Autonomic and Load-Adaptive Optimization of Beacon Exchange Rate for Proactive Configuration in Ubiquitous MANETs

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ABSTRACT

Proactive self-configuration is indispensable for MANETs like Ubiquitous Sensor Networks (USNs), as component devices of the network are usually exposed to natural or man-made disasters due to the hostile deployment and ad hoc nature of the USNs. Network State Beacons (NSBs) are exchanged among the key nodes of the network for crucial and effective monitoring of the network for steady state operation. The Rate of Beacon Exchange (F_E) and its contents, define the time and nature of the proactive action. Therefore it is very important to optimize these parameters to tune the functional response of the USN. This paper presents a novel F_E selection model based on autonomic, load-adaptive optimization of beacon exchange rate for monitoring and proactively reconfiguring the network. The results confirm the improved throughput while maintaining QoS with a little overhead control traffic.

Keywords- *Ad-hoc Wireless Sensor Networks, Proactive Self Configuration, Adaptive Optimization, Quality of Service*

I. INTRODUCTION

Ubiquitous Sensor Network (USN) is a special type of MANETs, comprising mostly low cost Pervasive Sensor (PS) nodes with low computation, communication, storage and energy resources. Examples of such devices include Smart Dust, Corner-Cube Retroflector and Motes [1]. Networks comprising hundreds of such nodes are deployed to accomplish highly sophisticated and critical biological, chemical and physical sensing tasks. The critical demands of the USN applications are fault tolerance, longer life, maximum throughput and self configuration etc. Also, optimized energy consumption and bandwidth conservation is crucial for QoS in ubiquitous computing.

In order to satisfy these operational requirements, intermediate nodes, called Parent Nodes (PN), with relatively high resources are used. A PN is responsible for various tasks including in-network data processing, communication delay minimization and routing the PS nodes data to the Central Commanding Infrastructure (CCI). These building blocks of a USN (the PNs) may fail because of many unprecedented local or non-local factors. In order to maintain the QoS of a USN, (which in our case is defined as the lossless information delivery with least control traffic) the PNs can be added or removed from the infrastructure on the fly. Also the unattended nature of USNs demands it to be self monitoring and able to take proactive actions to mitigate the malfunctions before they actually occur.

Proactive network monitoring and reconfiguration requires maintaining the network state across the PNs at optimized instants, with sufficient information for the decision to be taken to mitigate the prospective anomaly. This state is maintained through periodic exchange of Network State Beacons (NSBs) at a particular Beacon Exchange Rate (F_E). The contents of NSBs, the value of F_E and the way it is updated and propagated in the network are three important factors that define the extra load that the network has to bear for supporting the 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, like loss of connectivity due to energy loss. Accurate and timely network state information, including the estimated lives of key nodes and the network load profile, would result in an effective and successful proactive action to mitigate the network impairment. Therefore it is highly important to optimize these factors while considering the current network load, to maximize the throughput and minimize the risk of information loss due to node failures.

Earlier works on the self configuration protocols [8] lack a careful investigation of beacon exchange rate for maintaining network state for supporting QoS for longer term. However, Gupta [2] and Chiasserini [3] have focused on energy-efficient, hierarchical modeling of the sensor network through dynamic configuration of the tree nodes. The success of their dynamic tree models is based on a virtually inappropriate assumption for sensor networks, that a sensor node is capable of connecting to many parent nodes simultaneously. Some researchers like Cerpa [10] emphasized the need for a high degree of synchronization between network components in order to reconfigure correctly. Policy based self managing systems were also considered, but these impose a high computational and storage requirement on the individual sensing units. Extension of an existing network was discussed by Bulusu [4],[6], but this lacked a suitable strategy for self configuration.

This paper describes a proactive fault tolerant and configuration model to deal with the network impairments and also presents optimized bounds for the selection of F_E. A random F_E selection technique (RF_E) for investigating the core effects of proactive mitigation and a load-based F_E selection mechanism (LF_E) are presented to enhance the performance and minimize the overhead traffic.

In the remainder of the paper, Section II describes the underlying USN design and self configuration model, while Section III details F_E optimization aspects. Simulation results highlight the QoS maintainability and reliability of configuration model for various choices of F_E and are presented in Section IV with some conclusions presented in Section V.

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II. SENSOR NETWORK DESIGN & SELF CONFIGURATION MODEL

A. Network Design

Sensor network design is based on the optimal selection of density and locations of Parent Nodes (PNs) in a virtual hexagonal topology as detailed in our earlier work [7]. The design is optimized to achieve the best QoS by; ensuring the availability of PN to a maximum number of PS nodes, minimizing Grey Region (GR) areas (to reduce many-hop routing) and minimizing confusion / conflict zones.

