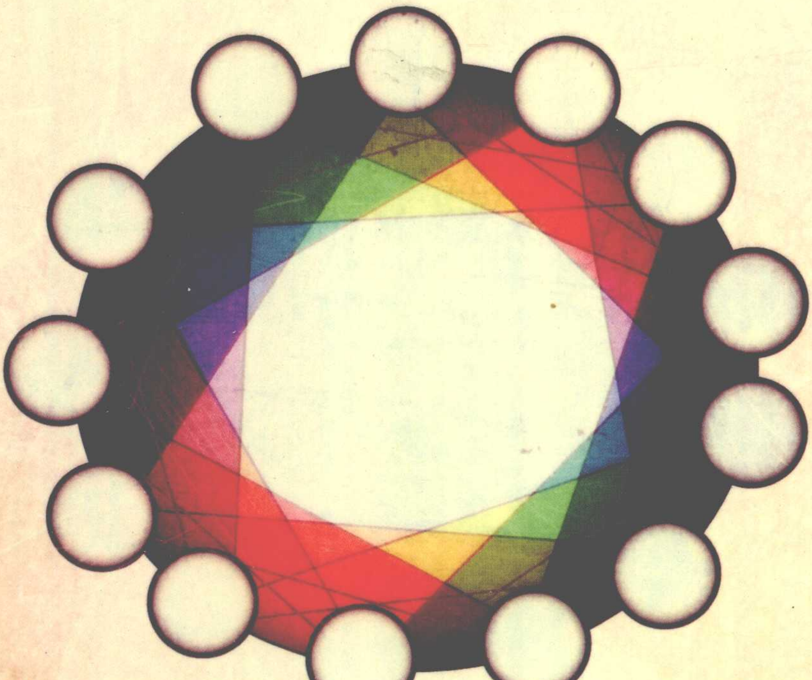
Computer Science, Technology and Applications

Wireless Sensor Networks



Liam I. Farrugia
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WIRELESS SENSOR NETWORKS

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COMPUTER SCIENCE, TECHNOLOGY AND APPLICATIONS

WIRELESS SENSOR NETWORKS

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PREFACE

A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance. They are now used in many industrial and civilian application areas, including industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control. This new book gathers and presents topical research data from around the globe in the field of wireless sensor networks.

Chapter 1 - Wireless Sensor Networks (WSN) are becoming more popular data gathering networks for monitoring a wide range of parameters. WSN are being used for monitoring various parameters such as environmental, industrial, in-house domestic parameters, medical and health parameters etc. WSN populates a huge number of sensor nodes. A typical architecture of sensor node is shown in Figure 1. Sensor nodes are tiny devices, which consist of three functional units: Sensing Unit, Computational Unit and Communication Unit. Sensing unit is composed of an array of sensors, which may include temperature, light, sound, humidity, seismic, and position sensors. Computational unit is usually a microcontroller which processes the sensor data. Communication unit is a radio device used for communicating the data to the neighboring sensor node. WSN populates a huge number of sensor nodes. These nodes form a self-organized network. These nodes coordinate and communicate to perform a common task of data gathering. For this purpose, different routing algorithms are used.

Chapter 2 - In this chapter, the authors will talk about Heterogeneous Sensor Networks key Management Protocol.

At the first of this part, the authors will talk about what is Heterogeneous Sensor Networks (HSN), and how to divide key management protocol by different method.

The second part of this chapter, based on different network threats and assumptions, the authors will introduce one key pre-distributed protocol, two key management protocols. About the key pre-distributed protocol, the key ring of nodes is based on divisible core pair-wise balanced design. The authors design two key pre-distributed protocol, Divisible Core Pair-wise Balanced Design Scheme shorted by DCPBD, and variant DCPBD shorted by VDCPBD. One of the key management protocols, the authors propose a key management protocol for heterogeneous sensor networks to improve the random key pre-distribution scheme using deployment knowledge of nodes and the prior area deployment information.

