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Energy aware topology control protocols for wireless sensor networks

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ENERGY AWARE TOPOLOGY CONTROL PROTOCOLS FOR WIRELESS SENSOR NETWORKS

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Table of Contents

List of Figures

Abstract

Wireless Sensor Network has emerged as an important technology of the future due to its potential for application across a wide array of domains. The collaborative power of numerous autonomous remote sensing nodes self configured into a multi hop network permits in-depth accurate observation of any physical phenomenon. A stringent set of computational and resource constraints make the design and implementation of sensor networks an arduous task.

The issue of optimizing the limited and often non-renewable energy of sensor nodes due to its direct impact on network lifetime dominates every aspect of wireless sensor networks. Existing techniques for optimizing energy consumption are based on exploiting node redundancy, adaptive radio transmission power and topology control. Topology control protocols significantly impact network lifetime, routing algorithms and connectivity. We classify sensor nodes as strong and weak nodes based on their residual energy and propose a novel topology control protocol (NEC) which extends network lifetime while guarantying minimum connectivity. Extensive simulations in Network-Simulator (*ns*-2) show that our protocol outperforms the existing protocols in terms of various performance metrics.

We further explore the effectiveness of data aggregation paradigm as a solution to the dominant problem of maximizing energy utilization and increasing network bandwidth utilization in sensor networks. We propose a novel energy efficient data aggregation protocol based on the well-known k-Means algorithm. Our protocol achieves energy efficiency by reduced number of data transmissions at each level of a hierarchical sensor network. Our protocol exploits the spatial and temporal coherence between the data sensed by neighboring sensor nodes in a cluster to reduce the number of packet transmissions. Sensor nodes apply k-Means algorithm to the raw data to generate a reduced set of mean values and forward this modified data set to cluster-head nodes. We further prove the

effectiveness of our protocol in providing increased energy conservation in the network by extensive simulation results.

Chapter 1

Introduction

1.1 Motivation

Current research in the areas of wireless communications, micro-electromechanical systems and low power design is progressively leading to the development of cost effective, energy efficient, multifunctional sensor nodes. Sensing, communication, processing and battery units are the primary components of a sensor node. Individual sensors have the capacity to detect events occurring in their area of deployment. A large number of tiny sensor nodes can be organized to form a distributed network where nodes collaborate to perform application specific functions.

Wireless sensor networks have their own set of unique characteristics which make them remarkably different from traditional wired and wireless networks and open up new avenues of interesting applications in real life. Some of the most popular application of sensor networks are environmental monitoring, smart spaces, surveillance, security, military, medical systems and disaster management. The key features of wireless sensor networks which make a wide array of real life applications feasible are as follows:

1. Tiny, cost effective sensor nodes can be deployed in a hostile environment in an adhoc fashion to create very large-scale dense networks. Wireless sensor networks thus provide us with the opportunity to study and understand any physical phenomenon with greater accuracy.
2. Sensor networks are characterized as data centric, with primary focus on the data generated by the sensor nodes. Sensor nodes using their on-board computational capabilities can partially process and aggregate useful information from the sensed data. Such multifunctional

capability of sensor networks emerges due to the collaborative power of the distributed, tiny sensor nodes.

3. What makes these networks interesting to study in greater details is its potential for application across a wide array of domains.The present and future applications of sensor networks involve domains like robotic exploration, pollution detection and control, biological systems etc.

Sensor networks present us with a unique set of characteristics and challenges which makes the design and implementation of these networks a nontrivial task. Sensor networks suffer from design constraints such as frequent topology failures, limited battery power, limited node lifetime, random unpredicted node failures, lack of infrastructure in the deployed region and the problem of self configuration for providing network connectivity. Despite the above set of unique challenges sensor networks are being actively researched due to their potential application in a wide array of areas.

1.2 Objectives of the Thesis

Unlike traditional wired and wireless networks energy consumption is the single most important constraint that dominates wireless sensor network due to its direct influence on the network lifetime. The primary objectives of this thesis are the following:

- To understand and analyze existing key topology control protocols for optimizing network lifetime in wireless sensor networks while ensuring minimum connectivity in the network. To study the drawbacks in the existing topology control schemes and provide solutions to overcome these drawbacks.
- To study and analyze existing data aggregation protocols and propose a novel data aggregation scheme for wireless sensor networks.
- To provide an overview of sensor networks with a deeper insight into the problem of energy conservation in the network.

1.3 Contributions of This Thesis

The main contributions of this thesis work are as follows:

- This thesis provides an insight into the concept of sensor networks, its applications, architecture, design challenges and key constraints.
- We study and analyze the cluster based energy conservation (CEC) topology control protocol [18] for wireless sensor networks and propose a novel protocol called Node Energy based clustering protocol (NEC) for wireless sensor networks with guaranteed connectivity which addresses and overcomes the drawbacks of CEC. We further evaluate our protocol with extensive simulation in *ns*2 and performance comparisons with existing protocols like GAF and CEC.
- We also study and analyze the problem of energy efficient data aggregation and propose a novel k-Means based efficient data aggregation protocol for wireless sensor networks.We further evaluate our protocol with extensive simulations in *ns*2.

1.4 Thesis Organization

This thesis is organized in four main chapters. Chapter 2 provides an overview of wireless sensor networks. Chapter 3 introduces and provides a solution the problem of energy efficient topology control for sensor networks. Chapter 4 likewise, introduces the problem of energy efficient data aggregation in wireless sensor networks. In Chapter 4 we also propose a novel energy aware data aggregation protocol. In Chapter 5 we present the conclusions of this thesis and direct to further possible research in this field.

Chapter 2

Overview of Sensor Networks

2.1 Sensor Networks: An Overview

One of the primary objective of current research in sensor networks is the development of protocols and algorithm subject to a severe set of resource constraints. Energy consumption is one such key constraint as the battery power cannot be replaced or recharged for sensor nodes deployed in a hostile environment. Multihop communication, topology control, data aggregation, exploiting node redundancy, inbuilt trade-off mechanisms between network lifetime and throughput are some of the standard energy conserving practices used in sensor networks. As the cost of designing, implementing and deploying sensor networks progressively reduces, these network will transcend from research labs to everyday life.

2.1.1 Applications

Sensor networks can be potentially used for a broad spectrum of applications across various domains [21]. The current popular application domains of sensor networks are environment, health, home, military, security and commercial areas. Sensor networks need to be designed and implemented keeping the application in view, as different applications may have different resource constraints. Minimizing energy dissipation in the network is one constraint that is universal to all applications. A brief overview of some of the key applications is as follows:

- Military - Sensor networks have the potential to be a key component of command, control, communications, intelligence, surveillance, reconnaissance and target systems. In future they can be used for the detection of nuclear, biological, and chemical attacks as well as improvised-explosive-devices (IEDs).

- Environmental Applications - These consist of applications like temperature monitoring, forest-fire detection, flood detection, wildlife tracking and precision agriculture. It is possible to deploy sensor networks for the above mentioned applications due to the remote sensing and automated data collection features of sensor nodes.
- Health Applications - These include applications like Telemonitoring of human physiological data, tracking doctors and patients etc.
- Home and Commercial Applications - Applications like smart spaces, office environmental control, home automation, management of inventory control, vehicle tracking and detection fall in this category.

2.2 Sensor Network Design Factors

Some of the parameters that influence the design of sensor networks are scalability, production cost, network topology, fault tolerance, power consumption and hardware constraints.

- Fault tolerance deals with the issue of minimizing the effect of failing nodes on the entire network.The required level of fault tolerance in the network is application specific. One of the models used for measuring fault tolerance of a sensor node is Poisson's distribution. Protocols and algorithms need to be designed which provide the application specified fault tolerance in the system.
- Scalability is determined by factors like total number of deployed nodes and density of sensor nodes. Density and number of nodes in the network should be exploited to increase the network operational lifetime.
- As wireless sensor networks are made up of a large number of densely deployed nodes, individual node cost greatly impacts the total network cost. The aim here is to keep the sensor node cost low enough so that the wireless sensor network cost is less than that of the traditional network.

- Topology control includes factors like mode of deployment, self configuration after deployment, deployment of additional nodes etc. Maintaining the topology of sensor network is particularly challenging as sensor nodes are mobile, prone to random failures, subject to harsh physical conditions is the deployment area and often have a nonrenewable energy source.
- The four basic units of a sensor network are sensing unit, processing unit, transceiver unit and power unit (power units may at times be supported by power scavenging solar cells). In a tiny sensor node all of these components have to be placed in an extremely small area. Power emerges as the most constrained resource as it might not be possible to physically replace the battery in a sensor network and at the same time the size of the sensor node itself limits the size of the battery component inside the node. Further hardware constraints include very low power consumption, autonomous operation capability, environmental adaptivity etc.
- The three factors that determine power consumption are sensing cost, communicating cost and data processing cost. Communication contributes the most towards the total energy consumption. Paradigms like in network data aggregation and localized data processing have the ability to greatly reduce the communication cost in the network.