B. Self Configuration Core Protocol

The proposed 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 [8]. During active network operation, the model can deal abnormalities including: a) increased traffic load leading to congestion and packet losses causing loss of information, b) decreased energy resources raising the threat of PN failure, c) sudden failure of a PN due to local or non-local disasters and d) addition of new PNs among others.

To address these various scenarios, a *Self-Configuration Protocol* is employed as described by Iqbal et al [8]. The key element of the protocol is continual geographically localized monitoring of the network state and then taking proactive measures to mitigate operational impairments.

Network State Management: In order to monitor the network for impairments and malfunctions, it is crucial to maintain the state of the network in some fashion. This state can be managed in both distributed and centralized manner. For this purpose, federation beacons (NSBs), are exchanged amongst the PNs throughout the network with periodicity F_E. The exchange of NSBs between neighboring PNs defines the local state of the network at each federation in terms of network load, remaining energy, remaining life of the PN and the PN availability. The following section describes the possibilities and issues in the selection and implementation of F_E, its criticality and its impacts on the overall network performance.

III. BEACON EXCHANGE RATE (BER[1])

We have investigated the impacts of two types of BER selection methods on the network performance and state management; A) Random BER, B) Load-Based BER. The following subsections give a detailed insight into the philosophy, implementation techniques, numerical methods for optimizing these types of FE and the network factors that must be taken into consideration. The comparative performance and impacts of random and load-based rates on proactive mitigation of prospective node failures are discussed with the simulations in Section IV.

A. Random Rate (RF_E)

One possibility is the random beacon exchange rate. The reason for investigating random rate is to find out the core effects of employing NSB exchange on self configuration in general and proactivity in particular.

B. Load Based Rate (LF_E)

A better option is to select the exchange rate according to the situation of the overall average load on network. The idea is to keep on tuning the exchange rate throughout the network operation time with respect to the amount of activity in the network. If the network is undergoing high load situations, the energy profiles of PNs would be degrading much quickly. In this situation, the network state is highly dynamic and beacons must be exchanged more frequently, but at a rate that consumes least amount of extra energy by optimally adapting to new load profile of the network and maintaining the actual state of the network across all PNs.

C. Implementation Method

In the above configuration, NSBs are exchanged by the neighboring PNs in the whole network with intervals selected randomly (RF_E) or depending upon the load (LF_E), during the entire course of network operation. This NSB exchange strategy requires the propagation of the global-exchange-interval throughout the network of PNs so that each PN can synchronize its NSB transmission and reception cycles with the neighbors.

If the network is assumed to be partially connected, a hybrid approach is adopted for interconnectivity of PNs. In this case, the core methodology employed is similar to cluster-based adhoc networks [3]. This technique makes clusters of nodes in the network with each cluster headed by one of the PNs in the cluster. The role of cluster head is randomly rotated among all the nodes in the cluster to ensure that 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 entire network [3] given by:

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

where L_s is the network life time defined as the time period from the start of the network to the instant at which all the cluster-heads run out of energy. S_c is the set of cluster heads while L_i is the life time of a single cluster head, defined by:

$$L_i = \frac{E_i}{\alpha c_i + f(n_i)} \tag{2}$$

where E_i is the initial amount of energy available at cluster head i and the two terms at the denominator represent the contribution to power consumption due to the output transmit power and the cluster-head transmitting/receiving activity, respectively. The cluster heads are either pre-programmed with the F_E or they connect to CCI individually for getting instructions on maintaining a particular exchange rate. To propagate F_E within a cluster, a geography-based adhoc routing strategies, the GEAR [9] protocol, is employed which is a recursive data dissemination protocol for wireless sensor networks. GEAR is selected for F_E propagation because of its

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[1]: BER and F_E are used interchangeably in the text

proven performance for highly dense wireless sensor networks, while consuming minimum energy.

D. Calculation and Optimization of RF_E and LF_E

Calculation of RF_E is not complex, but there are bounds within which this randomly picked rate must lie. The lower bound of this range defines the minimum rate with which the NSBs must be exchanged to maintain the network state even in case of significantly less load on network. On the other side the upper bound of rate puts a limit on the maximum value of F_E, exceeding which would put exceedingly extra load on the network due to very frequent NSB exchanges and, in fact, may result in redundant NSBs being observed and propagated. This rate expressed in seconds is distributed throughout the network by adopting hybrid methodology described in Subsection III-C. Mathematically:

$$F_E = RND(F_{E\min}, F_{E\max}) \quad (3)$$

Where:

F_E is the Beacon Exchange Rate in seconds. Its value states the time interval after which the NSBs will be exchanged. The two other terms $F_{E\min}$ and $F_{E\max}$ are the Lower and Upper bounds of F_E respectively. Fixing the lower and upper bounds of FEB is greatly influenced by two parameters of network design-policy:

Extra Load (U_x): Network overhead load caused by proactivity activities must not exceed k% of the total actual load on the network.

