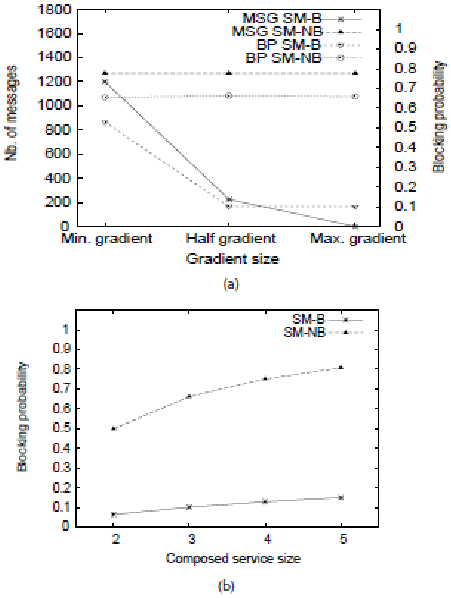

Figure 3. (a) No. of messages & Blocking rate vs. varying gradient size, (b) Blocking probability vs varying composition size

IV. PARAMETERISED GRADIENT BASED ROUTING

The objective of the dynamic routing mechanism is to support the changing traffic demand resulting from user's service requirement changes. The dynamic routing process is known as *Parameterised Gradient Based Routing* (*PGBR*) (full detail of the routing process can be found in [25]), and is inspired from the chemotaxis mechanism. Although the PGBR routing mechanism is similar to the service query search, the minor difference is how the gradient field is formed. In the case of PGBR it is formed based on the local interactions between nodes (Figure 4), unlike the service query search where the gradient is based on diffusion from the source. The route discovery is performed for each source-destination pairs, through a gradient attraction process. An example of route discovery is presented in Figure 4, where a route for S, D = (1→6) is found along path 1 – 4 – 5 – 6. An example of gradient attraction is at node 1, where node 1 selects the link to node 4 since it's gradient is higher than to node 2 (G1, 6,1→2 = 0.4 < G1, 6,1→4 = 0.6).

The advantage of using a gradient field that is set up by the environment is that the field is able to adapt and change with respect to the changes in network load. This is ideal for distributed routing, as it allows the route to divert around loaded nodes of the network (see Figure 4. (b)).

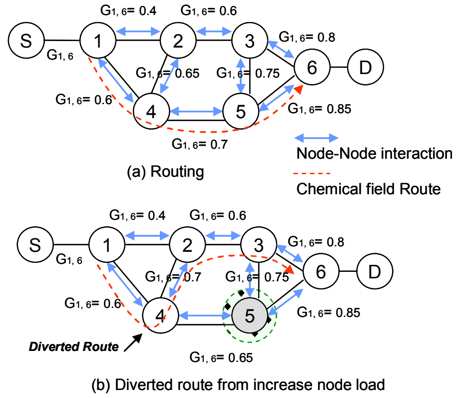

Figure 4. Illustrative example of PGBR routing

Our work on PGBR has been previously evaluated, where PGBR was compared with the Shortest Path (SP) algorithm as well as the ANTS distributed routing algorithm. More information can be found in [25]. In this paper, minor extensions were made to [25] (which had static α and β parameters), where these parameters adaptively change with respect to network load. Example of the changes for α and β for different traffic types are shown in Figure 5. (γ is always statically set to 1).

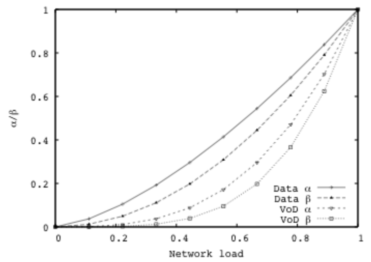

Figure 5. Selection of β and α with respect to network load

V. INTEGRATED SOLUTION

The previous sections presented the bio-inspired solutions for the Service Management Layer and the PGBR routing mechanism at the Infrastructure layer. Since our objective is to create a holistic solution to support the Future Internet, this section will present how the two layers will interact and integrate (Figure 6). The interaction of the two layers is similar to the co-evolution process in Biology. The process of co-evolution is where a change in a given system causes change in a related system. In this case, as the Service Management Layer copes with the changing demand from users, the underlying network supports this by manipulating the routing based on the node and link load observed in the infrastructure layer.