2.3 Sensor Network Protocol Stack

The architecture of sensor network is based on the source-sink paradigm. The sensor nodes act as the source and collect data and using multicolor communication route the data towards the sink. The top down version of the protocol stack consists of application layer, transport layer, network layer, datalink layer and physical layer. Sometimes the protocol stack is also assumed to have a three dimensional view consisting of the power management plane, mobility management plane and task management plane. Topology control protocol, the area of focus of this thesis, is a part of the network layer.

2.3.1 Protocols for Sensor Networks

Efficient well designed protocols tailored for different layers of the protocol stack already exist for sensor networks. Next we briefly describe some of the key protocols for sensor networks.

- Routing Protocols: SPIN [24], SAR [26], Directed Diffusion [27] are some of the routing protocols used for sensor networks.Leach another well known protocol for sensor networks which organizes sensor nodes into clusters, directed diffusion uses the concept of gradients for data flow. Some of the standard techniques used by network layer routing protocols are *flooding* where data is broadcasted to all neighbors, *gossiping* which consists of selectively sending data to a random neighbor, choosing the next hop node on the basis of various metrics like shortest route to the destination etc.
- In sensor nodes the radio has to be periodically switched off to reduce the energy dissipation of the node. Hence Mac protocols consist of TDMA, FDMA and radio on-off schedule based approaches. SMAC [19] is a key MAC layer protocol for sensor networks. SMAC periodically turns of the radio of idle nodes to conserve energy.

Current Research is focused on developing efficient protocols for each of these layers so that practical realization of these networks is possible. From this overview we can conclude that the residual energy of sensor nodes dominates all aspects of design and implementation of these networks.

Chapter 3

Energy Aware Topology Control Protocol

3.1 Need for Topology Control

Topology of a Wireless Sensor Network determines the connectivity of the wireless network and profoundly impacts the routing algorithms applied to the network. Topology also influences other important features of the network like resiliency and communication cost between nodes. Current research has established efficient network energy utilization as one of the fundamental research issues in wireless sensor networks. Controlling the topology of the network has emerged as an effective solution to the above problem. Like all other aspects of wireless sensor networks, topology control protocols have to be designed and implemented subject to a severe set of computational and energy constraints.

The radio in a sensor node is the primary source of energy dissipation. The radio consumes power in all of its four phases of operation namely listening, idle, transmission and reception. Some common metrics that are used for performance measurement of routing protocols in wireless adhoc networks are number of packets dropped, overhead in terms of routing messages, number of hops etc. But, compared to traditional wired and wireless adhoc networks, wireless sensor networks should be primarily evaluated in terms of energy depletion of sensor nodes. Sensor nodes have limited non-renewable battery sources, moreover once deployed there is seldom any means of recharging the battery of a sensor node in a hostile environment. These constraints make the above stated energy metric a primary concern. Choosing the approach to selectively switching off the radio of sensor nodes based on the availability of alternate routing paths is one way of optimizing the energy consumption in a wireless sensor network. Switching-off the radio of the sensor nodes is only possible if the topology is configured in such a way that the network is not partitioned due to those inactive nodes. Thus effectively controlling the topology of the network emerges as a solution to the problem of energy conservation for wireless sensor networks.

Topology control protocols are designed to exploit node density in the network to extend the network lifetime and provide connectivity. The following criteria have been identified as the key concepts for designing topology control protocols for wireless sensor networks.

- Sensor nodes should be able to self-configure to accommodate changing network dynamics.
- Selection of redundant nodes should be done based on distributed localized algorithms.
- Topology control protocols must ensure minimum connectivity in the network, so that the network is not partitioned.
- Topology control protocols should take advantage of the high node density in large-scale wireless sensor networks to reduce the energy dissipated in the network.

3.2 Literature Survey of Topology Control Protocols for Wireless Sensor Networks

Extending network operational lifetime seems to be a key factor in the design of network layer or MAC layer protocols for sensor networks. Topology control protocols can be classified into two groups depending on which network layer information is used for identifying redundant nodes:

- Protocols like CEC [18], GAF [18], ASCENT [1], LEACH [10] use information from the routing layer and above for identifying redundant nodes.
- Protocols like PAMAS [12], STEM [20] use MAC Layer information to identify redundancy in the network.

We next discuss some of the key, relevant network and MAC layer protocols for sensor networks. Protocols like ASCENT which use application level information display high energy savings. In ASCENT, neighbor density and packet loss information is used to determine local connectivity and there-after choose redundant nodes. In PicoNet [25], application specific hardware and protocols are used which display greater energy savings. LEACH (Low-Energy Adaptive Clustering Hierarchy) is a clustering based routing protocol that uses randomized rotation of cluster-heads to evenly distribute the energy load among the sensors in the network. In order to avoid the energy drainage of cluster-heads, in LEACH, the cluster-head positions are not fixed and are re-elected periodically. LEACH selects routing paths based on the total path energy. PAMAS uses a second radio channel to monitor neighbor traffic to determine the duty cycle of its main radio channel. AFECA[23] determines the radio on-off schedule depending on the degree of a node. In AFECA more energy savings are obtained with increasing node density.

GAF and CEC are the two protocols which provide the foundation for our topology control protocol (NEC). Hence GAF and CEC are next discussed and analyzed in greater details.

3.2.1 Geographic Adaptive Fidelity (GAF)

GAF is a location based energy conservation protocol. In GAF redundant nodes are identified based on their geographic locations. The radio of a node is periodically switched off for balancing the load. Location information in GAF is provided by Global Positioning System (GPS) and GAF assumes that the location information is correct. GAF uses the concept of equivalent nodes. Equivalent nodes are intermediate nodes which are same in terms of their connectivity to other nodes with respect to communication. In GAF the network area is divided into small virtual grids such that all nodes in adjacent grids are in each others radio range. Thus in each virtual grid any one of the nodes can be used for routing. In GAF thus energy saving can be done by keeping the radio of one sensor node active per grid and switching off the radios of all the other sensor nodes. To further balance the energy dissipation in each grid the nodes in a grid are periodically rotated to be active, so that at any given time only one node is switched on per virtual grid.

Issues with GAF:

- GAF is dependent on global information. It fails in applications were geographic location information is not available and hence GAF can be used in very limited applications
- In GAF if a grid has only one node then is not possible to balance the energy usage for that

virtual grid and the network may have pockets of low energy virtual grids which in turn may lead to network partitioning.

3.2.2 Cluster Based Energy Conservation Protocol(CEC)

We next studied the Cluster based Energy Conservation (CEC) protocol which directly and dynamically measures the network connectivity so that energy can be conserved by identifying the nodes which can be selectively powered off. CEC configures the nodes into overlapping clusters. CEC also has cluster-head node and gateway node for each cluster for the purpose of maintaining connectivity in the network. CEC tries to provide solutions for some of the problems of GAF.

Clustering is one of the most fundamental ways used to design scalable sensor networks. A clustering algorithm arranges the network into subsets of nodes each with a cluster-head at approximately the center of each cluster. A regular high level structure is obtained from good clustering [4]. It is easier to design efficient energy conserving protocols for for this kind of structured organization of nodes than at the level of individual nodes. This type of topology also eliminates the need for global information and localized algorithms can then be used in these clusters to reduce the centralized coordination and require that nodes interact with only their neighbors further reducing the communication costs. CEC defines a cluster as a subset of nodes which are mutually reachable in two hops. In CEC cluster formation takes place in a distributed fashion and clusters are interconnected to each other through overlapping nodes. Each cluster has a cluster- head and all the members are within direct radio range of the cluster-head. In CEC the cluster formation takes place in the following manner:

- Initially each node *broadcasts* a discovery message that contains its node ID, cluster ID and estimated lifetime.
- After receiving discovery messages from all its neighbors if a node sees that it has the highest energy among all its neighbors it declares itself as a cluster-head and broadcasts this.
- If a non cluster-head node receives cluster-head messages from more than one cluster-head it declares itself as a gateway node and broadcasts this information. CEC first selects the cluster-head and then the gateway nodes connecting the clusters. A node elects itself as the

cluster-head if it has the longest lifetime of all its neighbor, breaking ties by node ID. For gateway selection from multiple gateways the gateway with the longest lifetime is assigned highest priority.

- Next leaving the cluster-head and gateway nodes all the other nodes are powered off to conserve energy. After periodic intervals the entire clustering process is reiterated.

