Adaptive Self-Configuration for Distributed Load in Sensor Networks

Adaptive Self Configuration for Distributed Load in Sensor Networks

#Mudasser Iqbal, Iqbal Gondal, Laurence S. Dooley
GSIT, Faculty of IT, MONASH University, Churchill, 3842 Australia
[*#Mudasser.Iqbal, Iqbal.Gondal, Laurence.Dooley*]*@infotech.monash.edu.au*

Abstract- **The dynamic architecture of the network is monitored by exchanging so-called *Network State Beacons* (NSBs) between key network nodes. The *Beacon Exchange* rate and the network state define both the time and nature of a proactive action to combat network performance degradation at a time of crisis. It is thus essential to select and update the beacon exchange rate (F_X) according to the variations in the load profile of the network. This paper presents a novel localized method that for selecting and updating the F_X by adapting to the network load and energy constraints. The results indicating that the model reconfigures the network more effectively to achieve higher throughput as well as greater network integrity, with minimal resource overheads.**

Keywords- **High Density Ad-hoc Networks, Self Configuration, Distributed Adaptive Optimization, Beacon Exchange Rate**

I. INTRODUCTION

Certain time critical and emergency scenarios require very robust, unattended and large scale communication infrastructures to support collaborative operational and signal processing activities. In such situations, ad hoc networks play a critical role in places where a wired backbone is neither available nor economical to build, such as law enforcement operations, battle field communications and disaster recovery. Recent advances in wireless communications and microelectromechanical systems have further extended the capabilities of ad hoc networks, through the development of miniature, low-cost sensors that possess sensing, signal processing and wireless communication capabilities.

To satisfy operational requirements, intermediate nodes called *Parent Nodes* (PN), which have relatively high resources, are used. These nodes are responsible for such tasks as in-network data processing, communication delay minimization and routing of PS nodes data to the Central Commanding Infrastructure (CCI). As these USN building blocks can fail due to unforeseen local or non-local factors, in order to maintain a minimum QoS for a USN, (which in this context is defined as lossless information delivery at minimal control traffic rates), PNs can be dynamically added or removed from the infrastructure. The non-administrated USNs must be self-monitoring and able to take proactive action to mitigate certain malfunctions before they actually occur.

Proactive network monitoring and reconfiguration requires maintaining the network state across the PNs at optimized instants to militate against prospective anomalies. The state profile is maintained by periodic exchanges of NSBs at a set Beacon *Exchange Rate* (F_E). The rate of NSBs constitutes the additional load that the network must support in its reconfiguration activities. The load profile of the network is a key determinant of the network performance and typically defines the course of predictable anomalies in the network, such as the loss of connectivity due to energy shortage. Accurate and timely network information, including the estimated lifespan of key nodes and network load profile enables an effective and proactive strategy to be formulated to alleviate potential network impairments. It is therefore important to attempt to optimize these factors by considering the current network load and maximise throughput while concomitantly minimizing the risk of information loss due to node failures.

#Corresponding Author

Previous work on self-configuring protocols has not focused upon investigating the role the *beacon exchange rate* plays in maintaining a QoS for the network. Gupta [1] and Chiasserini [2] have focused on energy-efficient, hierarchical modelling of sensor networks through dynamic configuration of the tree nodes. The success of their dynamic tree models is based on a problematic assumption that sensor nodes are able to connect to many PNs simultaneously. Cerpa in [3] emphasized the need for a high degree of synchronization between network components in order to correctly reconfigure. Policy-based and self-managing systems have been also considered, but these impose a high computational and storage requirement on individual sensing units.

This paper presents novel improvements to a proactive self-configuration model [4, 5] by significantly reducing overhead traffic while maintaining a guaranteed QoS. The research establishes bounds for selecting F_E and develops a distributed adaptive model to dynamically update the rate in response to network load profile changes.

The remainder of the paper is organised as follows; Section II explores the underlying USN design and self configuration model, while Section III details the distributed load-adaptive F_E selection model. Simulation results focusing upon the maintenance of QoS and reliability of configuration model are given in Section IV and conclusions are presented in Section V.