Initially, a user request arrives and is processed by the CMS. The CMS determines the appropriate composed service for the request, maps it to actual SAs and then passes it to the closest AS. In the example in Figure 6. SA_1 sends parallel requests for SA_2 and SA_3. If SA_2 and SA_3 are available, they respond to SA_1 who then returns an invocation to begin streaming to the user. Each AS will independently discover the routes at the underlying layer and begin streaming.

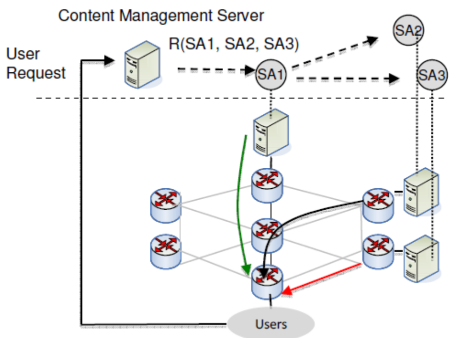

Figure 6. Integration of Service management layer and PGBR routing

VI. SIMULATION

This section presents the results for simulation of the integrated Service Management and Infrastructure Layers. The topology configurations used for the simulation is illustrated in Figure 7. The objective of the integrated solution is to investigate the improvements of applying bio-inspired techniques to both the Service Management Layer and the Infrastructure layer, and to compare this to standard approaches. Therefore, comparisons were made for full bio-inspired solution at service management layer and underlying network (SM-B: PGBR); bio-inspired service management and shortest path (SM-B: SP); and standard service management with shortest path (SM-NB:SP). The results are presented in Figure 8. – 13.

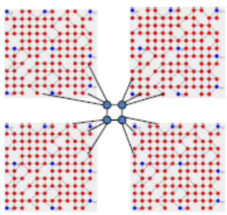

Figure 7. Topology configuration. 4 Domains - Blue nodes are AS and red nodes are Infrastructure router nodes

We have subdivided the simulation duration into 3 zones, where for each zone we bias the incoming request rate for a particular service type. Our objective is to see how the prioritization of services impacts on the lifecycle of the agents (e.g. death, replication, migration) and how this in turns affects the underlying routing. Zone 1 is biased towards HTTP services, while zone 2 is biased towards VoD (low) and zone 3 towards VoD (high). No particular service is biased before zone 1 and after zone 3. The average composition size is set to 3 services per group.

TABLE I. PARAMETERS FOR TOPOLOGY

Domain	No. of Nodes	No. of Links	No. of AS
1	107	360	16
2	103	342	16
3	109	386	16
4	106	366	16

TABLE II. TRAFFIC TYPE PARAMETERS

Traffic Type	Distribution for Service time (average - seconds)	Average Flow Quantity (Kbps)	Proportion of total requests (%)
HTTP	Uniform (5-25)	2	40
VoD (L)	Uniform (5-25)	300	30
VoD (H)	Uniform (5-25)	700	30

TABLE III. PARAMETERS FOR SERVICE MANAGEMENT

Parameter	SM-B	SM-NB
Arrival Rate	16 per/s	16 per/s
Average Composition size	3	3
Max. gradient size	14 hops	Flooding search
Replication Threshold	11 requests	-
Migration Threshold	17 agents per Platform	-
Energy To Replicate	200 units	-
Energy to Migrate	300 units	-
Gradient Search TTL	4s	4s
Agents Per Node	3	3
Starting Energy	1500 units	1500 units
Energy Per Request	5	5
Platform Energy Cost	3	3
Execution Time	25 s	25 s
Transmission Delay (sec)	0.0001s	0.0001s

Figure 8 presents the average throughput measured at the network level for the three different combinations of solutions. As expected, the SM-B:PGBR gave the best performance and was able to provide higher throughput for all zones. This is reflected in the ability of SM-B to efficiently discover SAs (including replicated SAs) while the PGBR was able to efficiently discover the routes at the Infrastructure Layer as the service demand changed between zones. Since zone 1 was biased towards HTTP services, the overall throughput is lower than in zone 2 and 3 which was biased towards VoD (L) and VoD (H), respectively.