Another key management protocol, the authors propose a Location-aware and secret share based dynamic key management protocol to effectively replace the compromised central node and enhance the security level of the network.

At the last of this chapter, the authors will summarize this chapter, and predict the future development of key management.

Chapter 3 – The basic role of Wireless Sensor Network (WSN) is to collect data from the environment by many sensor nodes. The WSN could be constituted by hundreds or thousands of sensor nodes; hence, it could generate a huge amount of data. The communication of all the sensed data causes high power consumption limiting, as a result, the lifetime of the sensor nodes and consequently the WSN lifetime. Whereas, processing data locally within the sensor node consumes much less than its communication. Thus, it is possible to reduce the power consumption of the sensor nodes and, hence, to extend the network lifetime, by reducing the number and size of the communicated data. This reduction of communicated data is possible, if the sensor nodes' data are aggregated instead of being sent directly to the sink (the base station in WSNs).

This chapter studies several methods of data aggregation in WSNs. It classifies them into three categories. The first category represents structure-free mechanisms which abstract the organization of the nodes within the network. It allows the end-user of the network to query each sensor node, if needed. In the second category, the authors find the structure-based mechanisms that solve the structure-free problems in terms of scalability. It organizes the sensor nodes into a well structured form, such as a tree, or a set of groups. It defines aggregator nodes to aggregate other nodes data. This aggregator node may be one head-node per group or one parent for several children in a tree. Then, the end-user of the network has the aggregated data through the aggregator nodes. The third one is a Multi-criteria Data aggregation (McDa) mechanism. It combines characteristics from the structure-free and the structure-based categories. It does not suppose any network structure. However, spontaneously during the same data aggregation session, it is possible to have cooperation between single nodes and groups of nodes. It eliminates the overhead and signaling needed in structure-based category to create and maintain an organization of the sensor nodes.

Finally, a discussion of the three methods of data aggregation is made in order to underline, according to their characteristics, their advantages and limitations. In addition, the chapter studies some methods to secure the aggregated data by treating confidentiality and integrity issues.

Chapter 4 – In wireless sensor networks, an attacker can physically capture and compromise sensor nodes because they are deployed in an unattended manner. However, it will take substantial time and effort for the attacker to widely spread node compromise by only physically capturing sensor nodes. To facilitate wide-spread node compromise, an attacker may launch \textit{malicious code injection attacks} in which he forces a few compromised nodes to inject malicious codes into a set of benign nodes, leading to the compromise of those benign nodes. To detect malicious code injection attacks, the authors propose a malicious code detection scheme by using the Sequential Probability Ratio Test in wireless sensor networks. The authors analytically show that the proposed scheme achieves effective and efficient malicious code detection capability.

Chapter 5 – Wireless sensor networks (WSNs) have attracted significant attention in the past few years and have been widely implemented in battlefield communication, environmental sensing, and traffic monitoring. They consist of large numbers of cooperating small-scale motes, each only capable of limited processing performance, short-range radio transmission, and low power sensing capacities. As such, there has been an increasing need to define and develop simulation frameworks for carrying out highfidelity WSN simulation, which should be easily chosen and employed by researchers as well. This book chapter surveys the recent simulation work on WSN and presents the available up-to-date simulators. Each simulation tool is described based on some certain criteria and compared under the appropriate evaluation standards in terms of different task requirements. This also provides the readers with a better understanding of the latest development of WSN simulation and helps them to incorporate their own WSN research work into the suitable simulation development environment in the future.

Chapter 6 - Wireless sensor networks have been widely used for surveillance in harsh environ-ments. In many such applications, the environmental data are continuously sensed, and data collection by a server is only performed occasionally. Hence, the sensor nodes have to temporarily store the data, and provide easy and on-hand access for most updated data when the server approaches. Given the expensive server-to-sensor communications, the large amount of sensors, and the limited storage space at each tiny sensor, continuous data collection becomes a challenging problem.