II. SENSOR NETWORK DESIGN & SELF CONFIGURATION

A. Network Design

The sensor network design approach described in [6] is based upon the optimal selection of PN density and location in a virtual hexagonal topology structured in autonomous clusters with each cluster headed by a PN. This approach is adopted to achieve the best QoS by ensuring the availability of PN to a maximum number of PS nodes, while minimizing Grey Region (GR) areas (to reduce many-hop routing) and minimizing confusion/conflict zones.

B. Self Configuration Core Protocol

The network design defines the initial configuration of the sensor network for best QoS with the communication and connectivity model for the PN and PS nodes described in [5]. In the steady state network operation, the model can handle a number of irregularities including: a) increased traffic load leading to congestion and packet losses causing loss of information, b) decreased energy resources increasing the risk of PN failure, c) sudden failure of a PN due to local or non-local disasters and d) addition of new PNs.

To address these various scenarios, a *Self-Configuration Protocol* is employed [5], with the key element being the continual local geographically monitoring of the network state.

Network State Management: In order to monitor the network for impairments and malfunctions, it is crucial to maintain the state of the network. This state profile can be maintained in both distributed and centralized manners. For this purpose, NSBs are exchanged amongst the PNs throughout the network at the F_E rate. The exchange of NSBs between neighbouring PNs defines the local state of the network at each cluster in terms of network load, remaining energy, remaining life of the PN and the PN availability. The rate of exchange and method of propagation of NSBs are the key factors in defining the nature, time and effectiveness of any proactive action. The following section discusses these two factors in presenting a model that achieves superior performance in terms of more effective energy consumption and reliable data transmission.

III. Beacon Propagation and Exchange Rate

A. Beacon Propagation

NSBs are exchanged by the neighbouring PNs in the whole network to maintain the state. As stated earlier, network state can be maintained either centrally or in a distributed fashion.

For central network monitoring, the NSBs from each cluster head must be propagated to the CCI and the rate of exchange should also be global and communicated to each cluster head. Fig. 1A illustrates the centralized propagation scheme. For connected networks, it is possible to declare a PN from within the network as a head node to minimize the long range

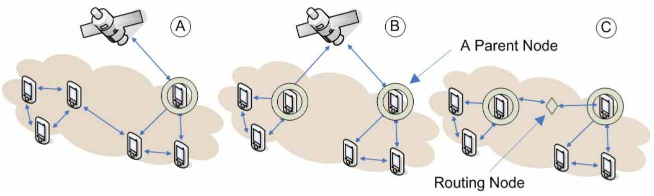

Fig. 1. A: For connected networks, in-network routing (GEAR) is employed for beacon and F_E propagation with one PN acting as gateway to external world, B: Partially connected networks employ Hybrid interconnectivity for maintaining the state and F_E centrally, C: Decentralized architecture lets clusters maintain the state and F_E locally

communication with CCI to one PN only to maintain the network state centrally. This head node also works as a gateway of the PN network to external world. The head PN periodically sends aggregated state information to CCI and takes input from the CCI for what F_E should be maintained and which reconfiguration is to be undertaken. This information is routed throughout the network by adopting one of geography-based ad hoc routing strategies. For this purpose, the GEAR [7] protocol is employed which is a recursive data dissemination protocol for wireless sensor networks. GEAR is selected for F_E propagation because of its proven performance in highly dense wireless sensor networks, while consuming minimum energy. Fig. 1B illustrates partially connected and a centralized network state management scheme in which a *hybrid* interconnectivity approach is employed, with each cluster headed by a PN which in turn connects to the CCI for sending NSBs and receiving F_E updates.

The inherent decentralized structure and high density of USNs reduces the importance of CCI for steady state operation and reconfiguration of the network. Fig. 1C illustrates decentralized clusters, with each cluster headed by a PN and each cluster maintains its local state and own F_E tuned to the requirements of that cluster. Subsection III-B details F_E selection and updating methodology. This distributed state management scheme prevents the need to have inter-cluster communication for NSB propagation, except appointing Associate Parent Nodes (APNs) [5]. These APNs are routing nodes for multi-hop linking between clusters, thereby forming a connected network within a decentralized one. Under steady state situations, these links remain inactive and clusters keep their operations isolated from each others, except mobile source localization and surrogate tracking. This idea of cluster activity optimization in isolation is based on decentralized and self configuring pheromone based communication in ants and termites while they locate food sources or build-up meters high mounds [8]. Simulations in Section IV show the comparative performance of the different propagation techniques discussed above in terms of their impact on network life and data transmission reliability.