3.3 Node Energy Based Clustering Protocol (NEC) [5]

In CEC we observed that if the gateway node between two clusters has a very small lifetime then that node may die and in that scenario the network connectivity is lost till re-clustering in the network is invoked again. Figure 3.1 shows the formation of clusters on the basis of CEC. Now we consider the situation where different node have different lifetimes. Here the wakeup time T_S [18] after which all the nodes in the cluster are powered on again is set to $enlt/2$ where $enlt$ is the estimated lifetime of the cluster-head. Thus the lifetime of the cluster ($LT_{cluster}$) depends on the lifetime of the cluster-head. Hence if the lifetime of any gateway ($LT_{gateway}$) of the cluster is less than the lifetime of that cluster-head, then there will not be any connectivity in the network for $LT_{cluster} - LT_{gateway}$ amount of time. Our protocol ensures that the connectivity in the network is maintained even in the case of the above stated scenario while consuming minimum energy.

We propose NEC, a clustering protocol which ensures minimum connectivity in the network, optimizes energy consumption and addresses the issue of problems with network connectivity in CEC. In this protocol we propose and define the concept of strong and weak sensor nodes based on their operational lifetime.

First we define the following :

- A cluster is defined as a set of nodes that are mutually reachable in at most two hops. Each cluster has a cluster-head which is directly reachable from all members of the cluster. A gateway is defined as a node which is a member of more than one cluster and provides interconnection between the clusters. In NEC, during clustering, a node can be in one of the four states, namely, cluster-head, gateway, potential cluster-head, ordinary node.

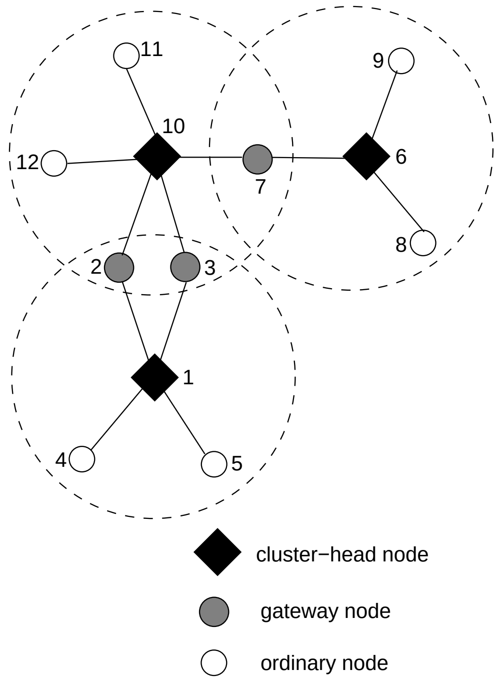

Figure 3.1: Example of clustering. The dotted circles show the radio range of the cluster-heads.

- Re-clustering Interval (I) is defined as the time after which re-clustering is initiated in a cluster.

  $I = \alpha \times$ Estimated lifetime of the cluster head, where $0< \alpha <1$.

  Both the value of the estimated lifetime of the cluster-head as well as I change with time. Each cluster has its own re-clustering interval.

- Strong and Weak nodes : A node is defined as a strong node if its lifetime is greater than I when it operates at full power for the entire duration of its lifetime otherwise it is defined as weak node.

3.3.1 Cluster Formation

Phase 1: Potential cluster-head selection

Initially each node broadcasts a discovery message which contains its node ID, its Cluster ID, and estimated lifetime. A node elects itself as a potential cluster-head if it has the longest lifetime among all its neighboring nodes (ties are broken by node ID). After a node elects itself as a potential cluster-head it broadcasts this information along with its lifetime to all its neighbors. ■

Phase 2: Gateway selection

A node which is directly reachable from more than one cluster-head is called a primary gateway. A node which is connected to the cluster-head of another cluster through a member of that cluster is called a secondary gateway.

When a node receives messages from more than one potential cluster-heads it knows that it is a gateway and then decides whether it is a strong node or a weak node with respect to the potential cluster-heads. The gateway node then passes the information whether it is a strong or a weak node to the potential cluster-heads. A gateway node between two potential cluster-heads can thus be a strong node with respect to one potential cluster-head and weak node with respect to the other potential cluster-head. In this case it sends two different messages to the two different potential cluster-heads. ■

Phase 3: Cluster-head selection and cluster formation

If a potential cluster-head receives the information that all its gateways are strong then it elects itself as the cluster-head and broadcasts this to all its neighbors which set their cluster Id to that of the cluster-head and a cluster is formed. The cluster-head broadcasts the value of re-clustering interval I to all the members of the cluster.

If a potential cluster-head receives the information that one or more of its gateways are weak nodes it elects itself as the cluster- head but while broadcasting this information to its neighbors it reduces the value of α hence reducing the re-clustering interval.

After the cluster formation except for the cluster-head and the gateways all the other cluster members switch off their radios for an amount of time equal to the re-clustering interval to minimize the energy consumption. ■

Figure 3.2. shows an example of a cluster formation according to NEC. Here node 2 and node 3 are strong gateways since their remaining energy will allow them to survive the usual re-clustering interval (when $\alpha = 0.50$) while node 7 is a weak gateway since its remaining energy will not allow

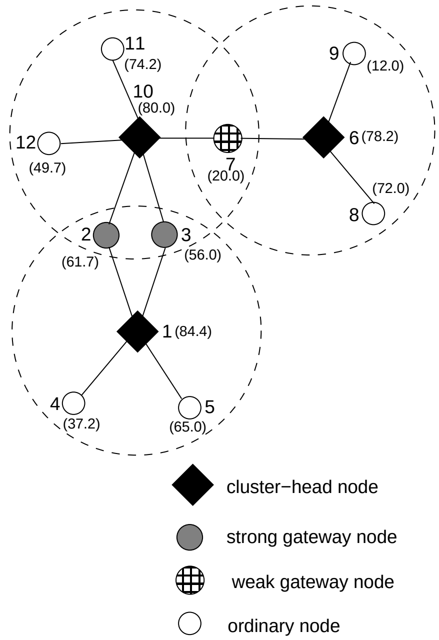

Figure 3.2: Example of NEC. The numbers within the parenthesis denote the energy of each node.

it to survive the re-clustering interval I if $\alpha = 0.50$.

In NEC, an alternative approach can be once a gateway discovers that it is a weak node with respect to a cluster-head it sends intermediate node search messages containing its cluster ID to all its neighbors at some fraction of its maximum transmission power (minimum transmission power is preferred so that the node can last for a longer time [13]). If it gets a reply from its neighbors having the same cluster ID it then uses this neighbor as a bridge node between the cluster-head and itself so that it can be operational for a longer duration of time and extend re-clustering interval. Clustering is expensive in terms of network resources and the number of re-clusterings should be kept to a minimum.

3.4 Analysis of NEC

We next NEC in terms of message complexity as communication between nodes consumes significant energy. For the problem of cluster formation in NEC the following network model is assumed.

- A node can directly communicate with its cluster-head.

- A cluster-head has at least one neighbor which is a gateway.
- An ordinary node has at least one neighboring node (a node within direct communication range) which is a cluster-head.

3.4.1 Conditions That Should be Satisfied by the Clustering Protocol

Based on the above assumptions, our cluster formation algorithm/protocol should satisfy the following criteria similar to the desirable clustering condition in [22].

- Cluster formation is completely distributed. Each node independently chooses to join a cluster based on local information.
- The cluster formation should terminate within a fixed number of iterations.
- By the end of one cluster formation period (T_c) a node is either a cluster-head, a gateway or an ordinary node. A gateway node can at the most belong to the number of clusters given by the number of its neighbors denoted by (m). An ordinary node will belong to only on cluster.
- Clustering should be efficient in terms of number of messages exchanged.
- Intercluster connectivity is assured.

3.4.2 Correctness Proof and Complexity

In this section we prove the correctness of NEC and also show that it satisfies all the criterion of a good clustering algorithm. We assume that n denotes the total number of nodes in the network and the m denotes the number of neighbors (within direct communication range) of each node. Note that NEC is a completely distributed algorithm. A node in NEC can either become a cluster-head or join a cluster according to received messages. The decision whether to become a cluster-head or a gateway or an ordinary node is based on local information.

Lemma 3.4.1 *By the end of the phase 3 of NEC, a node is either a cluster-head, a gateway or an ordinary node.*

Proof: Let us suppose that NEC terminates and a node is neither of a cluster-head, a gateway or an ordinary node. Then by the definition of states of a node in NEC, the node must be a potential cluster-head. By the end of Phase 1, of NEC a node may become a potential cluster-head. By the end of Phase 2, a node may still be a potential cluster-head. But by the end of Phase 3, of NEC the cluster-head selection in the network is completed. Hence a node which is not a cluster-head or a gateway or a ordinary node by Phase 3, by Assumption 3 of Section 3.4, will have a neighbor which is a clustered and hence its status will change from potential cluster-head to an ordinary node. This contradicts our assumption proving the lemma. ■

Lemma 3.4.2 *One clustering interval of NEC finishes in $O(1)$ iterations.*

Proof: From Lemma 3.4.1 we see that at the end of one complete iteration cluster formation is complete and each node is either a clustered or a gateway or an ordinary node. Hence one clustering interval NEC terminates in constant number of iterations. ■

Lemma 3.4.3 *In NEC the message complexity of one clustering interval per node is $O(m)$, and the message complexity of one clustering interval for the whole network is $O(n^2)$.*

Proof: By the end of one complete round of clustering, let n_{pch} denote the number of potential cluster-heads, n_{gw} denote the number of gateways and n_{ch} denote the number of cluster-heads in the network.