In this paper, the authors present *partial network coding* (PNC) as a generic tool for the above applications. PNC generalizes the existing *network coding* (NC) paradigm, an elegant solution for ubiquitous data distribution and collection. Yet, PNC enables ef-fiand collectio replacement for continuous data, which is a major deficiency of the conventional NC. The authors prove that the performance of PNC is quite close to NC, ex-cept for a sub-linear overhead on storage and communications. The authors then address a set of practical concerns toward PNC-based continuous data collection and replacement in sensor networks. Its feasibility and superiority are further demonstrated through simulation results.

Chapter 7 - A wireless sensor network (WSN) is an autonomous self-organizing system of sensor nodes, distributed over an area to sense data from its surroundings and gather it to a sink node for further processing. Sensor nodes are typically battery-operated and therefore severely energy constrained. Besides limited computation and data sensing, each sensor node dissipates most of its energy in transmitting and receiving data packets en route the sink node. The shortest path routing is good for overall energy efficiency since energy needed to transmit a packet is correlated to the path length. However this may load some nodes heavily, causing earlier deaths and creating holes in the network, which in the worst case may leave the network disconnected. Hence, load balanced data routing, considering load in terms of power consumption at individual nodes, emerges as an important issue in WSN's to enhance the network lifetime. Unfortunately, the problem to compute the most balanced routes for data gathering is NP-hard even in a very simple network. Extensive research has been done so far to solve the problem under various scenarios of traffic patterns, data aggregation techniques and node distribution policies. This chapter aims to present a comprehensive study of several load-balancing schemes for wireless sensor networks, proposed in recent research literatures, with special emphasis on the distributed ones that may lead the researchers to explore newer avenues for load balanced data gathering in WSN's to enhance network lifetime.

Commentary - Due to the saturation of the telecommunication markets in technologically advanced countries, network operators need to create a new market. One promising market is for mobile wireless machine-to-machine (M2M) communications. Current networks do not work well with many M2M applications; therefore, a new network is needed. To differentiate this new network from others, it should have the following features: 1) low power consumption, 2) be low-end-terminal friendly, 3) low cost, and 4) ubiquitous coverage. Current networks do not satisfy these features. Standardization bodies and forums may also be interested in the mobile wireless M2M communications market, but their main target at present seems to be the current network infrastructure with short range radio equipment purchased by customers. To implement the new network as a network infrastructure satisfying the above-mentioned features, R&D efforts are essential for developing a large cell with wireless terminals of low transmission power and a simplified security protocol implementable in a low-end wireless terminal. A Wide Area Ubiquitous Network has been proposed as one solution, and application experiments on this network have been conducted in Tokyo, Japan.

CONTENTS

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Chapter 1

IMPROVEMENT IN LIFETIME OF WIRELESS SENSOR NETWORKS USING PERFECT DIFFERENCE SET-NETWORKS

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1. WIRELESS SENSOR NETWORKS

1.1. Review and Introduction

Wireless Sensor Networks (WSN) are becoming more popular data gathering networks for monitoring a wide range of parameters. WSN are being used for monitoring various parameters such as environmental, industrial, in-house domestic parameters, medical and health parameters etc. WSN populates a huge number of sensor nodes. A typical architecture of sensor node is shown in Figure 1. Sensor nodes are tiny devices, which consist of three functional units: Sensing Unit, Computational Unit and Communication Unit. Sensing unit is composed of an array of sensors, which may include temperature, light, sound, humidity, seismic, and position sensors. Computational unit is usually a microcontroller which processes the sensor data. Communication unit is a radio device used for communicating the data to the neighboring sensor node. WSN populates a huge number of sensor nodes. These nodes form a self-organized network. These nodes coordinate and communicate to perform a common task of data gathering. For this purpose, different routing algorithms are used.