Since the cluster heads define the backbone of the network and their life is crucial to the overall life of the network, in this work, the role of cluster head is randomly rotated among all cluster nodes to ensure the network energy resources drain evenly thereby protecting the network from experiencing non-uniform impairments. To assign nodes to the cluster heads in an energy efficient way, the usual minimum transmission power criterion is not employed because of its excessive communication and processing overheads. Instead, the node assignment is optimized to maximize the lifetime of the entire network [2], which is given by:

$$L_s = \sum_{i \in S_c} L_i \tag{1}$$

where L_s is the network life time for a given energy for all clusters; S_c is the set of cluster heads while L_i is the lifetime of a single cluster head, defined by:-

$$L_i = E_i[\alpha c_i + f(n_i)]^{-1} \quad (2)$$

where E_i is the initial energy available at cluster head i and the two denominator terms respectively represent the power consumption contributions due to the output transmit power and cluster-head transmitting/receiving activity.

B. Beacon Exchange Rate (F_E)

The random beacon exchange rate [4] does not reflect the true state of the network. The selection of the exchange rate based on the load profiles of the clusters provides a better picture. This profile can be established either centrally or in a distributed fashion. The rationale is to keep tuning the exchange rate throughout the network with respect to the level of network activity. If the network undergoes a high load scenario, the energy profiles of PNs will degrade quickly. In this situation, the network state is highly dynamic and beacons must be exchanged more frequently, but at a rate that consumes the least additional energy by optimally adapting to new load profile of the network and maintaining the actual state of the network across all clusters.

In calculating the rate F_E two bounds need to be set, the lower being defined by the minimum rate with which the NSBs must be exchanged to maintain the network state even in the case of significantly lower network load. The upper bound limits the maximum value of F_E, exceeding which places extra load on the network due to very frequent NSB exchanges and, actually may result in redundant NSBs being observed and propagated [4]. The total load on the network for higher bound of F_E is:

$$\eta = U_{Total} + \left[\frac{T_f - T_i}{F_{E\max}}\right]\bar{U} \qquad \text{where} \qquad U_{Total} = \int_{t=T_i}^{T_f} \sum_{i=0}^{F_n} U_{it} \quad (3)$$

where U_{Total} is the total load on the network within a given time interval $\{T_i, T_f\}$; U_{it} is the load on PN i at time t, $\bar{U}$ is the extra load caused by one proactivity, F_n is number of clusters and η is the total load on the network, including the load caused by proactivity, at time T_f. The second term in (3) is the load caused in this interval by proactive activities. Given the extra load (U_x) policy factor k, η defines the upper bound of F_E satisfying:-

$$\eta \le \left(1 + \frac{k}{100}\right) U_{Total} \quad (4)$$

i.e. $F_{E\max}$ must maintain η within the allowed extra $k\%$ load.

The relationship between the lower bound ($F_{E\min}$) and minimum required update resolution (T_R) is given by:

$$F_{E\min} \le T_R \quad (5)$$

However, if $F_{E\min} << T_R$, then redundant NSBs may be propagated, resulting in significant overhead proactivity actions. Conversely, if $F_{E\min}$ is greater than T_R, the NSB propagation will be less frequent than required so there is a probability that at times the network will be *under-stated*, a condition where the actual picture of current network state is not available. To avoid these two extremes of *redundancy* and *under-stateness*, $F_{E\min}$ needs to be optimized. Consider the following relationship:

$$d = T_R - F_{E\min} \quad (6)$$

The optimal lower bound of F_E must be as close to T_R as possible so it minimizes the lower bound optimization factor $|d|$. This operational zone describes the optimal range for the selection of lower bound that would keep network state safely normal thereby avoiding the two extreme conditions. The relationship between the network state (δ) and lower bound optimization factor (d) is given by:

$$\delta \,\square\, d^3 (p)^{-1} \quad (7)$$

where p is a tuning factor, whose value depends upon the resolution of updating (T_R). The operational zone is defined by:

$$-2d \le \delta \le 2d \quad (8)$$

Fixing the upper and lower bounds of F_E is greatly influenced by two design parameters, namely the extra allowable network load U_x and the network state update resolution T_R, which are conditionally dependant on each other. This dependency states that for a particular U_x there is a minimum T_R, and vice versa, beyond which the update resolution starts placing an additional load on the network than that permitted. To numerically define this relationship, the extra load W introduced by F_{Emin} is given by:

$$W = \left[\frac{T_f - T_i}{F_{E\min}}\right]\bar{U} = \left[\frac{T_f - T_i}{T_R}\right]\bar{U} \quad for \quad F_{E\min} = T_R \quad (9)$$

In order to conform to the design-policy:

$$W \le .01k * U_{Total} \quad (10)$$

$$\Rightarrow \; k \ge .01W * (U_{Total})^{-1} \;\Rightarrow\; k_{\min} = .01W * (U_{Total})^{-1} \quad (11)$$

Equation (11) defines the minimum value of k that can be used while allocating the extra load for a particular update resolution T_R. Conversely the maximum value of k is not linearly dependant on the update resolution, but rather it is defined by the required lifetime of the network. From (2), the new lifetime of a single cluster head, after incorporating proactive activities is given by:

$$L_i = E_i(\alpha c_i + f(n_i) + p(W_i))^{-1} \quad (12)$$

where the term $p(W_i)$ represents the contribution to power consumption due to extra load introduced by cluster head i for proactive activities. From (10), if:

$$W = .01K_{max} * U_{Total} \quad (13)$$

then $k_{\max}$ should be selected so that $L_s \ge L_{REQ}$ with L_{REQ} as the required life of the network chosen by the network designer.

Having defined the exchange rate bounds, F_E is initially selected ($F_{E(t)}$ for t = 0) to be equal to the lower bound ($F_{E\min}$) and is updated dynamically according to the changes in the load profile of the network. This rate is then periodically updated to $F_{E(t+1)}$ using the following linear stochastic feedforward process:

$$F_{E(t+1)} = F_{E(t)}(1 + .01\lambda) \quad (14)$$

where λ is the parameter used to update the current exchange rate depending upon the change in load profile of the network, which is given by:

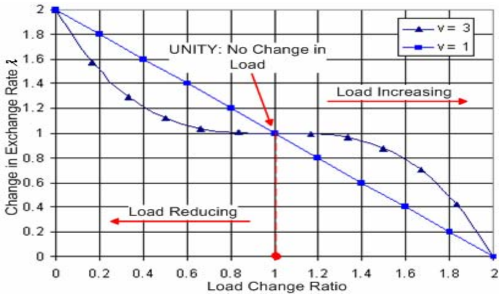

Fig. 2. Beacon Exchange Rate change induction curves defined by '*v*'

$$\lambda = 1 - \left[\frac{U_{Total(t)}}{U_{Total(t-1)}} - 1 \right]^{v} \tag{15}$$

v defines a series of curves that plot changes in F_E for unit changes in load, two examples of which are shown in Fig. 2, where the *Load Change Ratio* (LCR) is the ratio of the current load to the previous load. For *v*=1, the plot is linear which induces an inverse change in λ as the load changes, while for higher *v* values, the curve takes on the shape of a logistic change, which leads to better network performance due to a lower synchronization requirement amongst the PNs supported by less frequent changes in λ. This is clear from Fig. 2, where for *v*=3 the only notable change in λ occurs when the average load deviates significantly from *unity,* that is when LCR=1 so the current and previous loads are the same. An important design aspect is that for a particular load, the logistic change in λ only supports load changes by a factor of two. For other changes, the curve becomes linear and changes in λ are induced equivalent to the changes in load, until the logistic curve is again applied at some point on the network load prevailing at that time.

