Load-Balanced Clustering of Wireless Sensor Networks

Gaurav Gupta
Dept. of Computer Science and Elec. Eng.
University of Maryland Baltimore County
Baltimore, MD 21250
gagupta1@cs.umbc.edu

Mohamed Younis
Dept. of Computer Science and Elec. Eng.
University of Maryland Baltimore County
Baltimore, MD 21250
younis@cs.umbc.edu

Abstract- Wireless sensor networks have potential to monitor environments for both military and civil applications. Due to inhospitable conditions these sensors are not always deployed uniformly in the area of interest. Since sensors are generally constrained in on-board energy supply, efficient management of the network is crucial to extend the life of the sensors. Sensors' energy cannot support long haul communication to reach a remote command site and thus requires many levels of hops or a gateway to forward the data on behalf of the sensor. In this paper we propose an algorithm to network these sensors in to well define clusters with less-energy-constrained gateway nodes acting as cluster-heads, and balance load among these gateways. Simulation results show how our approach can balance the load and improve the lifetime of the system.

1. Introduction

Information gathering is a fast growing and challenging field in today's world of computing. Sensors provide a cheap and easy solution to these applications especially in the inhospitable and low-maintenance areas where conventional approaches prove to be very costly. Sensors are tiny devices that are capable of gathering physical information like heat, light or motion of an object or environment. Sensors are deployed in an ad-hoc manner in the area of interest to monitor events and gather data about the environment. Networking of these unattended sensors is expected to have significant impact on the efficiency of many military and civil applications, such as combat field surveillance, security and disaster management. Sensors in such systems are typically disposable and expected to last until their energy drains. Therefore, energy is a very scarce resource for such sensor systems and has to be managed wisely in order to extend the life of the sensors for the duration of a particular mission.

Typically sensor networks follow the model of a base station or Command node, where sensors relay streams of data to the command node either periodically or based on events. The command node can be statically located in the vicinity of the sensors or it can be mobile so that it can move around the sensors and collect data. In either case, the command node cannot be reached efficiently by all the sensors in the system. The nodes that are located far away from the command node will consume more energy to transmit data then other nodes and therefore will die sooner. In order to conserve energy to communicate with the command node various multi-hop and energy aware routing techniques have been suggested in the literature [4,5]. These techniques have overhead due to route discovery and to find optimum hops to communicate with the command node. In addition, there will be extra burden on the nodes, which are located around the command node as most of the traffic will be routed through them. As a result, these nodes will consume energy faster then other nodes and will die sooner.

To avoid these overheads and unbalanced consumption of energy we propose an approach where we have some high-energy nodes called *"Gateways"* deployed in the network. These Gateways, group sensors to form distinct clusters in the system and manage the network in the cluster, perform data fusion to correlate sensor reports and organize sensors by activating a subset relevant to required missions or tasks as shown in Fig 1. Each sensor only belongs to one cluster and communicates with the command node only through the gateway in the cluster.

Similar to other communication networks, scalability is one of the major design's quality attributes for sensor networks. A multi-gateway architecture is required to cover a large area of interest without degrading the service of the system. But, if the sensors and gateways are not uniformly distributed then it can cause few gateways to overload with the increase in sensor density, system missions and detected targets/events. Such overload might cause latency in communication and inadequate tracking of targets or events. In order to avoid such patches of dense clusters we balance the