Wireless sensor networks have become more popular because advances in sensor technology, low-power electronics, low-power radio frequency design, and VLSI & MEMS

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technology, have enabled the development of small, relatively inexpensive and low-power sensors, called microsensors. These wireless microsensor networks represent a new paradigm for extracting data from the environment and enabling the reliable monitoring of a variety of environments for applications that include surveillance, machine failure diagnosis, chemical/biological detection, habitat monitoring, environmental monitoring etc. WSN are effective ubiquitous computing systems used for medical and health care applications.

The sensor network is composed of a large number of sensor nodes which are densely deployed either inside the phenomenon or in its proximity. The sensor nodes may be randomly deployed in inaccessible terrain or disaster relief operations. Hence, sensor network protocols and algorithms must possess self-organizing capabilities. Wireless sensor nodes are battery powered and thus face energy constraint. Every node has limited power which decides the life span of the node and, in turn, the entire network. Many times, WSN include redundant nodes to provide fault tolerant capability. A few sensor nodes may die because of power exhaustion or any other failure. Even if few nodes die, the sensor network continues to function because of its fault-tolerant capability. One of the constraints on sensor nodes is the low power consumption. Hence, sensor network protocols focus on power conservation. Since the sensor nodes are often inaccessible, the lifetime of a sensor node must be assured. Sensor node lifetime depends on the lifetime of power resources; hence, power scarcity must be effectively managed. Figure 1 shows architecture of a typical sensor node. It basically consists of: sensing unit, computation or data processing unit and communication or radio unit. Daniele et al. [1] has discussed many hardware specifications/features of sensor node/mote for radio, microcontroller and the platform used.

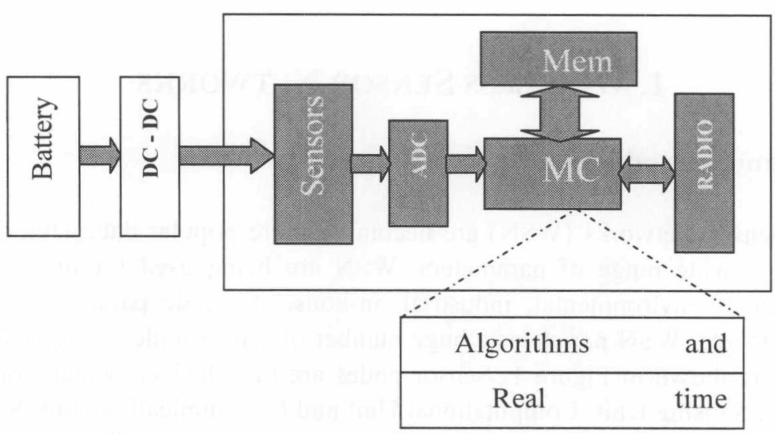

Figure 1. Architecture of a typical Sensor Node.

Typical sensor node block diagram is shown in Figure 1. It basically consists of: Sensing unit (sensors), computation or data processing unit (MCU: micro controller unit) and communication unit (RADIO). Sensor data is converted to digital streams using ADC. Microcomputer units (MCU) process data streams by executing algorithms, such as classification algorithm. Then the processed data is communicated over the network by radio unit. The entire sensor node works under a typical real time operating system such as TINY OS. The MCU also includes a protocol stack for efficiently routing the data over the sensor network.

Power consumption can be divided into three domains: sensing, communication and data processing. Sensing power varies with the nature of applications. Sporadic sensing might consume less power than constant event monitoring. Of the three domains, a sensor node expends maximum energy in data communication by radio unit. This involves both data transmission and reception. Sensor node architecture, wireless sensor network protocols, its applications, and wireless-networking issues are very well described in Akyildiz et al. [2]. Many categories of applications of WSN- such as industrial applications, domestic applications, military, public utilities, agriculture etc. are discussed by Carlos et al. [3]. Lewis [4] has described many topologies for WSN and has discussed network structures and hierarchical networks. Chong et al. [5] has elaborated on the history of research on sensor network research. He has discussed the prospects of sensor network research in 21^{st} century.