Update Resolution (T_R): The minimum resolution of time by which the updated network state is required should be T_R.

Keeping these parameters in consideration, the upper bound is given by:

$$\eta = U_{Total} + \left[\frac{T_f - T_i}{F_{E\max}}\right]\bar{U} \quad \text{where} \quad U_{Total} = \int_{t=T_i}^{T_f} \sum_{i=0}^{F_n} U_{it} \quad (4)$$

Where U_{it} is the load on PN i at time t and $\bar{U}$ is the extra load caused by proactivity in a unit time. η is the total load on the network, including the load caused by proactivity, after time T_f. U_{Total} in above equation gives total load on the network within the given time interval $\{T_i, T_f\}$. The second term in (4) 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 given by:

$$\eta \le \left(1 + \frac{k}{100}\right) U_{Total} \quad (5)$$

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

The lower bound, defined by the required update resolution (T_R), is given by:

$$F_{E\min} \le T_R \quad (6)$$

I.e. as long as lower bound $F_{E\min}$ is less than T_R, the state of the network is observed at higher resolution than required and therefore this network state will be available in any critical situation. However, if $F_{E\min} << T_R$, it is highly possible that redundant NSBs are propagated, resulting in exceedingly overhead proactivity actions. On the other hand, if $F_{E\min}$ gets greater than the T_R, the NSB propagation will be less frequent than the required and so there is probability that at times the network will be *under-stated*, a state where actual picture of current network state is not available. In order to avoid these two extreme conditions of *redundancy* and *under-stateness*, it is required to optimize $F_{E\min}$. Consider the following relationship:

$$d = T_R - F_{E\min} \quad (7)$$

The optimal lower bound of F_E should be as close to T_R as possible such that $F_{E\min}$ minimizes $|d|$, the lower bound optimization factor.

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. This relationship that ties the network state (δ) to the lower bound optimization factor (d) is given by:

$$\delta \simeq \frac{d^3}{p} \quad (8)$$

where p is a tuning factor and its value depends upon the resolution of updation (T_R). The operational zone is given by:

$$-2d \le \delta \le 2d \quad (9)$$

The two parameters of network design-policy, extra load (U_x) and update resolution (T_R) are conditionally dependant on each other. This conditional dependency states that for a particular U_x, there is a minimum T_R, and for a particular T_R, there is a minimum U_x, beyond which the update resolution starts putting exceedingly extra load on the network than the allowed (k). To numerically define this relationship, the extra load (W) introduced by $F_{E\min}$ is given by:

$$W = \left[\frac{T_f - T_i}{F_{E\min}}\right]\bar{U} = \left[\frac{T_f - T_i}{T_R}\right]\bar{U} \quad for\ F_{E\min} = T_R \quad (10)$$

In order to conform to the design-policy:

$$W \le \frac{k}{100} U_{Total} \quad (11)$$

$$\Rightarrow \quad k \ge \frac{W * 100}{U_{Total}} \qquad \Rightarrow \quad k_{\min} = \frac{W * 100}{U_{Total}} \quad (12)$$

Equation (12) defines the minimum value of k that can be used while allocating the extra load for a particular update resolution (T_R). On the other hand, the maximum value of k is not linearly dependant on update resolution; rather it is defined by the required life time of the network. Recall equation (2) that defines the lifetime of a single cluster head, after incorporating the proactive activities, the new life time is given by:

$$L_i = \frac{E_i}{\alpha c_i + f(n_i) + p(W_i)} \quad (13)$$

where the added term $p(W_i)$ represents the contribution to power consumption due to extra load introduced by cluster head i for proactive activities. Now, from (11), if:

$$W = (U_{Total})(K_{max})/100$$

then $k_{\max}$ should be selected in such a way so that: $L_s \ge L_{REQ}$ where L_{REQ} is the required life of the network and is decided by the network architect.