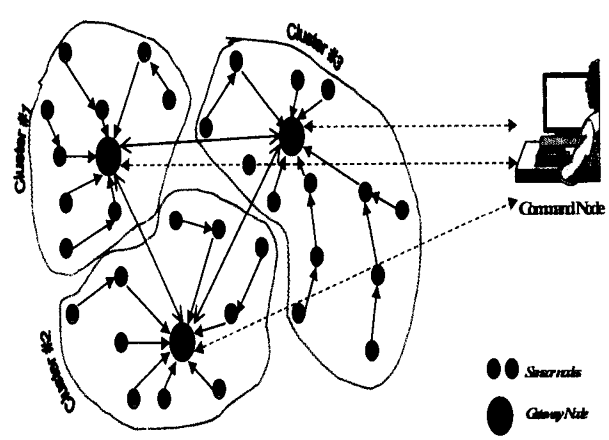

Fig. 1: Multi-gateway clustered sensor network

Moreover these protocols do not consider any balancing of load among clusters. System can have patches of high-density clusters and very low-density clusters. In such scenarios the high-density cluster-head will be overwhelmed with processing and communication load and will consume its energy soon, while the low density cluster-head will sit idle wasting precious time.

4. Load-Balanced Clustering

The main objective of our approach is to cluster sensor network efficiently around few high-energy gateway nodes. Clustering enables network scalability to large number of sensors and extends the life of the network by allowing the sensors to conserve energy through communication with closer nodes and by balancing the load among the gateway nodes. Gateways associate cost to communicate with each sensor in the network. Clusters are formed based on the cost of communication and the load on the gateways.

Network setup is performed in two stages; 'Bootstrapping' and 'Clustering'. In the bootstrapping phase, gateways discover the nodes that are located within their communication range. Gateways broadcast a message indicating the start of clustering. We assume that receivers of sensors are open throughout the clustering process. Each gateway starts the clustering at a different instance of time in order to avoid collisions. In reply the sensors also broadcast a message with their maximum transmission power indicating their location and energy reserve in this message. Each node discovered in this phase is included in a range set per gateway.

In the clustering phase, gateways calculate the cost of communication, with each node in the range set. This information is then exchanged between all the gateways. After receiving the data from all the other gateways each gateway start clustering nodes based on the communication cost and the current load on its cluster. When the clustering is over, all the sensors are informed about the ID of the cluster they belong to. Since gateways share the common information during clustering, each sensor belongs to only one cluster. For inter-cluster communication all the traffic is routed through the gateways.

4. 1 Problem Formulation

Each gateway constructs a range set of all the nodes that can communicate with it. A sensor 'S_j' belongs to range set 'RSet' of gateway 'G_i' if it satisfies the following criteria:

$$S_j \in RSet_{Gi} \Leftrightarrow [(R_{Gi} > d_{Sj\text{->}Gi}) \wedge (R_{Sj,max} > d_{Sj\text{-->}Gi})]$$

Where, R_{Gi} is the range of gateway G_i, $R_{Sj,max}$ is the maximum range of sensor S_j and $d_{Sj\text{->}Gi}$ is the distance between sensor S_j and Gateway G_i. Each node in the range set is associated with a communication cost calculated as a function of communication energy dissipated in transferring 'r' bits of data over a $d_{Sj\text{->}Gi}$ distance. Using the energy model described in section 2.1, the cost '$C_{j,Gi}$' calculated by gateway G_i is:

$$C_{j,Gi} = E_{tx} + E_{rx} = (\alpha_t + \alpha_{amp} (d_{Sj\text{-->}Gi})^2) * r + \alpha_r * r$$

A per cluster record is created with all the nodes in *RSet* and their associated cost. The record is exchanged by all the gateways to gain global knowledge of the network. Depending on the range of the sensors there can be two kinds of nodes in the system: the first can only communicate with one gateway, 'exclusive nodes' and the second can communicate with more then one gateway. The reach of a node is defined as the number of gateways it can communicate with. The first step towards clustering is to separate exclusive nodes from the rest, because these are compulsory nodes to be accommodated by a gateway. To do so, gateways construct another set called exclusive set 'ESet' which consists of nodes that can satisfy the following criteria:

$$S_j \in ESet_{Gi} \Leftrightarrow [(S_j \in RSet_{Gi}) \wedge (\forall k \neq i,\ S_j \notin RSet_{Gk})]$$

