CHAPTER 1

INTRODUCTION

1.1 AN OVERVIEW OF WIRELESS SENSOR NETWORKS

A wireless sensor network (WSN) consists of a large number of sensor nodes deployed over a geographical area for monitoring physical phenomena like temperature, humidity, vibrations and seismic events. Each sensor node in the wireless sensor network is a tiny device that includes three basic components: a sensing subsystem for data acquisition from the physical surrounding environment, a processing subsystem for local data processing and storage, and a wireless communication subsystem for data transmission to a central collection point (sink node or base station) as shown in the Figure 1.1.

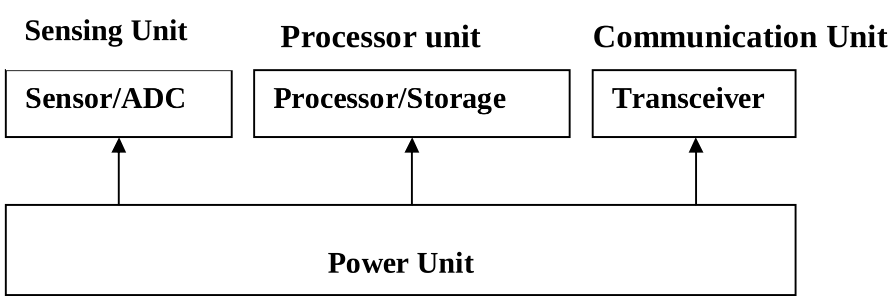

Figure 1.1 Essential Components of a Sensor Node

Sensor networks generate large amount of data. For extracting information, the end user needs to collect and query the data from sensor networks. Each sensor periodically produces information as it monitors its vicinity. The basic operation in such a network is the systematic gathering and transmission of sensed data to a base station for further processing.

Large-scale wireless sensor networks represent a new generation of real-time embedded systems with significantly different communication constraints from traditional networked systems. Thus, unlike traditional networks, where the focus is on maximizing the channel throughput or minimizing node deployment, the major consideration in a sensor network is to extend the system lifetime as well as the system robustness (Bulusu et al 2001). Despite the diverse nature of applications, sensor networks pose the following unique challenges:

- The sensor nodes have to be deployed in very large numbers. Therefore, the solutions designed for WSNs must scale to hundreds or thousands of entities.
- The life span of WSN nodes has a deep impact on the system as the nodes are limited in power and the battery is usually unattended and not rechargeable.
- Sensor nodes may not have global identification (ID) because they are deployed in very large numbers and the need to address any single node is usually not necessary.
- The traffic characteristic of WSNs is uneven i.e. very low data rates over a long period but becomes bursty whenever an event of interest occurs.
- Network architecture is data-centric rather than node-centric, as the low cost sensor nodes are redundantly deployed and as a consequence the importance of any one particular node is considerably reduced. More important is the data that these nodes can observe.

- The topology of a sensor network changes very frequently mainly because of the disconnection of the nodes with depleted batteries. This necessitates the sensor nodes to learn and update their current topology.
- Sensor nodes are very much prone to faults and failures.

1.2 THE GENESIS OF THE THESIS

The Wireless Sensor Networks are networks of numerous inexpensive, battery powered sensor nodes with limited processing, storage and radio capabilities. Designing protocols and applications for such networks are therefore expected to be energy aware in order to prolong the lifetime of the network. Additionally, sensor nodes are mostly deployed in unattended and unsafe environments and hence individual sensor nodes are highly vulnerable to faults. The availability of scarce resources and the presence of faulty nodes make the designing of energy efficient and reliable data collection and transport mechanisms for the wireless sensor networks particularly challenging.

The studies carried out in the thesis assume a heterogeneous network architecture with two types of traffic models viz. *Periodic* and *Event-driven*. In a heterogeneous sensor network, a certain percentage of the total population of sensor nodes is equipped with higher computing and communication potential. These *advanced* nodes automatically become Cluster Heads (CH) and the other *normal* nodes report their sensory data on a regular basis to its cluster head (CH) which then aggregates the data collected from all its member nodes and sends it to a base station/sink for further processing. In-network data aggregation and local data cleaning is usually warranted for the wireless sensor networks, owing to the aforementioned *reliability* and *energy efficiency* reasons.

Additionally, when an event of interest is recognized, all the sensors influenced by this event will start sending details about the event in a burst transmission. Congestion will inevitably occur in this case if no countermeasures are implemented. Therefore, these design themes guide the multi-step solution proposed in this thesis. In short, the purpose of this research work is to propose certain solution methodologies to improve the performance of the energy constrained and reliability craved wireless sensor networks under the continuous data gathering and event driven traffic models.

1.3 OBJECTIVES OF THE THESIS

The objectives of the thesis are:

- To improve the energy efficiency of the wireless sensor networks by
  - balancing the energy expended by CHs in periodically reporting the sensor data to the base station, by building energy efficient and load balanced clusters thus resulting in a network with prolonged connectivity.
  - reducing the communication overhead by exploiting the temporal-spatial correlations existing in sensor data, and thus saving significant amount of energy.
- To improve the reliability of wireless sensor networks by
  - adopting a method to precisely identify and remove the fraudulent /inconsistent data produced by faulty sensor nodes.

- incorporating a reliable event data transport technique that minimizes the packet drops due to congestion and thus improving the reliability observed by the end applications.

1.4 OVERVIEW OF THE RESEARCH WORK

As the wireless sensor networks are generally deployed to work with several hundreds of nodes, scalability is a fundamental issue. Clustering has been widely accepted in the literature as a technique to achieve scalability. An essential operation in sensor network clustering is to select a set of cluster heads and assign nodes optimally to these heads in such a way that the energy spent in communication from nodes to the sink is minimized.

An Energy and Stability Aware Clustering Protocol (ESAC) for heterogeneous sensor networks is introduced as the first proposal of the thesis. In heterogeneous sensor networks, the advanced nodes act as cluster heads and it is essential to decide an optimal mapping of normal nodes to the cluster heads. ESAC considers energy efficiency as a network wide issue and focuses on improving the overall stability period of a wireless sensor network when associating the nodes to the CHs. Stability period of a WSN is defined as the period for which all the cluster heads remain alive. When a cluster head depletes its energy, it is no longer operational, and all its member nodes lose their ability to communicate their data to the sink. Therefore, the early expiry of a cluster head due to heavy relay load results in a part of the network getting disconnected from the rest of the network. ESAC prolongs the stability period of the network by balancing the load at each cluster head. It is shown by simulation that ESAC provides an extended stability period, an average of around 300 rounds more than the class of clustering protocols that are unbalanced in nature.

The most energy intensive operation that a node performs is communication. According to Pottie and Kaiser (2000), the cost of transmitting a bit is many folds higher than executing an instruction. Hence, it is proposed to address the problem of reducing the communication cost and thus the energy cost incurred during continuous data gathering operations. Data collected from physical environments depicts a huge amount of correlation in both space and time domains. It is proposed in this thesis to exploit these temporal-spatial correlations to address the above-said problem. Each sensor node builds a data model that represents the underlying structure of the data. *Feature regions* are then formed which consist of nodes observing similar data patterns. A designated node in each feature region communicates only the model coefficients to the CH. These model coefficients are used by the CHs to answer queries from the base station. As long as the spatial stability holds, no new communication needs to be initiated from that region. This eliminates the need to periodically send across a vast quantity of raw sensor data from numerous sensor nodes. This huge savings in communication cost is achieved by leveraging the processing potential available in individual sensor nodes.

After the data from all the sensor nodes are collected at the CHs, the next step is to aggregate the individual sensors' data to prepare higher-level message digests to answer queries from the end users. The next solution proposed in this thesis is to improve the reliability of the sensor data aggregation process. Local data aggregation is essential in the WSNs because an individual sensor node has only a limited view of the sensing field, and therefore it sends the sensed values to an aggregator which then aggregates the reports collected from multiple sensor nodes. For the set up assumed in the thesis, the cluster heads do the role of the aggregators.

Improving the reliability of the sensor data aggregation process should be given due importance because in most of the applications, the sensor nodes are deployed in open and unsafe environments. So they are vulnerable to many intentional and unintentional damages. Individual nodes are prone to different type of faults such as hardware faults, crash faults etc., and other security vulnerabilities by adversaries wherein one or more nodes are compromised to produce bogus data so as to confuse the rest of the network in collaborative sensing applications. These faulty and inconsistent sensor data are called *outliers*, the presence of which affects the precision of the aggregation process and thus may lead to imperfect sensing results. An improved aggregation strategy that uses a statistical test called the *modified z-score test* is proposed in this dissertation work that precisely detects and removes the outliers. It is shown by simulation that the proposed strategy is able to tolerate up to 40% of faulty data in target detection applications and up to 35% of faulty data in continuous data gathering applications.

Once the outliers are precisely labeled and then cleaned locally, the next step is to transport the outlier free data streams to the sink. Sankarasubramaniam et al (2003) proposed a reliable and energy efficient data transport mechanism for event detection applications called ESRT. Whenever an event of interest occurs in the sensing region, all the nodes in the event epicenter send event related data to a sink. The authors define reliability in terms of the number of such event related data packets successfully reaching the sink. ESRT tries to maintain the protocol state near *optimal operating region* (OOR) by adjusting the sources' sending rates. OOR is characterized as the state where the network is kept uncongested whilst the reliability observed at the sink is very close to the application's desired reliability. When the observed reliability falls below the desired reliability, the sink asks all the sources to increase their sending rates incrementally until OOR is reached and similarly, a higher observed reliability causes all the sources to reduce their sending rate exponentially until OOR is reached.

ESRT employs a simple CSMA/CA based MAC protocol for medium arbitration and AODV protocol for construction of routes. However, it is observed that the handling of large bursts of event packets can cause significant local delays and packet drops along the best paths chosen by the existing routing schemes (Savidge 2006). This affects the reliability obtained at the end applications. Hence, a Congestion Free, Location Aware Routing scheme called CF-LAR is proposed which can be used as the underlying routing protocol of ESRT to improve the packet delivery efficiency in congested network conditions. CF-LAR employs a weighted cost function based on the location information as well as the current queue lengths and remaining energies at the neighboring nodes as a basis for next hop selection. Simulation results show that when CF-LAR is used as a routing component of ESRT, the packet delivery efficiency improves by 45%.

In short, prolonging the lifespan of sensor networks and improving the dependability of the reported results are most important to the success of the WSNs. All the four solution methodologies reported in this thesis have the common goal of utilizing the scanty network resources in an efficient manner while improving the overall proficiency of the resource constrained wireless sensor networks.

1.5 ORGANIZATION OF THE THESIS

The problem of enhancing the performance of the energy limited and reliability craved wireless sensor networks is attacked in this thesis in terms of the following four issues:

(i) partitioning the network into a set of energy efficient and load balanced clusters

(ii) demarcating the feature regions based on the trend and spatial distribution of the observed phenomenon in order to reduce the amount of raw data communicated

(iii) cleaning the outliers present in the sensor data and

(iv) enhancing the data delivery efficiency in transporting the outlier free data stream to the sink

The major findings, results and the conclusions yielded from the dissertation work are reported in seven chapters including the introduction.

Chapter 1 has given an introduction to the wireless sensor networks and the various design challenges involved in large scale distributed wireless sensor networks. It has presented an overview of the research work carried out. A review report on some of the important works on design related optimization problems and clustering techniques reported in the literature is presented in chapter 2.

The details about the proposed Energy and Stability aware Clustering (ESAC) is presented in chapter 3. The effectiveness of the proposed approach is demonstrated through simulation studies by assuming valid simulation models and the outcomes of the experiments are subjected to standard statistical tests to verify the credibility of the reported results.

Chapter 4 talks about the communication efficient framework proposed to minimize the communication overhead involved in continuously reporting the raw sensor data. The chapter contains details about how each node computes the feature model based on the sensed data and how the feature (dis)similarity among the nodes can be used to build feature regions.

Chapter 5 deals with the reliability constraint of sensor networks. Details regarding the proposed aggregation strategy and its efficacy in precisely labeling the outlier values demonstrated using simulation studies can be found in this chapter.

Generally in case of event detection applications, the reliability of the reported results is most often measured in terms of the number of event related packets received at the sink. Chapter 6 deals with this aspect of reliability and it gives a solution to minimize packet losses in the event of congestion thus satisfying the reliability requirement placed by the sensor network based applications. A congestion free routing scheme called CF-LAR is proposed in this chapter and its performance is demonstrated using simulation studies.

A comprehensive summary of conclusions obtained from the research work is presented in chapter 7. This chapter also gives certain clues on future directions for pursuing further research in this area.