- The total number of messages exchanged in Phase 1 in the network due to the discovery and potential cluster-head messages is $(m \times n) + (n_{pch} \times m)$. In the worst case when the graph is fully connected, $m = n$ and the complexity becomes $O(n^2)$.
- Total number of messages exchanged in Phase 2 due to gateway messages is $n_{gw} \times m$.
- Total number of messages exchanged in the network in Phase 3 for cluster-head notification is $n_{ch} \times m$.

Thus for a single clustering interval of NEC the message complexity is $O(n^2)$. ■

Lemma 3.4.4 *NEC ensures minimum connectivity in the network once the clusters are formed.*

Proof: By Phase 3, of NEC the clusters are formed. Further, phase 3 of NEC algorithm ensures that gateways are alive for the entire period of time till the next clustering takes place. Hence minimum network connectivity is ensured in NEC. ■

3.5 Simulation of NEC

The primary objective of NEC is to optimize the energy conservation in the network while ensuring guaranteed connectivity of the network. We initially simulated our protocol with a small network consisting of a few nodes . The results indicated that NEC performed better than CEC in providing network connectivity. We next implemented our protocol (NEC) in *ns*-2 simulator. We ran GAF/AODV, CEC/AODV and NEC/AODV for the same simulation scenarios to compare their performance. The nodes move randomly with a speed within 0 to 20m/s in a 1500m by 300m area. For simulating a wireless sensor network 50 nodes are used to route data while 10 nodes are used as sources and sinks. The traffic generated was characterized by constant bit rate (CBR). The packet size was set to either 512 bytes. The 10 nodes generating the traffic data were given infinite amount of energy. These nodes just generate data and do not participate in data routing. The fifty nodes used for routing were assigned an initial energy values to keep them alive for 500s.

We next evaluate the performance of NEC with respect to performance metrics like network connectivity, energy consumption, network operational lifetime etc.

3.5.1 Residual Node Energy and Network Operational Lifetime

We first study the survivability of the nodes in all of the three protocols NEC, GAF and CEC. From Figure 3.3. We see that for a simulation time of 1000s in NEC on an average $36-37\%$ of more nodes are alive when compared to GAF. In CEC the number of alive nodes is more than in NEC. This is an expected result as more number of nodes survive in CEC than in NEC due to more frequent re-clustering in NEC to ensure inter-cluster connectivity. The re-clustering interval in NEC is reduced for clusters with weak gateways. Clustering is expensive in terms of network resources due to the messages exchanged for cluster formation.

To study the network operational lifetime we consider the average energy of the network at different instances of time. To obtain the average energy of the network at a given simulation time we consider the summation of the energy of all the nodes at that instant of time. From Figure 3.4 we see that the average network energy in CEC and NEC are much higher than in GAF. CEC shows 20%

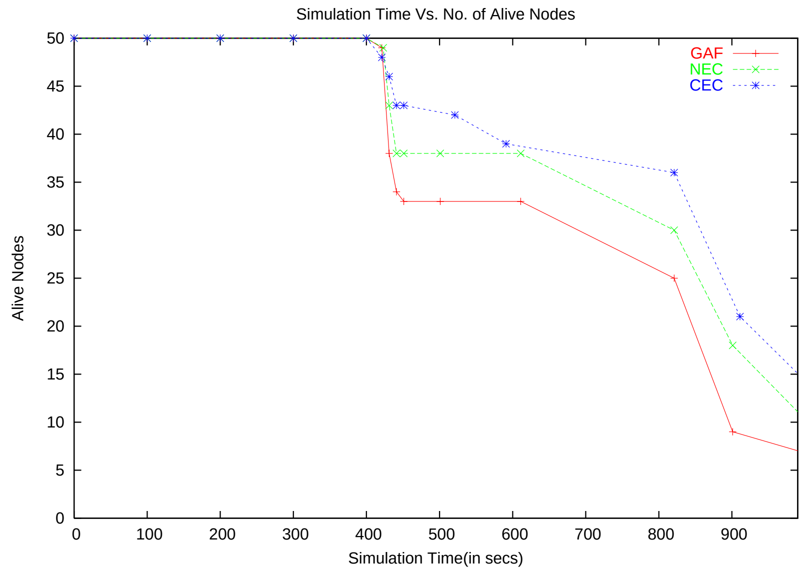

Figure 3.3: The number of alive nodes with simulation time.

more average energy than NEC. The nodes in the network display varying residual energy levels after being operational for some period of time. In case of NEC to ensure connectivity, re-clustering takes place much more frequently. The increased average network energy in case of CEC comes at the cost of partitions in the network. In Figure 3.5 we plot the time at which only 20% of the node are alive with varying degrees of mobility. This figure illustrates the impact of node mobility on the network operational lifetime. In CEC ideally high mobility causes more frequent clustering leading to reduced energy conservation. From Figure 3.5 for higher pause times (lower mobility) NEC and CEC show increased network operational lifetime. GAF displays increased network lifetime at higher mobility as with dynamic nodes the nodes in the virtual grids keep rotating and hence energy expenditure of the nodes is balanced across the virtual grids in the network.

3.5.2 Network Connectivity

For analyzing network connectivity we performed two sets of simulations. Initially, the simulations were performed on a simple topology consisting of eleven nodes. We first ran NEC on this simple topology and initially obtained three clusters with one weak and one strong gateway. For simulation purposes we assumed for both the protocols that a constant amount of energy is expended for

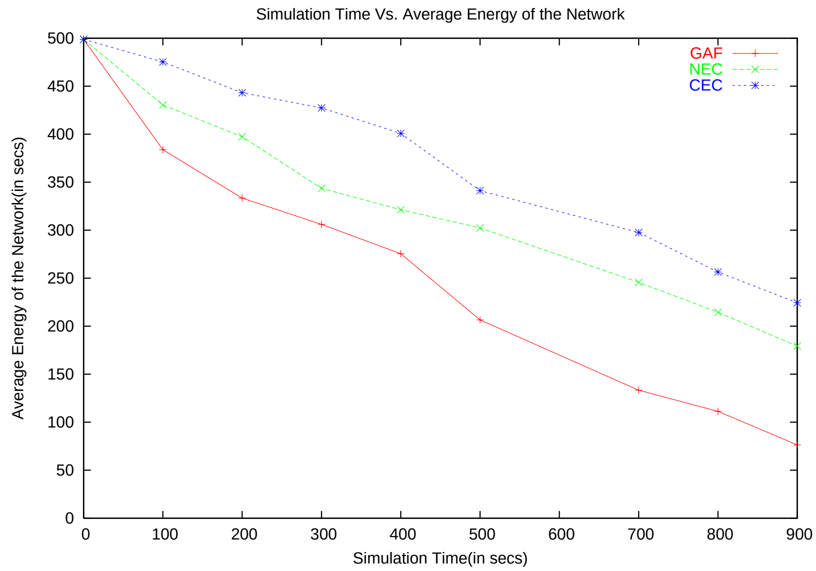

Figure 3.4: Average energy of the network with simulation time

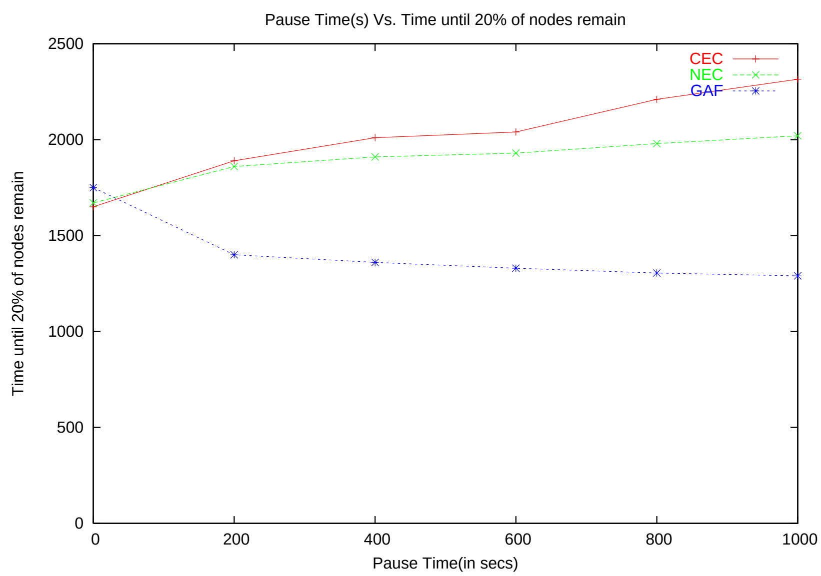

Figure 3.5: Pause time vs time until which 20% of nodes remain

transmitting a message as well as for receiving a message. In the definition of re-clustering interval (I) we used a value of $\alpha = 0.50$ for strong gateways and $\alpha = 0.25$ for weak gateways.