C. Implementation Method

F_E selection and tuning model defined by the boundary equations (3)—(6) and update equations (14) and (15) is implemented in both centralized (Fig. 1A, 1B) and distributed (Fig. 1C) fashion. In case of centralized control, the CCI governs the calculation of F_E which is then communicated to the cluster heads for implementation. Also the cluster heads send the updates on network state to CCI and, in response, receive necessary reconfiguration instructions. The load parameter in the equations would refer to the total load on the network while the life would be defined as the sum of the lives of all cluster heads. When the model is decentralized, the clusters behave as autonomous network regions and calculation of F_E is devolved at cluster head level. Also the state of the network is managed locally and communicated to other clusters only in the case of anomalies through routing nodes. This methodology makes the structure self-sufficient in its operation not depending upon external communication infrastructures (such as CCI) for F_E tuning and reconfiguration. Simulation results in the following section further quantify these arguments and provide a performance comparison of the model.

IV. SIMULATIONS

Simulations were carried out to evaluate the performance of the network with F_E selection and communication model implemented in both centralized (CF_E) and distributed (DF_E) ways for different load profiles and PN malfunctions. Table I details the complete simulation environment parameters. Network Throughput, Overhead Control Traffic and Synchronization Maps were used to analyse the performance of the system under various environmental parameters. These metrics are defined in the following paragraphs:

- *Throughput*– It is defined as:

  $$Throughput = \frac{EnergyConsumed}{PacketLoss + c}$$

  where $c=0.01$ is a constant chosen to avoid division by zero. This metric is calculated in order to quantify the benefit of proactivity at the cost of extra energy consumption.
- *Control Overhead*– The number of control packets generated over the life of the network. Since the amount of control traffic, generated by our model, is defined by the λ curves, this metric compares the performance of employing different curves for different load profiles in terms of minimization of overhead traffic.
- *Synchronization Map*– A two dimensional graphical interpretation of instants (and F_E maintained) when the NSBs are exchanged to synchronize the network state information across the PNs in the backbone. The map helps to analyse graphically the cause of lesser overhead traffic generated by a particular λ curve. This helps in the selection of a particular F_E update method (value of v) for a specific load profile.

The following subsections analyse each of these performance metrics in detail.

A. Network Throughput

Fig. 3 shows the aggregate energy drainage profile of the PNs, which reveals a minimum increase of up to 10-15% in the energy consumption for Hybrid technique over the no-F_E technique. Fig. 4 illustrates that proactivity improved overall throughput for all types of beacon exchanges, with the Hybrid method maintaining the best QoS for an additional 25% of the network operation time compared to the no-F_E scenario.

Comparing graphs A and B, it is evident that a higher F_E

TABLE IV. SIMULATION ENVIRONMENT PARAMETERS

Attribute	Value			
Area under Surveillance	Open irregular terrains of dimensions 25000m²			
Deployment Topology	Random for both PS & PN nodes			
CH Comm. Range (m)	50-450			
Density of PS nodes	200-500			
Density of PN nodes	30-50			
F_E Implementation	No, Centralized, Distributed			
Sampling Rate	5 Sec			
Control Packet Size	2 Kbits			
Network Activity Time (mins)	80 Sequential experiments, 900-1800 seconds time for each run			
Power Consumption (mW)	Tx	Rx	Idle	Sleep
	14.88	12.50	12.36	0.016