The load on a gateway is defined as a function of processing load 'PL_{Gi}' and communication load 'CE_{Gi}' in the cluster:

$$L_{Gi} = f(PL_{Gi}, CE_{Gi})$$

Processing load on a gateway is due to processing the data from the sensors and energy consumed in doing so. Communication energy, 'CE_{Gi}' of a gateway is calculated to be the summation of the communication cost of all sensors in the cluster. That is,

$$CE_{Gi} = \sum_{j=0}^{n} C_{j,i}$$

Since, we assume that all sensors are identical and produce data at the same rate, PL_{Gi} of a gateway is directly proportional to the number of sensors 'n' in the cluster. It implies that, to balance load in the system we have to balance the number of nodes in a cluster and the communication energy required per gateway. In order to keep the system close to the average load, we choose an objective function that minimizes the variance of the cardinality of each cluster in the system. That is,

$$\sigma^2 = \frac{1}{G} \sum_{i=0}^{G} (X - X')$$

Where 'σ^2' is the variance of load in the system, X is cardinality of gateway G_i and X' is the average cardinality including the node under consideration, G is the total number of gateways in the system.

4.2 Optimization Heuristics

Before minimizing the objective function we allocate the nodes in the *ESet* to their respective clusters and calculate the load. If we allocate the remaining nodes to the clusters only by minimizing the objective function we experience large overlapping of clusters. Considering only the load on gateways as a factor for clustering might do so at the expense of sensors. Our experiments also show that some sensors are not part of the gateways nearest to them. This will increase the communication energy of the sensors.

Exhaustive search methods like simulated annealing can be used to find the optimum results to balance the load as well as maintain the minimum distance with the gateway. But by using these methods the complexity of the algorithm is deviation in load by varying the number of gateways from 2 to 10 in a fixed 100 nodes network. In order to demonstrate that the load is balanced for any setup we ran the same experiments for 10 different normal distributions. Same experiments are performed with shortest distance clustering and the results are compared with our approach. Variance in load signifies that load is not uniformly distributed among the clusters. Results demonstrate that for all distributions our approach outperforms the shortest distance clustering.

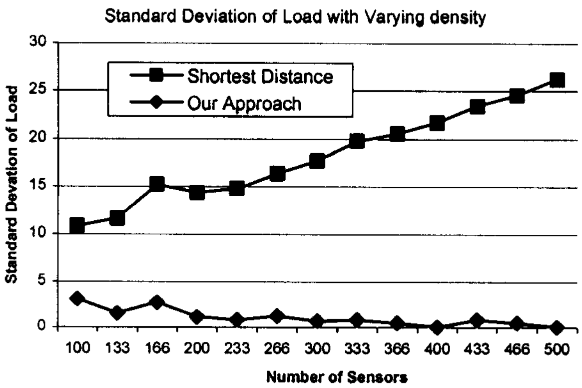

Fig 3. Standard Deviation of Load with increase in sensor's density

To test our system for different sensors densities we measured standard deviation of load by using 5 gateways and increasing the number of sensors in the system from 100 to 500 with uniform increments. The graph shown in Fig 3 clearly indicates that our approach increase the scalability of the system. The performance of our approach remains constant with increase in density. The rising curve of the shortest distance clustering indicates that variance in load is increasing with increase in density. The demonstrated results are based on the normal distribution of sensors.

<u>Average communication energy per cluster</u>: We measure total energy required to communicate between gateway and all the sensors in its cluster. Communication energy is directly proportional to the distance between two nodes (Section 2.1). If clusters are formed based on shortest distance the average energy consumed will be minimal but the load will not be balanced. Sensors clustered by shortest distance method will consume less communication energy in the beginning but will consume more energy later due to overhead of re-clustering. We try to minimize the average communication energy to perform as good as shortest distance algorithm in terms of communication energy. The experimental results, in Fig. 4, show that the performance of shortest distance clustering decreases with the increase in number of clusters.