From the results of our simulation for the above stated scenario we found that the first node dies at 19 secs (from Figure 3.6) in our NEC protocol. As the re-clustering interval for the cluster to which this node belonged to was 23 secs, the network was partitioned and connectivity was lost for 4 secs in this case. For CEC under the same simulation scenario we found that the network was disconnected for a longer period of time of about 23 secs. Figure 3.6, which shows the connectivity/disconnecting of the network, is an illustration of this result. This happens because NEC takes into consideration the effect of the energy level of the gateway node during cluster formation and if the energy level of the gateway node is low, NEC causes the cluster to re-cluster according to a reduced re-clustering interval. Thus in the case of NEC a weak node is not usually selected either as a gateway or a cluster-head during re-clustering and behaves as an ordinary node which is powered off after the cluster formation. Thus the energy of the weak nodes is conserved. NEC thus balances the energy usage of the nodes in the network.

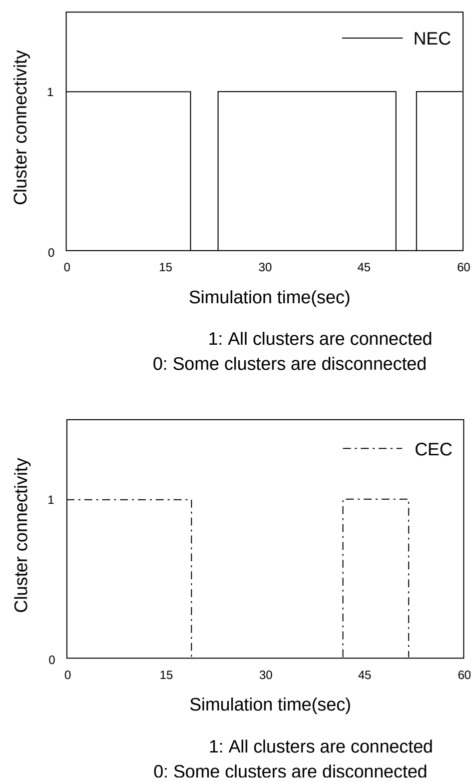

Figure 3.6: The connectivity status of the network with time in case of NEC and CEC.

It is important to ensure that energy conservation in the network does not come at the cost of connectivity. We next analyze the simulation results in *ns*-2 with respect to connectivity metric.

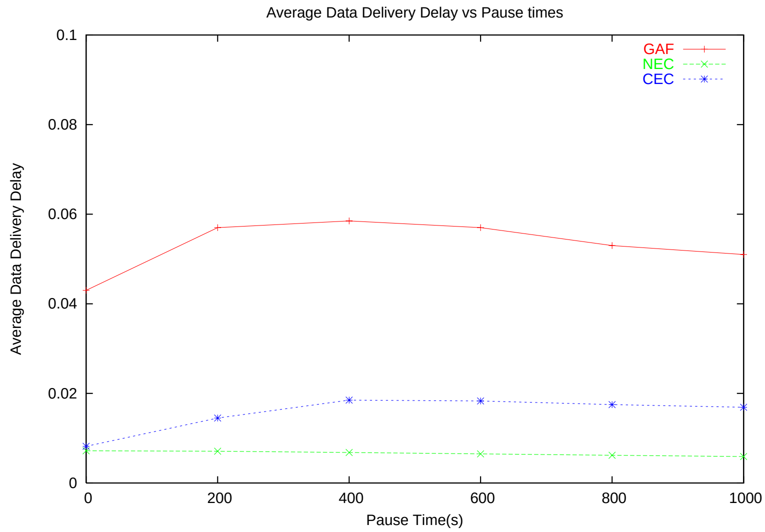

Figure 3.7: Average data delivery delay with pause times

We use average data delivery delay defined as the mean delay of received packets to measure the connectivity in the network. From Figure 3.7. We see that GAF shows better data delivery ratio at higher mobility. At high mobility the nodes are constantly moving in and out of the virtual grids and thus the energy dissipation of the nodes is balanced, but at low mobility as the node density decreases with time the connectivity in the network is affected in case of GAF. Here we use pause time to indicate mobility of the nodes. Pause time of 0s indicates that the nodes are constantly moving while a pause time of 1000s indicates that the nodes are almost static. The spikes in the graph of CEC denote network partitions which are caused when gateway nodes run out of energy. No such spikes are observed for NEC as NEC tracks the gateway node residual energy and reclusters before the connectivity is broken. In NEC the density of nodes is exploited to conserve energy. Thus with higher node density, even more energy savings can be achieved.

3.5.3 Trade-off between Network Connectivity and Residual Energy of the Nodes

From all of the above figures we see that the performance of NEC and CEC are comparable in terms of performance metrics like network operation lifetime, average energy of the network etc., but NEC outperforms CEC with respect to connectivity. Hence NEC is more suitable for critical real-time applications than CEC. Comparing NEC and GAF we see that NEC outperforms GAF in terms of all the performance metrics. The above simulation clearly establishes the existence of trade-off between network connectivity and energy conservation in the network based on a given topology. The optimal value of this trade-off can be set by the specific application in question.

3.6 Conclusion

NEC is an energy efficient topology control protocol for wireless sensor networks which ensures minimum connectivity in the network at all times. Simulation results and analysis of the NEC algorithm prove that NEC outperforms existing topology control protocols in terms of performance metrics like network lifetime and average data delivery delay.

Chapter 4

Topology Dependent Energy Aware Data Aggregation Protocol

4.1 Introduction

In recent years there has been a significant increase in the real life applications of wireless sensor networks. Sensor nodes when deployed in large numbers can monitor large scale physical systems accurately [2]. Wireless sensor networks are ideally suited for applications like environmental monitoring, surveillance, habitat monitoring where large amounts of data is being collected continuously and transmitted to the central station [7]. As wireless sensor networks become part of everyday life, one problem that still remains central to the operability and applicability of these networks is the limited energy and computational resources of the sensor nodes, which has a direct impact on the network lifetime. Thus there is a need for developing techniques and methods which increase the productivity and efficiency of these networks [6].

Given the present limitations of wireless sensor networks, data aggregation is an important paradigm that assists in decreasing the energy consumption, eliminating data redundancy and increasing the useful information flow from the source to the sink thereby prolonging the network lifetime. Data aggregation can be incorporated with other routing protocols or can be implemented as individual protocols/techniques that interact closely with routing protocols. In this paper, we propose a novel data aggregation protocol which uses standard techniques from data mining to aggregate the sensed data and eliminate redundancy in data. Previous research shows that data transmissions account for almost 70% of the energy consumption in the network. In our protocol there is a significant decrease in the amount of data transmission and hence the protocol exhibits better performance specially effective in applications where large amounts of data are being collected continuously.

To develop an efficient data aggregation protocol, the inherent properties of the sensed data should be utilized. This implies that in a large scale densely deployed sensor network the redundancy in the data sensed by a group of sensors due to relatively close locational proximity should be exploited. It has been shown that that amount of data aggregation in sensor networks is a function of the degree of spatial correlation in the sensed phenomenon [14]. If we assume that the sensors are placed within a certain distance of each other then barring some unusual event there should be some redundancy in the data sensed by neighboring sensors. The degree of redundant data again depends on the specific application in question. Thus considering the above scenario, in the proposed protocol we aim to create a resultant data set from the sensed data set that eliminates the redundant data but at the same time provides a good representation of the original sensed data set.

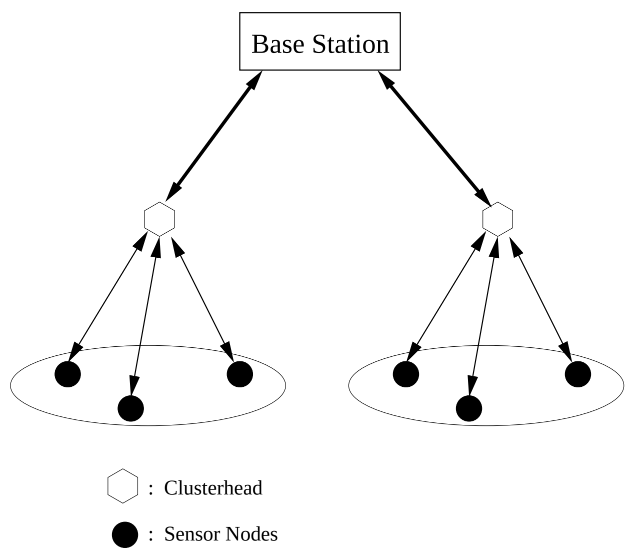

Figure 4.1: Network Architecture for KMBDA Protocol.