The main functional blocks in sensor nodes that consume power are: sensing unit, computation unit and communication unit. An important challenge in the design of these networks is that two key resources - communication bandwidth and energy - are significantly more limited than in a tethered network environment. These constraints require innovative design techniques to use the available bandwidth and energy efficiently. The communication consumes the major part of the energy budget, thus attempts must be made to implement techniques to save energy on communications. Every aspect of WSN is designed with energy constraints. There are three basic units in sensor nodes which consume power: communication, computation and sensing unit. Hence, all the attempts are being made to reduce the energy consumption at each unit. Many energy aware protocols are developed for reduced energy consumption and thereby improve the life span of the WSN. Wireless sensor network bears very specific characteristics that are described in following section.

1.2. Characteristics and Requirements of Wireless Sensor Networks

1. **Low bit rates:** Sensor networks have low bit rates (~1kbps). The low bit rate is due to the fact that the sensor parameter varies at very low rates. This is a very important feature of WSN which needs to be fully explored at each design step. This feature makes it possible to keep the WSN in deep sleep mode.

2. **Low duty cycle**: The sensor nodes are kept in sleep mode for most of the time. The duty cycle for sleep and wake up mode is typically around 1%. Thus, the node is kept on only when it is sensing data with its sensor or transmitting/receiving data from other nodes. The strategy is to keep the sensor node in sleep mode for most of the time to reduce energy consumption.

3. **Size constraints:** In order to deploy the sensor nodes unobtrusively for environment monitoring, the sensor nodes need to have miniature size. The current focus of the research community is to achieve dust-sized sensor nodes. Advances in VLSI and MEMS are leading to smaller sensor nodes. Further advances in nanotechnology and organic sensors are likely to help in reduction in the size of the nodes. Currently, the power supply (battery or energy scavenging technique) is leading to larger sensor

nodes. It is possible to employ renewable energy resources within the nodes. Research in this area would definitely help in achieving smaller sensor nodes.

4. **Low cost:** Sensor nodes should be cheap. Since this network will have hundreds or thousands of sensor nodes, these devices should be low cost. Even the research community is expecting and striving for sensor nodes with negligible cost as compared to network infrastructure cost.

5. **Energy constraints**: Energy constraint is the most important factor influencing the design of the sensor nodes and the choice of algorithms for the sensor networks. Due to energy constraints, sensor nodes need to have ultra-low power circuitry. The algorithms for sensor networks need to be energy-efficient.

6. **Data-centric**: WSN are data-centric in nature, meaning that the emphasis is on data to be routed. This can be contrasted with traditional wireless networks which are essentially node-centric. WSN are basically data gathering networks.

7. **Multi hop:** The signal from a wireless sensor node may not reach the base station straight. The solution is to communicate through multi-hop. Another advantage is that radio signal power is proportional to r^4, where r is the distance of communication. Thus, depending on radio parameters, it can be more energy economic to transmit many short-distance messages than one-long distance message.

8. **Localization:** The data from a sensor node is meaningless if it is not associated with the position of the sensor node. Localization is important for wireless sensor networks and the data from a node is sent along with the co-ordinates of the sensor node.

9. **Scalability:** Wireless sensor networks consist of thousands of sensor nodes, while traditional wireless networks contain a maximum of hundreds of nodes. As a result, care needs to be taken in the design of algorithms for WSN. The sensor network should scale from ten to thousands or millions of sensor nodes. This needs automatic-configuration, maintenance, and upgrading of individual devices. Another important attribute is scalability and adaptivity to changes in network size, node density and topology. Some nodes may die over time; some new nodes may join later; some nodes may move to different locations. Hence, WSN must be scalable and adaptive.

10. **Distributed Network and Distributed Processing:** WSN consists of large numbers of nodes that are distributed over a region of interest. Each sensor node should be able to process local data, using filtering, data fusion and aggregation algorithms to collect data from the environment and aggregate this data, transforming it to information.