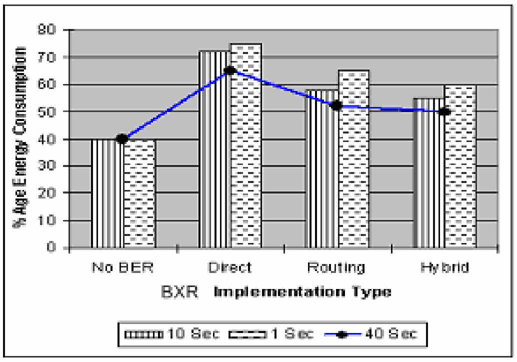

Fig. 3. Energy consumption profile for implementation methods of F_E

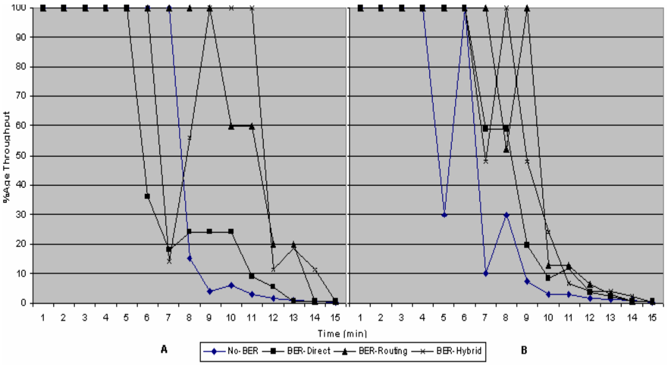

Fig. 4. Comparison of throughput for various implementation methods of F_E for (A): 10 Sec F_E, (B): 40 Sec F_E

value leads to less energy consumption but also less confidence in maintaining QoS for a longer time period, so mandating proper selection of F_E within the bounds. Also the unstable throughput in the case of large F_E in Fig. 4B shows the *understated* condition where the value of F_E fails to keep the network state updated so proactive action of the model is unable to counter possible impairments in time.

B. *Control Overhead*

To quantify the impact of the λ curves on the overhead control traffic required for maintaining the network state across all PNs, the network was tested under various load profiles, with Fig. 5A showing increasing, normal and random load profiles applied on the network. From earlier theory, the logistic change in F_E was developed to support only network load changes by a factor of two. It was anticipated that for random load changes, the straight line (v = 1) would perform better, and this is borne out in Fig. 5B where by inducing an equivalent change in F_E as the load changes keeps the network well informed about the network

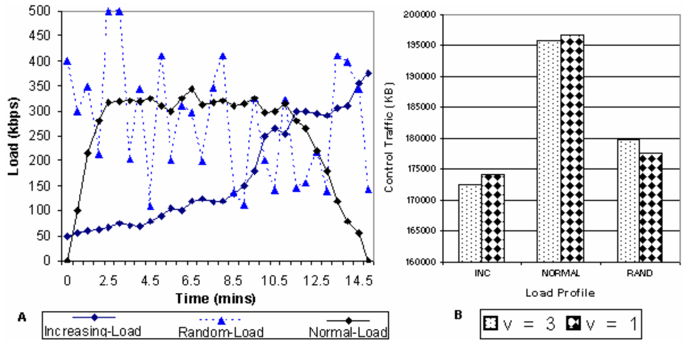

Fig. 5 (A): Increasing, Normal and Random Loads applied on the network to test the comparative performance of lambda curves, (B): Amount of control traffic generated by various load profiles for different λ curves

state, with lower control traffic than that of the logistic change. Conversely, when the network load underwent smooth changes from start to finish, it was found that inducing logistic change helped conserve bandwidth by minimizing control traffic as observed in the increasing and normal load profiles in Fig. 5B.

The reason for the improved performance of the logistic curve is found to be that for increasing and normal load profiles, the logistic curve updates exchange rate at a higher value (i.e. lower beacon exchange rate) earlier than the straight line. This earlier updating reduces traffic and conserves overall network bandwidth. Similar trends are observed in the case of random loads where the straight line performed better. It was found that the straight line established higher F_X values quicker than the logistic curve which also reduced network traffic more quickly and for a longer period, making it suitable for random load situations.

C. *Synchronization Maps*

To investigate the superior performance in different load situations of one λ curve over the other, an analysis of the exchange rates that are maintained by the two curves throughout the operation of network was performed. Fig. 6 shows the synchronization maps for the curves v = 1 and v = 3, for the load profiles in Fig. 6A. Each map shows the actual F_E maintained on the horizontal axis, while the vertical bars show the time instant when these rates are synchronized between all PNs. Examining the maps for increasing and normal load profiles, it is observed that the logistic curve updates the exchange rate to a higher value, which means both earlier and less frequent exchanges of beacons, than the straight line. This earlier update reduces traffic and conserves overall bandwidth. A similar occurrence was observed in the case of random load where the straight line performed better