Load based rate is also bound by the two limits given by (4) and (7). Having defined the bounds, the minimum bound

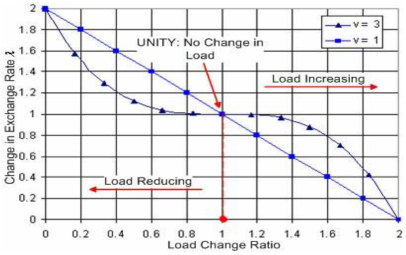

Fig. 1. Beacon Exchange Rate change induction curves defined by '*v*'

($F_{E\min}$) is selected as the initial exchange rate (LF_{Ei}). This rate is then periodically updated to $LF_{E(t+1)}$ using the following linear stochastic feed forward process:

$$LF_{E(t+1)}=LF_E(1+.01\lambda) \tag{14}$$

where λ is the process that updates the current exchange rate depending upon the change in the load profile of the network. It is given by:

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

'*v*' defines the curve that induces a change in exchange rate with a unit change in load as shown in Fig. 1. Here, Load Change Ratio (LCR) is the ratio of the current load to the previous load. It is evident that the amount of change in LF_E (λ) depends upon the value of '*v*'. For *v*=1, the curve, which is a straight line induces an equivalent inverse change in λ as the load changes, while for higher values of '*v*', the curve takes the shape of a logistic change. This logistic change resulted in better performance of the network, which when investigated, turned out to be due to lesser synchronization requirements among the PNs supported by less frequent changes in λ. This fact is clear from the curve for *v*=3, that a notable change in λ occurs only when the average load deviates significantly from the *unity* (i.e. LCR=1 where current load is same as the previous load). An important design aspect here is that for a particular load, this logistic change in λ is only supported for a load change by a factor of two, whether increasing or decreasing. For changes beyond this factor, the curve takes the shape of a straight line as for *v*=1 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.

IV. SIMULATION RESULTS

Simulations were carried out to evaluate the performance of network when beacon exchange is applied with different load profiles and PN malfunctions. TABLE I describes the simulation environment parameters. Packet Loss, Overhead Control Traffic and Network Integrity were used as QoS performance metrics for 10 to 40 seconds RF_E and various load profiles for LF_E.

TABLE I: SIMULATION ENVIRONMENT PARAMETERS

Attribute	Value			
Area under Surveillance	Open irregular Terrains of near 25000m² dimensions			
Deployment Topology	Random for both PS & PN nodes			
PS Comm. Range	3m			
PN Comm. Range	3m-13m			
Density of PS nodes	125-143 Randomly Deployed			
Density of PN nodes	25-30			
Mobility	Stationary PNs & Mobile PS nodes			
F_E Implementation	Random, Load Based			
QoS Metrics	Packet Loss, Overhead Control Traffic, Network Integrity			
Control Packet Size	500bytes			
Network Activity Time	15 min			
Power Consumption (mW)	Tx	Rx	Idle	Sleep
	14.88	12.50	12.36	0.016

A. Packet Loss

Fig. 2 illustrates packet losses due to randomly failing nodes in the network for the RF_E, LF_E and no-F_E strategy. Overall observation indicates that there is a savings of up to 65% in the packet losses due to failing nodes in case of incorporating beacon exchange for network state management as compared to without F_E strategy. Out of the two types of beacon exchange, the random (RF_E) and the load based (LF_E), the latter performed better than the former and resulted in 5% more savings in packet loss as a whole. Since $LF_{E(i)}$ was taken to be 10sec, the performance of RF_E with 10sec rate was found quite similar to load based exchange initially but declined at latter stages due to LF_E adapting to the load profile of the network.

Comparing 10sec and 40sec RF_E graphs in Fig. 2, it is revealed that as the F_E value increases, the network state is maintained less frequently which leads to a serious increase in packet loss. This phenomenon testifies our arguments for optimizing the bounds of F_E. Moreover, the smoother transition of the LF_E curve illustrates a better optimized proactive action of the self configuration model that protects the network from facing unprecedented losses and arranges a solution to the malfunctions beforehand. The graphs also show a very important impact of F_E on the life time of the network; the network life is reduced in all F_E types as compared with the No-BER. The result is as expected, but the point to be focused is the trade-off of life with the reliability of data transmission. In case of LF_E and RF_E, the network life is reduced from 15 to 14 and 13 minutes respectively, but the confidence of data transmission is leveraged up to 70%, which is indeed, a worth trade with the network life.