6. Conclusions and future work:

In this paper we have introduced an approach to cluster unattended wireless sensors about few high-energy gateway nodes and balance load among these clusters. The gateway node acts as a centralized manager to handle the sensors and

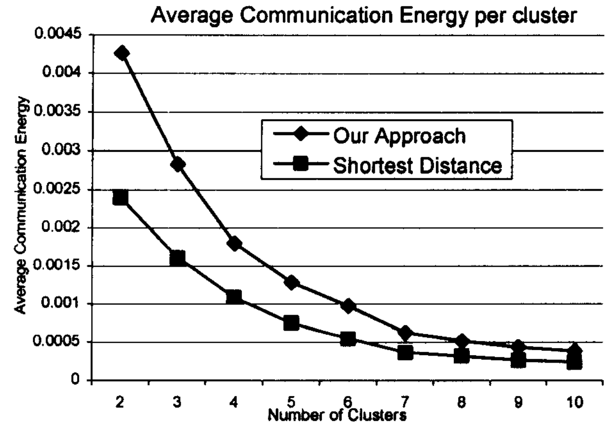

Fig 4. Average Communication Energy/Cluster

serves as a hop to relay data from sensors to a distant command node. If nodes are not uniformly distributed around the gateways the clusters formed will be of varied load, which will effect the lifetime and energy consumption of the system. Simulation results demonstrate that our algorithm consistently balances load among different clusters and performs well in all distributions of nodes. Our future plan includes extending the clustering model to allow gateway mobility. Also, we plan to study different failure scenarios in sensor networks and introduce run-time fault-tolerance in the system.

References

[1] "Data sheet for the Acoustic Ballistic Module", SenTech Inc., http://www.sentech-acoustic.com/

[2] M. Bhardwaj, et. al, "Upper Bounds on the Lifetime of Sensor Networks", In *Proceedings of ICC 2001,* June 2001.

[3] A. Sinha, et al., "Energy Aware Software", Proc. of the 13th Int. Conference on VLSI Design, Calcutta, India. January 2000.

[4] S. Singh, et al., "Power-Aware Routing in Mobile Ad-Hoc Networks", *Proc. of ACM MOBICOM'98,* Dallas, October 1998

[5] D. Estrin, et.al. "Scalable coordination in sensor networks." *Proc. of ACM/IEEE MOBICOM'99,* Seattle, WA,August 1999.

[6] K. Arisha, M. Youssef, M. Younis, "Energy-Aware TDMA-Based MAC for Sensor Networks," *(IMPACCT 2002),* May 2002.

[7] R. Min, et. al, "An Architecture for a Power-Aware Distributed Microsensor Node", *IEEE Workshop on Signal Processing Systems (SiPS '00),* October 2000.

[8] J.M. Kahn, et al., Next century challenges: Mobile networking for 'smart dust', In *Proc. of MOBICOM'99, Seattle, 1999*

[9] A. Cerpa et al. , "ASCENT: Adaptive Self-Configuring Sensor Networks Topologies," *Proc. INFOCOM 2002,* NY, June 2002

[10] W. Rabiner, et. al, "Energy-Efficient Communication Protocols for Wireless Microsensor Networks," *Hawaii International Conference on System Sciences (HICSS '00),* January 2000.

[11] D.J Baker and A. Ephremides, "A Distributed algorithm for Organizing Mobile Radio Telecommunication Networks", in the *Proceedings of the 2nd International Conference in Distributed Computer Systems,* April 1981.

[12] M. Gerla and J.T.C Tsai, "Multicluster, mobile, multimedia radio network," ACM/Baltzer Journal of *Wireless networks,* Vol. 1, No. 3, pp. 255-265, 1995.

[13] B. Chen, et al., "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks", in the *Proc. of the 7th ACM Mobile Computing and Communication (MobiCom 2001),* Rome, Italy, July 2001.