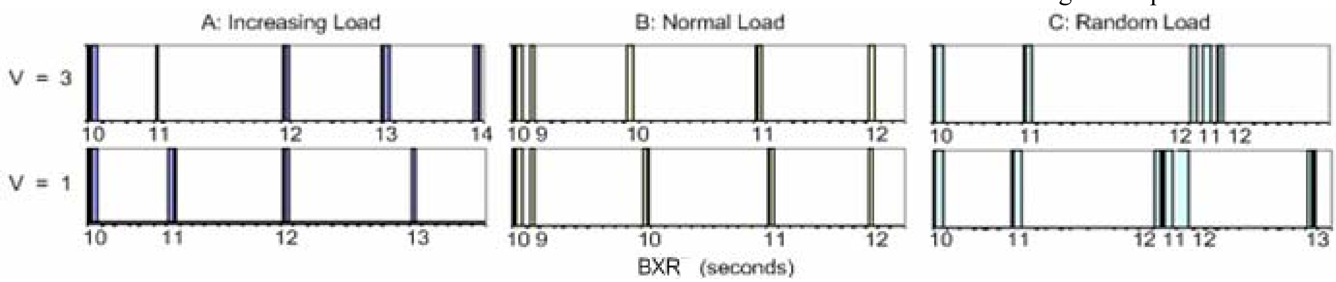

Fig. 6 Synchronization Maps for the two λ curves when applied on *increasing*, *normal* and *random* load profiles. The numbers on the horizontal axis are the actual F_E (in seconds) maintained by the two curves for an active network

(Fig. 6B), while the map in Fig. 6C shows that the straight line establishes higher F_E values earlier than the logistic curve, so reducing network traffic sooner and for a longer period of time making it suitable for random load situations. Another observation relates to the increased control traffic in the case of normal load. The synchronization maps of Fig. 6B reveal that this is due to the curves maintaining the exchange rate closer to the initial rate posing a requirement of tuning the initial F_E within the lower and upper bounds defined previously.

V. Conclusions

This paper has presented a new *beacon exchange rate* selection and tuning technique for centralized and distributed load based methods. Both analytical and simulation results have shown that adapting the F_X according to the load variations provided a significant performance improvement in terms of network throughput, that helped in proactively handling network malfunctions, including node failure and overload. The results also confirmed the model's stability in terms of inducing logistic changes in F_E for a normal network load profile which adapts to load changes in such a way that network synchronization requests are minimized. The proposed model was found to be very robust with more than 70% of component devices observed connected through development of multi-hop routes in a sensor network.

References

[1] H. Gupta, S.D., Q. Gu. *"Connected Sensor Cover: Self-Organization of Sensor Networks for Efficient Query Execution"*. in *ACM,MobiHoc*. 2003.

[2] C.F. Chiasserini, I.C., P. Monti, A. Nucci, *"An Energy efficient method for nodes assignment in cluster-based ad hoc networks"*. ACM/Kluwer Wireless Networks Journal, 2003.

[3] A. Cerpa, D.E. *"ASCENT: adaptive self-configuring sensor networks topologies"*. in *IEEE INFOCOM*. 2002.

[4] M. Iqbal, I.G., L. Dooley. *"Optimizing the Beacon Exchange Rate for Proactive Autonomic Configuration in Ubiquitous MANETs"*. in *Proc of IFIP International Conference on Wireless and Optical Communications Networks*. Mar 2005. Dubai UAE.

[5] M. Iqbal, I.G., L. Dooley. *"LACON: Localized Autonomic Configuration in Pervasive Sensor Networks"*. in *Proc of IEEE Intelligent Sensors, Sensor Networks and Intelligent Processing Conference*. Dec 2004. Melbourne Australia.

[6] M. Iqbal, I.G., L. Dooley. *"Investigating the Dynamics of Pervasive Sensor Networks through Parent Localization"*. in *Proc of Australian Telecommunication Networks and Applications Conference*. Dec 2004.

[7] Y. Yu, R.G., D. Estrin. *"Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks"*. in *UCLA Computer Science Department Technical Report*. May 2001.

[8] Camazine, S., *"Self-organization in Biological Systems"*. 2001: Princeton, N.J. Princeton University Press.