In this paper, we use a cluster based hierarchical architecture for sensor networks to achieve and support scalability as shown in Figure 4.1. In our protocol we essentially use *k*-Means algorithm and other optimizations like sending only the difference values between the previously transmitted data values and the current data values if it reduces the number of packets transmitted to extract a resultant representative set with a much reduced number of elements from the sensed data set. By sensed data set we imply the data sensed by a sensor node for a certain interval of time. Hence due to the reduced volume of data traffic in the network it takes less number of transmissions for sending this new data set to the base-station leading to energy conservation and increased network lifetime. In this paper, we further analyze the trade-off between the number of representative mean data values being transmitted (*k* of *k*-Means algorithm) and how much the set of computed mean data values reaching the end-user deviates from the original data values.

4.2 Literature Survey on Data Aggregation

Optimizing energy consumption has been the focus of recent research in sensor networks. Data aggregation has been proposed as one of the most important techniques for conserving energy [11]. ESPDA protocol [3] is one such data aggregation protocol which uses the pattern code generated from the raw data to eliminate redundancy in data transmission. ESPDA thus uses pattern codes which represent the characteristics of the actual data to perform data aggregation. SRDA [16] is another data aggregation protocol which compares the raw data and the reference data to determine the difference data to reduce the number of data transmissions.

In all of the above protocols sensors generate codes based on the sensed data and send it to the cluster-head. The cluster-head then compares these codes and requests for the actual data corresponding to distinct codes. One of the problems with the above protocols is that in case of multi-dimensional data the corresponding codes generated are also going to be quite large and the data transmission efficiency will be affected. Again, in ESPDA if a node is corrupt it may be able to send false data to the cluster-head by generating a distinct pattern code corresponding to an inaccurate data value. SIA [15] protocol proposes a number of aggregation functions like mean, maximum, minimum, sum etc. Thus SIA provides data summarization and only the aggregated data is sent to the base-station. A data aggregation scheme that extends the class of queries that can be answered using sensor networks has been proposed in [17]. The queries use approximate values like median, consensus values etc. Here a senor aggregates the data it has received from other sensors into a fixed size message. A few other protocols perform data aggregation by alleviating localized congestion problems [9].

Previous research [14] also includes techniques like opportunistic routing driven compression (RDC), distributed source coding, compression driven routing etc. In this thesis, we explore techniques from the field of data mining to assist in data aggregation. Our data aggregation is efficient in terms of energy and computational resource usage.

4.3 *k*-Means Based Data Aggregation Protocol (KMBDA)

Given the energy as well as other resource constraints in wireless sensor networks the proposed *k*-Means Based data aggregation protocol (KMBDA) is designed to provide energy efficient data aggregation. In this aggregation protocol we make the following assumptions.

1. A large scale network with a large number of nodes exists where the sensors are grouped into clusters. Each cluster has a cluster-head which communicates with the base station and the nodes in its cluster.

2. In a densely deployed large scale sensor network, there is a higher degree of spatial correlation between the data sensed by the sensors in a cluster. Data aggregation is thus used to eliminate redundancy and minimize the number of transmissions in a cluster in order to save energy.

3. The clusters of sensors are formed in such a way that in a cluster no two sensors are more than some constant distance (d) apart which is specified according to the type of application. This assumption is made in order to ensure a higher degree of correlation between the data sensed by the sensors in a cluster.

Our protocol uses the *k*-Means algorithm with certain modifications for in-network data processing and aggregation. The *k*-Means algorithm is a well known partition based algorithm for clustering of data sets. We next give a brief description of *k*-Means algorithm.

4.3.1 *k*-Means Algorithm

K-Means is a partition based clustering algorithm for large scale data analysis. In partition based cluster analysis of large data sets, optimal solution is obtained by computationally intensive extensive enumeration of all possible partitions of the data set. For practical purposes, hence, two heuristics *k*-Means and *k*-Medoids algorithm are used. In *k*-Means each data cluster(partition) is represented by the mean value of the cluster. *k*-Means algorithm tries to minimize some defined function/parameter like the squared error function. We choose *k*-Means algorithm because it is scalable and can efficiently process large data sets. The computational complexity of the algorithm is $O(nkt)$ where n is the total number of data values, k is the number of data partitions or clusters and t is the number of iterations requires to reach a local optimal solution. Usually $k \ll n$ and $t \ll n$.

Given a set of n objects, *k*-Means algorithm [8] constructs k ($k \leq n$) partitions of the data where each partition represents a cluster. Hence it classifies the data into k groups which satisfy the following criteria:

1. Each group contains at least one data item.

2. Each data item belongs to exactly one group.

Thus k such clusters are formed to optimize a similarity function such as distance, so that the objects within a cluster are similar and objects of different clusters are dissimilar in terms of attributes. The algorithm takes the input parameter k, and partitions a set of n objects into k clusters so that the resulting intra-cluster similarity is high while the inter-cluster similarity is low. The cluster similarity is measured with regards to the mean value of the objects in the cluster. The algorithm first randomly selects k objects each of which initially represents a cluster mean or center. For each of the remaining objects an object is assigned to the cluster to which it is most similar based on the distance between the object and the cluster mean. The algorithm then computes the new mean for each cluster. These means or the centers of the data clusters are representative of the whole data values of the data clusters. This process iterates until the criterion function converges.

4.3.2 Details of KMBDA

We next describe our protocol as well as the distributed algorithms that are executed at the sensor nodes and the cluster-head. We define the following terms:

k : Denotes the number of partitions or groups of a set containing n data values at each sensor obtained by executing k-Means algorithm on the sensed data set at that sensor.

K : Denotes the number of partitions or groups of a set data values at each cluster-head obtained by executing the k-Means algorithm at the cluster-head.

In this protocol every sensor operates in two phases: Sensing Phase and kMeans Phase.

Sensing Phase : The sensing phase is the time interval during which the sensor collects data. As soon as a sensor has sensed substantial amounts of data values it goes into the next phase.

*k*Means Phase : In this phase k-Means algorithm is executed over the data values collected during the sensing phase. As a result we get a reduced set of k ($k \ll n$) data items which give a good representation of the n data items sensed by the sensor.

We use the following terms in our algorithm,

C_i : Denotes the cluster-head of the cluster with cluster ID i.

s_i : Denotes a sensor s_i.

d_{s_in} : Set of n data values sensed by sensor s_i.

m_{s_ik} : Set of k mean values computed at sensor s_i from the set d_{s_in}.

q : number of sensor nodes in a cluster i.

D_{C_ip} : Set of p data values received by cluster-head C_i from the sensor nodes in its cluster. Note that each sensor node s_i belonging to a cluster with cluster-head C_i will send m_{s_ik} of size k to C_i. Hence p is the collection of mean values received from each sensor s_i and $p = q \times k$.

M_{C_iK} : Set of K mean values computed at cluster-head C_i from the set D_{C_ip}.

$diff_{s_ik}$: Set of differences between individual elements of the current set m_{s_ik} and the corresponding elements of the current set M_{C_iK}.

$diff_{s_ik} = \{diff_j | diff_j = a_j - b_j$, where a_j is the jth member of M_{C_iK} and b_j the corresponding jth member of m_{s_ik} and $1 \leq j \leq k\}$.

Now we present our algorithm in pseudo code format. Our algorithm is a distributed algorithm which executes independently at the sensor nodes and the cluster-heads. The algorithm for sensor nodes and cluster-heads are different and so we present them as follows. For simplicity, we assume that K is equal to k here.

At the cluster-head C_i

Initialization

C_i sets $M_{C_iK} = \{a_j | a_j = 0, 1 \leq j \leq K\}$.

C_i sets

for $i = 1$ *to* q

$diff_{s_ik} = \{diff_j | diff_j = 0, 1 \leq j \leq k\}$.

end for

Step 1: C_i constructs set D_{C_iK} as follows:

for $j = 1$ *to* q

$m_{s_jk} = \{a_r | a_r = b_r + c_r$, where $b_r \in M_{C_iK}$

and $c_r \in diff_{s_ik}, 1 \leq r \leq k\}$,

here b_r is the rth element of M and c_r is

the rth element of D.

$D_{C_iK} = D_{C_iK} \cup m_{s_jk}$.

end for

Step 2: C_i calculates M_{C_iK} by executing k-Means algorithm on D_{C_iK}.

Step 3: C_i broadcasts M_{C_iK} to all sensor nodes in its cluster and the base-station.

Step 4: C_i initializes a timer.

C_i starts decrementing the timer and receives $diff_{s_jk}$ from the sensor nodes in its cluster.

Step 5: go to Step 1 when the timer expires.

At the sensor node s_i

Initialization

$m_{s_ik} = \{a_j | a_j = 0, 1 \leq j \leq k\}$.

Step 1: On receipt of M_{C_iK} from C_i, s_i switches from sensing to kmeans phase and computes m_{s_ik} by executing k-Means algorithm on d_{s_in}.

Step 2: s_i calculates $diff_{s_ik}$

Step 3: s_i sends $diff_{s_ik}$ to C_i.

Step 4: s_i sets d_{s_in} to $\emptyset$. s_i switches to sensing phase and continues to add sensed data values to d_{s_in}.

Step 5: s_i goes to Step 1.

Next we briefly describe the above stated algorithms. Initially both the set of means values at the cluster-head and the sensor nodes are set to zero. Next at the cluster-head the set of means is computed and broadcasted to all the members in its cluster and this set is also transmitted to the base-station. Next a timer is set and the cluster-head starts receiving the sets of mean values from the individual sensors. When the timer expires the cluster-head computes the means by executing k-Means algorithm.

At the sensor nodes the following operations take place. The sensor senses and stores the sensed data values in the sensing phase. On the receipt of broadcast message containing the set of mean values from the cluster-head the sensor goes into the $k$means phase and the k-Means algorithm is executed on the data values collected by the sensor in the sensing phase. For optimization, the sensor next computes the difference between the set of means sent by the cluster-head and the its own set of computed means. The sensors then send the the set of difference values obtained to the cluster-head. This is done so that if there is not much of a difference between the previous mean values and the current mean values then in this case, transmitting the difference values takes less number of bits and thus the number of data transmissions are reduced. The sensor next goes back to the sensing phase. Note that in the algorithm presented above we have assumed $k = K$ for simplicity. If k differs from K , then the algorithm for sensor nodes remains unchanged. The algorithm to be implemented at the cluster-head will be slightly modified. The cluster-head will now compute from the set $D_{C_i p}$ two sets of mean values, one of size k and the other of size K. The former set of mean values containing k elements will be sent to the sensor nodes while the later set containing K elements will be sent to the base station.

4.3.3 Analysis

We next analyze the message complexity of KMBDA protocol. We use the following notation for the analysis.

Let n denote the total number of nodes in the network, m the average number of nodes per cluster and n_{ch} the number of cluster-heads. We compute the message complexity for each iteration of the KMBDA algorithm.

We assume that the set of means generated by k Means algorithm from the raw sensed data set is transmitted as the payload of one packet. KMBDA algorithm is executed in two phases, at the cluster-head and the sensor node. Therefore, the total number of messages in one iteration at the cluster-head is given by, number of messages exchanged = $(n_{ch} \times m + n_{ch}) \ll n^2$. The first term is due to broadcast of the set of means by the cluster-head to the sensor node in its cluster and the second term is due to the message sent by the cluster-head to the base-station. The total number of messages exchanged in one iteration due to the senor nodes is given by, number of messages

$= n - n_{ch}$. This is due to the difference set sent by the sensor nodes to the base-station. Hence the total message complexity in the network in one iteration of kmbda is *O(n)*. Now if we assume that representative data set has k values and can be transmitted using k packets/messages then the resultant message complexity is given by $k \times n_{ch} \times m + k(n - n_{ch}) \approx O(n)$. Further if we assume that one iteration of kmbda takes t units of time, then for the execution of KMBDA for a time period of T amount of time, the number of iterations is T/t and the message complexity is given by $O(Tn/t)$.

4.4 Simulation of KMBDA

To analyze the performance of KMBDA, we simulated our protocol in *ns*-2. The simulation scenario was set up in the following way. We consider a wireless sensor network topology consisting of sixty nodes in total. Ten nodes are set up as the sources or sink for data and generate traffic at constant bit rate. All of the other fifty nodes are used for routing and perform local processing on the data. The nodes are setup to be mobile with a speed varying form 0-20m/s, but for our experiment we set the pause time to 1000s which implies that the nodes exhibit very low mobility. In this simulation we use the energy of node expressed in terms of time to live(*ttl*) as the data sensed by the sensor. We use *ttl* as the sensed data as it varies dynamically with the simulation time and hence shows a range of variation. Here other types of data, for example real temperature data during a whole day etc. can also be used as the initial sensed data. Here we assume that at any instant of time a sensor node stores twenty five sensed data values.

We primarily evaluated our protocol with respect to the following performance metrics.

- Number of data packets transmitted : Previous research regarding energy optimization in sensor networks has shown that both the energy spent in transmission and reception of packets contributes significantly to the energy dissipation in the network. Hence reducing the number of packets transmitted and received results in significant network energy savings. From Figure 4.2 we see that for k=6 the the number of packets transmitted is reduced by 60%. From Figure 4.2 we notice that during the initial simulation period the number of packets transmitted directly is less than our protocol and then increases quickly compared to our protocol.

This characteristic is due to the number of overhead messages exchanged during the initial cluster setup phase in our protocol.

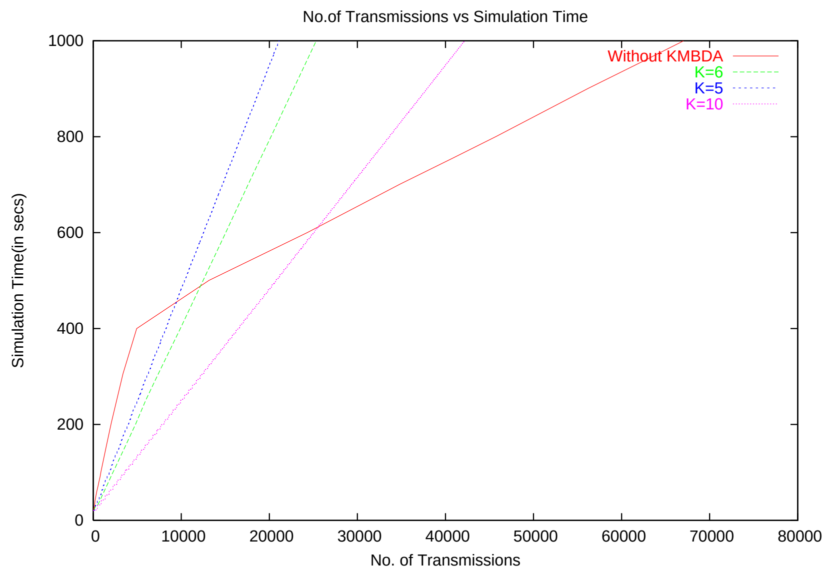

Figure 4.2: No. of Packets transmitted with simulation time

- Network energy dissipation: Next we study the impact of our protocol on the network lifetime. In Figure 4.3 we plot the number of nodes alive at any instant. The graph clearly shows that network lifetime is extended significantly with our protocol due to the reduced traffic in the network.

- The percentage of error introduced in the final data set sent to the end user: In KMBDA, the sensors locally process the sensed data set and send a computed representative reduced data set to the cluster-head. The cluster-head in turn forwards a locally computed further modified reduced data set to the base-station. Hence we next explore the percentage of error introduced between the actual sensed data and the modified final data value sent to the base-station. Figure 4.4 shows the variation of the percentage error introduced in the final data sent to the base-station from the corresponding data sent to the cluster-head. The computed data sent to the cluster-head from the senor nodes is a acceptable representation of the actual data sent as proved by previous research with respect to k means algorithm and hence here

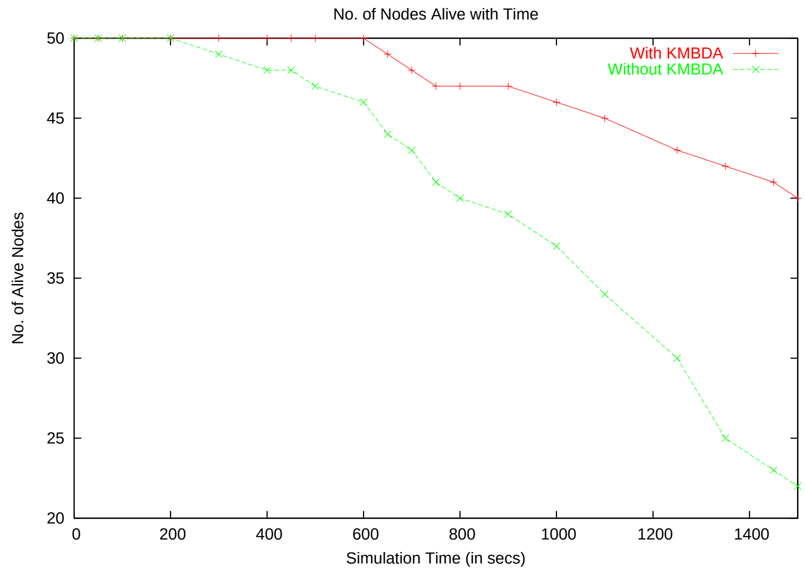

Figure 4.3: No. of nodes alive with simulation time

we explore the deviation introduced in the final data set sent to the base-station and the data set sent by the sensor nodes to the cluster-head. Depending on the constraint parameters like error tolerance of an application, the value of k can be manipulated to control the number of packets transmitted and percentage of error introduced. In Figure 4.5 the actual data being sent from the sensor nodes and the cluster-heads have been plotted for some time period.

From the above simulation results we observe a clear trade-off between the value of *k* and the amount of data transmitted in the network i,e. the energy conserved in the the network.

4.4.1 Conclusion

In this thesis, we propose a novel energy efficient data aggregation protocol for wireless sensor networks called KMBDA. Our protocol achieves energy conservation by reducing the number of packets transmitted at every stage i.e, from the sensor node to the cluster-head and the cluster-head to the base-station. Our protocol uses *k*-Means algorithm to reduce the volume of data transmitted from the cluster-head to the base-station. Extensive simulations in *ns*-2 prove the effectiveness of

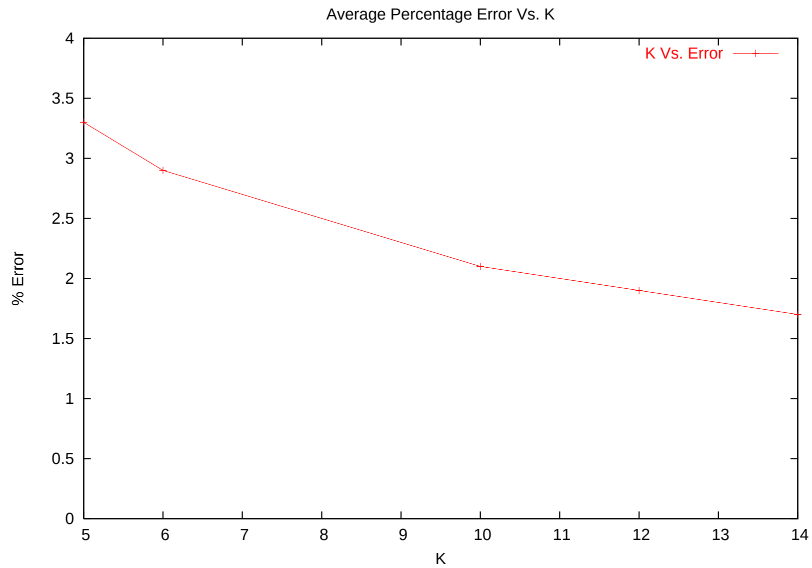

Figure 4.4: Average percentage error vs K

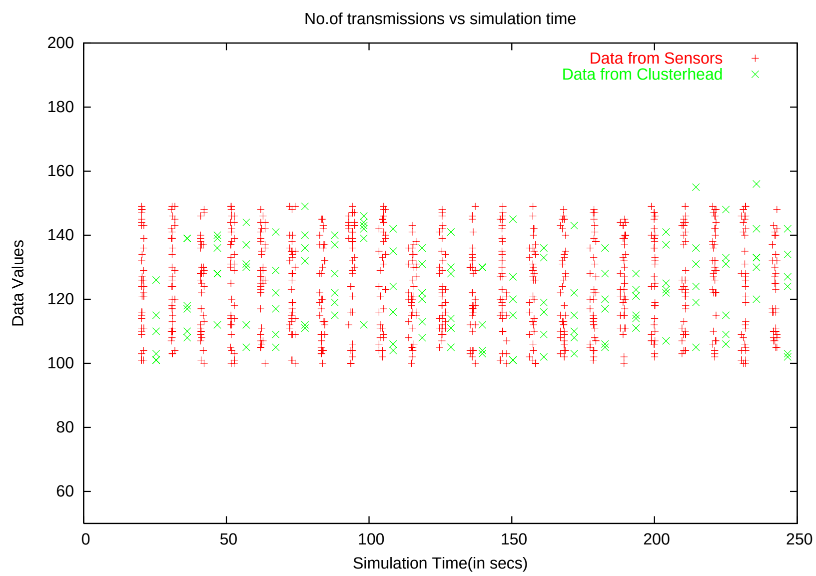

Figure 4.5: Data values with simulation time

our protocol. Even though we have used *k*-means algorithm in our protocol, yet our protocol is very general and will work when other algorithms like *k*-Medoids is used without any major modification.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The primary objective of this thesis is to understand in-depth and analyze the problem of energy constraint in wireless sensor networks. Energy of the nodes is the primary metric that dominates wireless sensor networks due to its profound impact on features such as network operational lifetime, connectivity and routing protocols. Energy saving techniques and protocols are being developed and implemented for each layer of the protocol stack for sensor networks.We approach the problem of energy conservation from the aspect of topology control protocols. We propose a novel cluster based topology control protocol called NEC which outperforms the existing topology control protocols while providing guaranteed connectivity in the network. We next study the problem of data aggregation in wireless sensor networks and propose a novel data aggregation protocol known as KMBDA which displays higher energy savings in the network by significantly reducing the number of packet transmissions in the network.

Topology control protocols determine the energy consumption as well as connectivity of the network. NEC is a distributed localized protocol independent of the routing protocol used in the network. NEC exploits the node redundancy in large scale dense sensor networks for network energy conservation. NEC classifies nodes as strong and weak based on their residual energy and uses this classification to to achieve a balanced distribution of energy across the network. NEC organizes the topology of the network into overlapping clusters, elects a cluster-head and gateway nodes for each cluster. Next all other nodes in the cluster except the cluster-head and gateway are identified as redundant nodes and powered off. The underlying principle in NEC is to minimize the power consumption of the radio in sensor nodes. Previous research has proved that radio is the primary source of energy dissipation in sensor networks. NEC provides ensured connectivity in the network via gateway nodes. In our protocol the decision of reclustering is based on the residual energy of both the cluster-head and gateway nodes. In NEC further energy optimizations are achieved by powering off redundant gateways. As the process of cluster formation is message intensive NEC invokes clustering only after the nodes show unequal distribution of residual energy. We simulated NEC in Network Simulator *ns*-2 and evaluated the performance of NEC in terms of various performance metrics such as average network energy, network operational lifetime, connectivity. NEC clearly displays superior connectivity and network energy optimization with respect to existing protocols like CEC and GAF.

Given the severity of resource constraints of wireless sensor networks, data aggregation emerges as a fundamental paradigm that provides increased bandwidth and energy efficiency. We propose a new data aggregation protocol known as *k*-means based data aggregation protocol(KMBDA). Compared to conventional data aggregation protocols KMBDA eliminates redundancy in data transmission by avoiding the transmission of the redundant data from the sensor nodes to the cluster-head. To develop an energy and bandwidth efficient data aggregation protocol we utilize the spatial correlation of the data sensed by the sensor nodes of a cluster to perform data aggregation. In KMBDA we use *k*-Means, a standard algorithm from the field of data mining along with various optimization techniques to extract a representative data set of mean values from the real sensed data. The representative data set has reduced number of elements. Simulation results and analysis show that the number of data transmissions (the main contributing factor towards the energy consumption in the network) is greatly reduced in our protocol when compared to the traditional data aggregation protocols and recent protocols like ESPDA. In our protocol the deviation introduced in the computed set of mean values when compared to the original raw sensed data values is very low and the can be further reduced by increasing the value of parameter *k* which determines the number of partitions of original sensed data set. We simulated our protocol in *ns*-2 and evaluated its performance with respect to performance metrics like number of packet transmissions, network energy dissipation and percentage of error introduced in the representative data set.

5.2 Future Work

There are still a wide array of open research problems relevant to the issue of efficient energy utilization in sensor networks. My research on topology control protocol and data aggregation can be extended in the following ways:

5.2.1 Topology Control Protocol

- The concept of strong and weak nodes can be extended to strong and weak clusters. Further the issue of inter-cluster connectivity can be explored in this scenario.
- Topology control protocols influence routing protocols. Recent research has started to focus on the Quality of Service provided by wireless sensor networks in real life applications. In future, I, plan to study and analyze the impact of topology of the network on the QoS provided by the network.
- Another interesting research problem would be study the impact of topology on various security protocols for wireless sensor networks.

5.2.2 Data Aggregation

- We need to study and analyze the amount of redundant data generated in applications like temperature monitoring, weather and environment monitoring.
- We need to formulate some analytical model which takes the parameter k as input and provides an upper bound on the error tolerance.
- In future we would also like to explore the performance of other partition based data clustering algorithms like k Medoids for data aggregation.
- As sensor networks are data centric, the proposed data aggregation should also be extended to incorporate security measures to detect corrupt data.

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