11. **Dynamic Networks:** Sensor nodes are mobile so that during deployment they can be placed as per needs of the application. Due to node mobility, environmental

obstructions, restricted resources etc., the sensor networks exhibit a highly dynamic network topology.

12. **Redundancy in data:** There is inherent redundancy in the readings from the sensors. This redundancy can be further characterized as spatial redundancy and temporal redundancy. Spatial redundancy arises from the fact that sensor nodes, which are physically placed close to each other, will give similar value of the measured quantity. In addition, the value of measured physical quantity will not change abruptly in short span of time, and, therefore, the data measured over a short time span is likely to remain same. This gives rise to temporal redundancy. Hence, WSN must have efficient data processing and management algorithms.

13. **Application-specific:** WSN are deployed in a wide-range of scenarios. Hence, they would be application-specific in nature. For instance, a WSN deployed in a forest for wildlife or habitat monitoring is likely to have different requirements than a WSN deployed in indoor spaces for temperature monitoring.

From the literature review, we identified that the communication unit consumes major part of the energy available in the sensor node, as discussed by Raghunathan et al. [6]. This research work discusses classification technique using ART1 (Adaptive Resonance Theory) and Fuzzy ART (FA) neural networks model. ART1/FA has a specific feature that allows it to classify real time data, hence being called real time classifier. Real time classifier classifies the sensor readings and then the classified sensor data is communicated further. This saves a sufficient amount of energy.

The next sections describe the issue of fixed deployment of sensor nodes, introduce the research approach, and briefly describe UbiSens: Project at VLSI Lab VNIT.

1.3. Fixed (Non Mobile) Deployment of Sensor Nodes

Deployment of sensor nodes includes many possibilities. Traditionally, sensor nodes are randomly deployed over a geographical area. This includes routing protocols which use random deployment principle. Random deployment needs a location finding system in the node, which could find the neighboring nodes and decide whether to connect and transmit data. In such protocols, a large part of the energy is consumed in executing long programs by the computation unit. We pondered over the idea of reducing energy consumption on executing routing protocols. Today, WSN are also becoming popular in applications such as smart houses, intelligent offices, mines, nuclear installations, large buildings, government installations, etc. Hence, for such applications, fixed geometrical deployment could be employed. Sensor nodes while deployment adheres to some geometrical form. We chose to implement the concept of Perfect difference set networks for wireless sensor nodes. In PDS networks, any node can communicate with other node within a hop count of one or two. This makes it possible to use simplest possible routing technique. This routing technique can be effectively implemented in VLSI while designing the node. This routing technique reduces the computation time of the processor and hence in turn saves power consumed by the computation unit.

1.4. Research Approach

We propose to use ANN (artificial neural network) based ART1 neural network model for classification of sensor data. By classification, huge sensor data traffic can be reduced and hence it lowers the energy consumption on the communication unit and also improves the bandwidth of the network. This classifier is supposed to be a part of the (ubiquitous sensing) UbiSens: Low power sensor node. When this node is deployed in WSN, the life span of the network is improved by about 40%. Many classification and clustering algorithms are available and are being developed for data management in sensor networks.

Most of the energy-aware routing algorithms are designed for the random deployment of sensor networks, which are suitable for large geographical deployment. Fixed geometrical deployment strategy can be more efficient and economical for deploying sensor network in smart houses, offices, hospitals, mines, nuclear installations, and many other domestic applications.

We propose to use Perfect Difference Set (PDS) network for the fixed geometrical deployment of sensor networks. In this research work, we propose to reduce the energy consumption by computation unit by using PDS-Networks for deploying WSN. By using classification techniques, a large amount of sensor data traffic can be reduced and, thereby, energy spent on communication unit is saved. The lifetime of WSN with popular cooperative routing is compared with PDS-WSN. The ART1 neural network model is used for the classification of sensor data. The lifetime of WSN with and without classification in both the cases – with PDS-WSN and with cooperative routing is also presented.