B. Network Integrity

Fig. 3 shows the effects of PN failure on overall connectivity of PS nodes in the network. The PNs were triggered to die randomly one after the other. The effect on sensor-parent connectivity was analyzed for both situations when self-

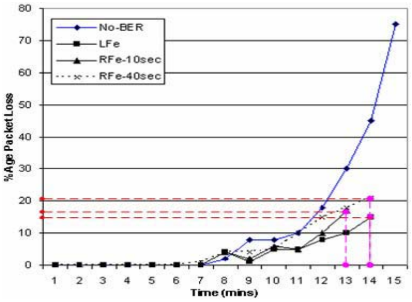

Fig. 2. Comparison of Average Packet Loss for RF_E, LF_E and no Beacon Exchange

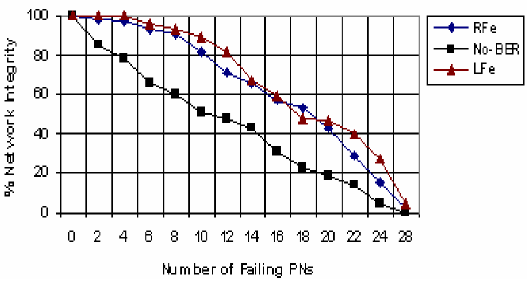

Fig. 3 Effect of Parent Node Failure on Network Integrity

configuration was active with LF_E and RF_E and when it was held inactive. The graph confirms that network could capture nearly 70% of network traffic through proactively reconfiguring connections through routing nodes, even when half of the PNs failed. Moreover LF_E stood 5 to 10 percent higher in keeping the network integrated from RF_E due to its savings in overhead control traffic which helps PNs sustain longer than they could in case of RF_E.

C. *Control Overhead*

In order to quantify the impacts of the two λ curves, introduced in subsection III-D, on the overhead control traffic required for maintaining the network state across all PNs, the network was put to performance test under different load profiles. Fig. 4A shows two normal and one random load profiles applied on the network. From the theoretical basis developed earlier, the logistic change in LF_E was developed to support only as far as the network load changes by a factor of two, it was expected that for random load, oscillating between high and low load conditions, the straight line curve (v = 1) would perform better. This was found true as shown in Fig. 4B that inducing an equivalent change in LF_E as the load changes randomly keeps the network well informed about the network state with quite few control traffic than that of the logistic change. On the other side, when the network load undergoes smooth changes from start to end and takes a normal curve shape, inducing logistic change helps more since it induces less frequent changes in exchange rate thereby initiating fewer synchronization cycles. This fact was observed for two different normal load profiles, one with quite higher load than the other one as shown in Fig 4B.

V. CONCLUSIONS

This paper has presented beacon exchange rate optimization technique for random and load based methods of beacon propagation. The numerical as well as simulation results have shown that the optimization of F_E is a significant improvement over the proactive self configuration protocol to deal with various malfunctions and abnormalities in USNs including node failure and node overloading. Results and analysis indicate that the most critical aspect of network design based on such proactive self-configuration model is the selection of F_E. For this purpose, numerical bounds on the maximum and minimum values of F_E were presented. This operational zone for the selection of F_E, eliminates/reduces the risk of getting into *Redundancy* or *Understate* situations. The simulations have demonstrated that incorporation of beacon exchange has provided a trade off between the network life and reliable data transmission.

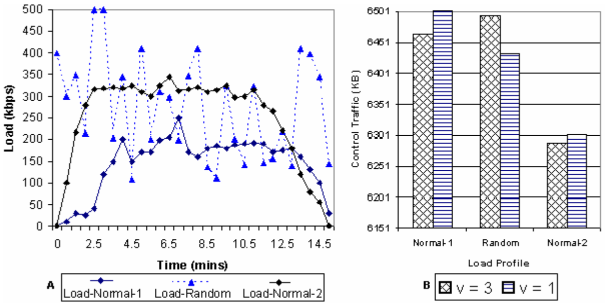

Fig. 4 (A): Normal and Random Loads applied on the network to test the comparative performance of lambda curves, (B): Amount of control traffic generated by various load profiles for different λ curves

Out of two types of F_E, load based technique has shown promising results while putting lesser overhead control traffic on the network and providing over 65% savings in packet losses. Also the results have confirmed the continuing stability of the model in terms of inducing logistic change in LF_E (v = 3) for normal network load profile which adapts to load changes in such a way that network synchronization requests are minimized. On the other side, for oscillating load situations, the equivalent LF_E change methodology (v = 1) suits better since it equivalently responds to the drastic changes in the network. The proposed model is found robust as more than 70% of component devices are observed connected through development of multi hop routes in the USN, thereby keeping the communication integrated, even when half of the PNs failed to work. This implies that the model keeps maximum components connected to the network in case of node failures and failovers with smooth degradation of performance.

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