The average throughput results also reflect on the average blocking probability (Figure 9) (includes blocking at both layers). The blocking probability in zone 1 was lowest for SM-B: PGBR (0.02) compared to SM-B:SP (0.06) and SM-NB:SP (0.32). For zone 2 and 3, we can see that average blocking probability for SM-B:PGBR was 0.3 compared to SM-B:SP (0.46) and SM-NB:SP (0.56). The results also show the improvement of PGBR routing in comparison to SP for SM-B. Figure 10 illustrates the number of agents throughout the simulation and complies with the biasing of each type of agent for each zone (where zone 1 had the largest amount of replication for HTTP agents, while zone 2 and 3 replicated a large number of VoD (L) and VoD (H) agents, respectively).

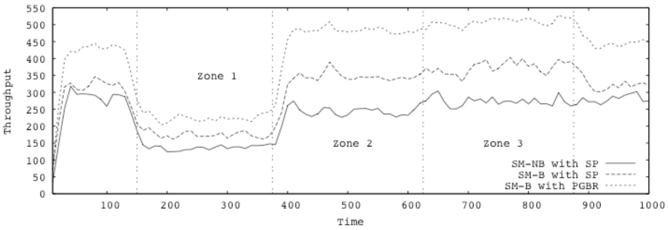

Figure 8. Average throughput

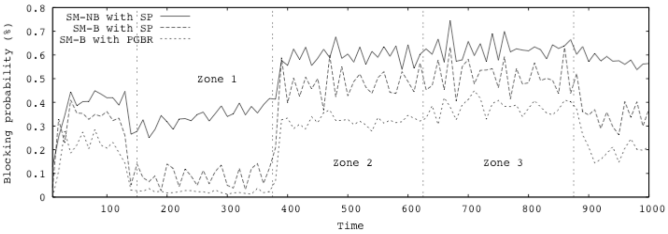

Figure 9. Average Blocking Probability

Figure 11 compares the average energy attained by the SAs and compares this to SM-NB. As shown in the figure, the SM-NB has constant energy consumption for all its SAs (due to the constant execution of the SAs on the AS), while for the SM-B the average energy was affected by service demand. Although there is an increase in the number of SAs in Figure 10 for zone 1, there is a slow decline of energy in Figure 11. A similar trend can also be observed when VoD (L) and VoD (H) demand started to increase. This is due to the replication process, where the parent agents offload energy to the child. As zone 1 transitioned to zone 2, we can see the number of HTTP SAs reduce (caused by death) in Figure 10 and this reflects the lower demand for those agents. At the same time, we can also see an increase in energy, since the death of a SA means that the remaining SAs will need to serve more requests. Figure 12 presents the migration number of each type of SA and shows that in zone 2 there was a high number of migration for HTTP SAs even though their demand has dropped. The is because there was a large number of HTTP SAs replicated in zone 1 still present in zone 2, and as VoD (L) increased its replication, this started loading the AS. As the AS gets loaded, the migration process of the HTTP SAs is triggered (HTTP SAs require less energy to migrate and so would migrate before the others). However, the migration starts to stabilize when the HTTP SAs die off towards the middle and end of zone 2. Zone 3 demonstrated a high migration rate for VoD (H) since the demand was the highest.

While the SA's are changing from zone to zone, this also causes the PGBR to discover new routes as the demand evolves and changes. This has been reflected in the average blocking probability as well as the throughput in Figure 8. and Figure 9. Figure 13 presents the average network load balancing, and shows that the PGBR support for SM-B improves the load balancing over SP. This is also supported by the average link utilization, where SM-B:PGBR utilizes a larger amount of link capacity (0.307) than other solutions (SM-NB:PGBR = 0.239, SM-NB:SP=0.134, SM-B:SP=0.169).

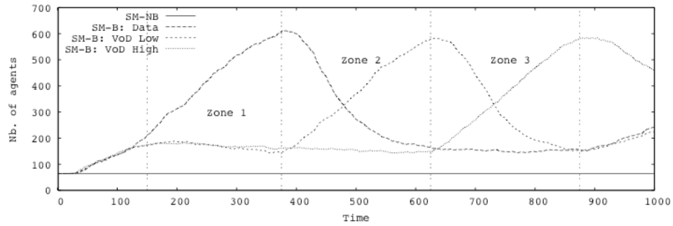

Figure 10. Number of Service agents

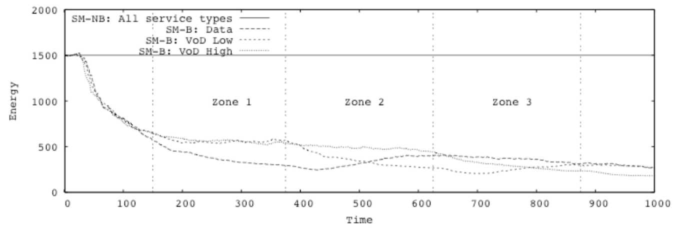

Figure 11. Average Energy for all Service Agents

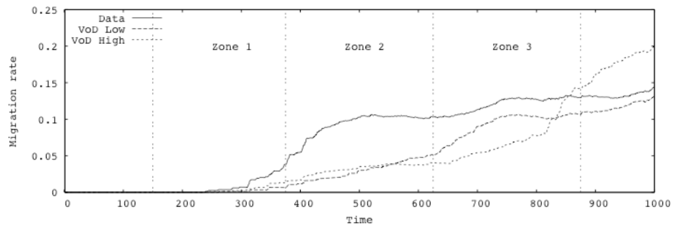

Figure 12. Average number of Migration by Service Agents

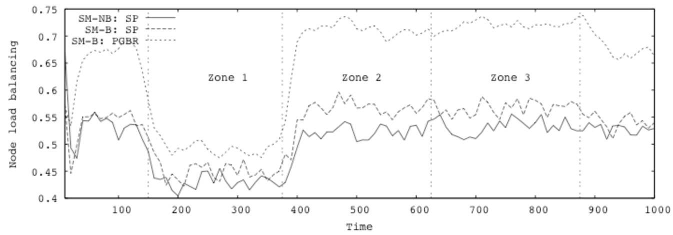

Figure 13. Average network load balancing

Therefore, the combined SM-B:PGBR demonstrated the benefits of applying bio-inspired techniques to both layers. The results demonstrate how the PGBR was able to adapt to any load resulting from service demand changes (low load in zone 1 to higher load in zone 2 and 3). Even though the two layers function independently, this reflects on the process of co-evolution where the changes in the Service Management Layer will change the behaviour of the PGBR and cater for varying types of load in the underlying networks.

VII. CONCLUSION

In defining a Future Internet there are clearly many fundamental issues that need to be resolved. We propose that more dynamic service management will be required as the volume, complexity and flexibility of services grow to meet the increasing sophistication of user requirements. These mechanisms should ensure more efficient management, allowing the service environment to find a 'natural equilibrium', removing the need for intervention by the service developer/provider. Given this dynamic service-oriented environment we also suggest that a more flexible and robust routing mechanism is needed to handle the huge fluctuations in traffic type and demand.

In this paper we presented a Bio-inspired Future Internet solution to address these challenges. The Service Management and Infrastructure Layers both adopt biological mechanisms to achieve their individual goals of improved capabilities and performance. We have also shown how both layers work in harmony, with the service management layer improving the user experience while providing more efficient management, which in turn is supported by the underlying Infrastructure layer. Finally, we have also provided validation of our architecture through simulations, which show that our proposed solution out performs the current standard techniques, outlining its pertinence to the foundation for the Future Internet.

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REFERENCES

[1] D. Miorandi, L. Yamamoto, P.Dini, "Service Evolution in a Bio-inspired Communication System", International Transactions on Systems Sciences and Applciations, vol. 2, no. 6, October 2006, pp. 573 – 587.

[2] T. Nakano, T. Suda, "Self-organizing Network Services with Evolutionary Adaptation", IEEE Transaction on Neural Networks, vol. 16, no. 5, September 2005.

[3] S. Herborn, Y. Lopez, A. Seneviratne, "A Distributed Scheme for Autonomous Service Composition", in Proceedings of 1st ACM International Workshop on Multimedia Service Composition, Singapore, 2005.

[4] X. Gu, K. Nahrstedt, "Distributed Multimedia Service Composition with Statistical QoS Assurances", IEEE Transactions on Multimedia, 2005

[5] S. Balasubramaniam, D. Botvich, W. Donnelly, M. Ó Foghlú, J. Strassner, "Bio-inspired Framework for Autonomic Communication Systems", book chapter in "Advances in biologically inspired information Systems: Models, Methods, and Tools", Studies in Computational Intelligence, Springer Verlag. Editors Falko Dressler and Iacopo Carreras, 2007.

[6] G. Canright, A. Deutsch, T. Urnes, "Chemotaxis-Inspired Load Balancing" ComPlexUs, 3, August 25, 2006, pp. 8 – 23.

[7] M. Dorigo, G. Di Caro, L. Gambardella, "Ant algorithm for discrete optimization", Artificial Life, vol. 5, no. 2, 1999, pp. 137 – 172.

[8] C. Prehofer, C. Bettstetter, "Self-Organization in Communication Networks: Principles and Paradigms", IEEE Communication Magazine, July 2005.

[9] R. Schoonderwoerd, J. L. Bruten, O. E. Holland, L. J. M. Rothkrantz, "Ant-based load balancing in telecommunications networks", Adaptive Behaviour, vol. 5, no. 2, 1996, pp. 169 – 207.

[10] J. Moy, "OSPF: Anatomy of an Internet Routing Protocol. Addison-Wesley, MA, 1998.

[11] Y-W. Chen, R-H. Hwang, "QoS Routing Algorithms for Multiple Traffic Classes", IEEE International Conference on Communications (ICC), 2002.

[12] B. Fortz, N. Thorup, "Internet traffic engineering by optimizing OSPF weights", in Proceedings of IEEE INFOCOM, 2000.

[13] J. Rexford, "Rethinking Internet Routing", in Proceedings of Symposium on Theory of Computing Conference (STOC'08), Victoria, Canada, May 2008.

[14] K. Leibnitz, N. Wakamiya, M. Murata, "Biologically inspired Self-Adaptive Multi-path routing in overlay networks", Communications of the ACM, vol. 49, no.3, March 2006.

[15] M. Kodama, G. Hasegawa, M. Murata, "Implementation experiments of TCP Symbiosis: bio-inspired mechanisms for Internet congestion control", in Proceedings of Communications Quality and Reliability 2008, April 2008.

[16] P. Hui, J. Leguay, J. Crowcroft, J. Scott, T. Friedman, V. Conan, "Osmosis in Pocket Switch Networks", in 1st International Conference on Communications and Networking in China (Chinacom), Beijing, China, 2006.

[17] F. Dressler, "Bio-inspired Network-centric Operation and Control for Sensor/Actuator Networks, in Transactions on Computational Systems Biology (TCSB), vol. 3 (LNCS 4780), 2007, pp. 1 – 13.

[18] I. Carreras, I. Chlamtac. F. De Pellegrini, D. Miorandi, "BIONETS: Bio-Inspired Networking for Pervasive Communication Environments", IEEE Transactions on Vehicular Technology, vol. 56, no. 1, Jan. 2007. Pp. 218-229.

[19] J. O. Kephart, "A Biologically Inspired Immune System for Computers", in Proceedings of the 4th International Workshop on the Synthesis and Simulation of Living Systems, 1994.

[20] T. Bokareva, N. Bulusu, S. Jha, "SASHA: toward a self-healing hybrid sensor network architecture", in Proceedings of the 2nd IEEE Workshop on Embedded Networked Sensors, 2005.

[21] A. F. G. Bourke, N. R. Franks, "Social Evolution in Ants, Princeton University Press, 1995.

[22] NSF NeTS FIND Initiative, http://www.nets-find.net/

[23] 4WARD project page, http://www.4ward-project.eu

[24] GENI: Global Environment for Network Innovations, http://www.geni.net/

[25] S. Balasubramaniam, D. Botvich, J. Mineraud, W. Donnelly, "Parameterised Gradient Based Routing (PGBR) for Future Internet", in Proceedings of Advanced Information and Networking (AINA 2009), Bradford, UK, May 2009.