In this research work we attempt to reduce the power consumption on communication unit by using classification techniques and by deploying the sensor nodes as per PDS – network power consumption by computation unit can be reduced. PDS-WSN takes care of geometrical deployment of the nodes.

Many research efforts are being carried out for designing low power sensor nodes. One such sensor node architecture – UBISENS – is proposed and undertaken at VLSI Lab, VNIT, Nagpur. The proposed classifier in this work is to be used in this sensor node. With classification technique, it is proposed that a Low power sensor node with an improved lifetime can be designed.

The low power sensor node was achieved using the classification technique. Then we thought of deploying the sensor node with effective and least power consumption. Why we should not have a network strategy where we have minimum hops and simpler routing? We ponder over the concept and we used the concept of perfect difference set networks to be used for WSN.

PDS-WSN strategy is explored and experimented for its fixed (non mobile) geometrical deployment. PDS-WSN facilitates minimum hop counts (one or two) to reach cluster head. This feature provides low power consumption by the network and simplest routing technique, which leads to improvement in the lifetime of WSN. Thus, the low power sensor network can be realized. Hence, it can be called a low power network. A further advantage of PDS-WSN is that the routing technique is simple and can be realized as VLSI implementation. We had VLSI framework in mind while proceeding on this research work. ART1/ Fuzzy ART classifier algorithms are proposed which provides features for its easy VLSI implementation. This ART1 classifier can be effectively used in noisy industrial environments by using DWT input layer filter. Many possible VLSI implementations of DWT are available. Thus, the research output provides a framework for VLSI implementation of Low power Sensor node with Low power Sensor network.

We have implemented cooperative routing techniques for data dissemination in the network, which give the advantage of equitable distribution of energy over the network and thereby improving the average lifespan of the network. We have deployed two separate radios; a low bit rate (1Kbps) MAC Radio with 100% duty cycle and a high bit rate (10Kbps) data transmission Radio with low duty cycle (1%). The MAC radio is always ON for maintaining the network while the data transmission radio is under sleep or wake up mode. It wakes up only during data transmission. This strategy also contributes to the saving of energy consumption by the communication unit. This technique is suggested in Berkeley Motes and discussed by Miller et al. [7].

The lifetime comparison for cooperative routing and PDS-WSN with and without classification techniques is presented in this chapter. The WSN is modeled [8] in Ptolemy-II: Visualsense [9,10]. The ART1 neural network model is implemented in MATLAB. ART1 classifier implemented in MATLAB is interfaced with WSN model implemented in Ptolemy-II.

1.5. UbiSens: Project at VLSI Lab VNIT Nagpur

The UbiSens (Ubiquitous Sensing) project [11] at VNIT is targeted towards exploring novel architecture for ultra-low power sensor nodes. Typically, a sensor node consists of a microcontroller, a power supply, sensor, ADC, memory and RF transceiver to achieve wireless connectivity between different nodes. The design of sensor node circuitry is driven by the need for ultra-low power operation. We propose the strategies to use in the UbiSens project to achieve low power operation. Our approach is to partition the system in such a manner that each sub-system part contributes towards the overall reduction of power consumption. In addition, sensor networks can be used in numerous applications and hence, they are application-specific. Thus, partitioning the system into several subsystems can make it possible to tailor certain subsystems to suit the application for which the sensor node is intended. A model in which, instead of having a single microcontroller, there are a number of subsystems that are meant for a specific purpose, is proposed.

These subsystems are referred to as "processing elements". This division of the computation between parallel processing elements is beneficial since each processing element may be tailored for a particular task and specific techniques could be used for reducing power consumption. Further ambient RF energy scavenging to ensure long lifetime of the sensor nodes is used. The proposed architecture for sensor nodes is shown in Figure 2. The various processing elements in the proposed architecture are: