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A Crosslayer Routing Protocol (XLRP) for Wireless Sensor Networks

Raghul Gunasekaran
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Raghul Gunasekaran entitled "A Crosslayer Routing Protocol (XLRP) for Wireless Sensor Networks." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Hairong Qi, Major Professor

We have read this thesis and recommend its acceptance:

Dayakar Penumadu, Itamar Elhanany

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Crosslayer Routing Protocol for Wireless Sensor Networks

A Thesis

Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Raghul Gunasekaran

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Abstract

The advent of wireless sensor networks with emphasis on the information being routed, rather than routing information has redefined networking from that of conventional wireless networked systems. Demanding the need for content based routing techniques and development of low cost network modules, built to operate in large numbers in a networked fashion with limited resources and capabilities. The unique characteristics of wireless sensor network's have questioned the applicability and effectiveness of conventional algorithms defined for wireless ad-hoc networks, leading to the design and development of protocols specific to wireless sensor network. Many network layer protocols have been proposed for wireless sensor networks, identifying and addressing factors influencing network layer design, this thesis defines a cross layer routing protocol (XLRP) for wireless sensor networks. The submitted work is suggestive of a network layer design with knowledge of application layer information and efficient utilization of physical layer capabilities onboard the sensor modules. Network layer decisions are made based on the quantity of information (size of the data) that needs to be routed and accordingly transmitter power levels are switched as an energy efficient routing strategy. The proposed routing protocol switches radio states based on the received signal strength (RSSI) acquiring only relevant information and piggybacks information in data packets for reduced controlled information exchange. The proposed algorithm has been implemented in Network Simulator (NS2) and the effectiveness of the protocol has been proved in comparison with diffusion paradigm.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Sensor network is a dense spatial distribution of networked devices, serving the purpose of sensing on both civilian and military grounds. The sensor modules incorporate sensing, processing and communicating modules, powered by an energy source (battery). The unique characteristic of sensor network is its inclination towards its utility or application; the entire design of sensor network, hardware and software, are focused on an application. The application biased nature of sensor network has distinguished itself from the conventional IP Network, in terms of operation and functionality, divulging into a field of its own. Also supported by the technological development of Micro-electro-mechanical devices (MEMS), leading to the development of micro and nano scale devices, aiding in the production of small and low cost sensor modules. The development in CMOS technologies has enabled in the production of low energy consuming modules.

1.1 An Overview of Sensor Networks

The advent of sensor network was towards the development of low cost, energy efficient modules with adequate computational power on a low bandwidth wireless capability, with small form factor and functional sensing modules. Typical applications where in military intelligence, surveillance, target tracking and identification. Civilian applications include habitat monitoring and disaster relief operations [21]. Such applications characterized sensor nodes to operate in large numbers, a few hundreds or thousands, and operate in a networked fashion. These applications characterized the sensor network for rapid deployment, self organization, collaborative processing and fault tolerant behavior. The need for low cost modules constrained resources on the node platform and was driven by the fact that deploying fresh nodes would be inexpensive than recovering the node from remote locations. Certain application required powerful sensor modules in addition to the resource constrained modules, sensor networks where designed to support heterogeneity and distributing work load among themselves for increased efficiency. Others also support mobility based on the application and the network was designed to accommodate the changing network dynamics or topology.

However, recent developments and growing applications for sensor networks resulted in new branch of sensor networks in contrast to the initial idealogy, as discussed in the above paragraph. The sensor nodes are deemed powerful modules, with high computational power, cost and energy availability not a limiting factor and high bandwidth connectivity. These sensor modules are deployed in locations accessible for maintenance and redeployment with no limiting factors on the lifetime of the network. The sensor systems can be compared to a powerful ad-hoc node, identifying themselves as a part of the conventional network. However, the network differs in its operating functionality from the IP based network and retains its application specific behavior. Schemes are being developed for a smooth integration of the sensor network with that of the IP based network [12, 15, 16].

1.2 Sensor Network Protocol Stack

The sensor network protocol stack is as shown in fig 1.1 [21] . The stack consists of a physical layer, data link layer, network layer, transport layer and an application layer. Cutting across all these layers are management planes which make the nodes function efficiently as a group. There are three management planes; power management, mobility management and task management plane. The power management plane manages the utilization of power in the sensor node, determines the functionality of each layer depending on the energy availability at the node. In case of low energy, the sensor broadcasts to neighbors on its energy level, its inability to route messages and functions only for sensing events. The mobility management plane acknowledges the changing environment of the sensor network, keeping track of the changing neighbor nodes. The task management plane balances and schedules task among a group of nodes. Acknowledging the distance and density of neighbor nodes, optimizes the radio power levels and resource utilization among nodes. All nodes in close proximity share task efficiently. The management planes are required for a collaborative effort of the networked nodes. As for the implementation of the management layer functionality, these management planes are implemented in one or more layers of the sensor nodes, relying on information from other layers in the protocol stack.

The **Physical Layer** works on the modulation scheme, frequency selection, modeling signal propagation, transmitting and detecting signals. Sensor nodes operate in the ISM band, 915MHz and 2.4GHz band are widely used. ZigBee or 802.15.4 is the widely adopted standard for sensor network. The standard defines the channels of operation, power levels and supports a data rate of 250 Kbps, detailed in chapter 3. ZigBee is adopted by energy aware sensors, while nodes tending to applications which require high bandwidth connectivity follow the Wi-Fi standards. The physical layer design is critical for sensor networks deployed in remote terrains, the physical

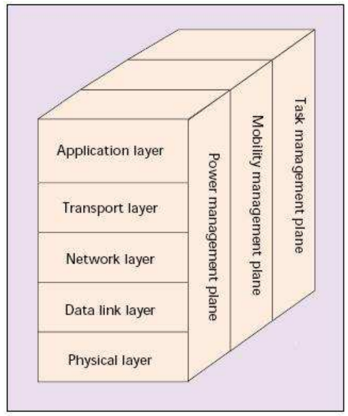


Figure 1.1: Sensor Network Protocol Stack.

environment might be prone to multi-path, shadow regions and interfering signals, which prevent the efficient functioning of the designed physical layer.

The **Data Link Layer** holds responsibility for multiplexing data streams, media access and link level error control. This layer is also referred to as the Media Access Control (MAC) layer. MAC layer is responsible for the efficient usage of the bandwith, with minimum collisions and retransmissions of frames in the network. MAC decides on the communication between entities based on the infrastructure of the network; the system might adopt a fixed allocation or an on demand based channel assignment techniques [21]. The layer should be aware of the changing network topology and should be capable of serving new nodes and detect the absence of nodes, in case of fixed channel assignment schemes. In order to achieve maximum energy efficiency, the amount of control information exchanged should be minimum.

The **Network Layer** functionality largely differentiates sensor network from the conventional network. Sensor network calls for a data-centric routing mechanism, where nodes are queried for a particular data or nodes advertise on detecting an event of interest. With the density of nodes above par in comparison to the capability of the nodes, demands the need for an efficient network layer protocol design. The changing network dynamics and multiple paths existing between a pair of nodes; the network layer needs to determine an optimal path, based on energy and Quality of Service

(QoS) metrics as desired by the application. Moreover, with the dense deployment of sensor nodes ranging from a few hundreds to thousands, an addressing scheme would add to the overhead, thereby forcing a network layer design without an addressing scheme for nodes.

The **Transport Layer** is one of the less researched areas in sensor network, this is because of the data-centric communication system which does not need an efficient transport layer. The transport layer guarantees end to end communication, but in sensor network the concern of every node is in transmitting it to the next hop neighbor and does not follow an end-to-end data delivery model. Transport layer is of growing importance with the integration of sensor network to the IP based network or Internet. Currently, User Datagram Protocol (UDP) is used for sensor networks, since it contributes less overhead compared to Transmission Control Protocol (TCP).

The **Application Layer**, based on information available from the sensor module, advertises sensed data or reports events to querying nodes. The application layer's concern is in delivering useful information interpreted from the sensors raw signals. The application layer is built to support the information delivery mechanism opted by the sensor network, broadcasting information as and when detected to neighbor nodes or reporting events on interest messages received from a central node. The application layer can be supported by intelligence in prioritizing information based on the sensor output or taking remedial action as in the case of sensor cum actuator networks. Sensor Management Protocol (SMP), Task Assignment and Data Advertisement Protocol (TADAP) and Sensor Query and Data Dissemination Protocol (SQDDP) are a few protocols which have been proposed for the Application layer.

The emphasis in this thesis is towards the design of a network layer protocol for wireless sensor networks and the following section detail's the design criteria's and challenges to be considered in designing a network layer protocol for sensor networks

1.3 Challenges in Routing Protocol Design for Sensor Networks

Sensor networks are designed towards a specific application and different architectures have been proposed catering to the needs of a specific application. Though the design challenges for sensor networks would not vary drastically based on application but the priorities of the design issues would vary based on the application. Sensor network's constraints and goals are different from contemporary wireless network design issues, thereby forcing development of new paradigms. In this section some of the design challenges are highlighted with their influence on routing information through a sensor network.

1.3.1 Energy Efficiency

Energy is one of the prime factors to be considered while designing protocols for sensor networks. Energy determines the sensor network's lifetime; defined as the time taken for the first node to fail due to energy depletion. On the sensor node hardware, the development of CMOS technologies has reduced the size and energy consumption in the modules; shifting the energy efficiency paradigm on the development of efficient protocols. The communication circuitry consumes the maximum power compared to all other modules on the sensor node. An efficient protocol design is to have minimum message exchanges, both data and control messages. The transmission power on the wireless channel is proportional to the square of the propagation distance, resorting to multi-hop techniques would be energy efficient compared to direct communication reaching far off distances. In most sensor network platform design, the battery has a large form factor compared to other modules; thus reducing energy consumption, would result in smaller battery modules and would further reduce the form factor of the sensor node.

1.3.2 Network Dynamics

The changing network topology affects the path of data routing. During the initial setup phase of sensor network, random deployment of nodes would result in non-uniform node densities and multiple paths to reach a destination node; an optimal routing path needs to be determined. Mobility of the sensor nodes drastically affects the route stability and necessitates periodic route discovery. Mobility would lead to bottle necks in the network, resting the connectivity of the network on few strategically located nodes. Apart from the nodes the dynamic nature of the sensed event, target tracking application, would demand dynamic path setup and periodic routing, demanding efficient routing mechanism.

1.3.3 Scalability

The number of nodes deployed vary, from a few hundred to thousand nodes, depending on the application or the area of coverage. With no specific addressing scheme or identification for sensor nodes, the routing protocol should be capable of routing without relevance to an addressing scheme. An optimal routing protocol design should be capable of operating over large number of nodes with not much depreciation in performance with increasing number of nodes.

1.3.4 Data Aggregation

Most routing protocols designed for sensor networks are multi-hop and with large number of nodes sensing identical events, a data aggregation mechanism would help reduce redundancy and amount of information transmitted over the radio, thereby saving energy. However, data aggregation should not degrade the performance of the network. Data fusion process would result in nodes waiting for information from neighboring nodes and delay in information delivery to the intended node. Protocols need to tradeoff between aggregation and latency based on nature of the application.

1.3.5 Node Capabilities and Task Balancing

All sensor nodes are designed to perform the basic functionalities of sensing, processing, communicating and relaying information. However, it is not necessary that every node needs to be perform all the operations or identical operations at the same time and each process consumes different energy. Nodes in close spatial proximity can coordinate and balance work among themselves. As an example, one node could sense, one other could relay and another node could be a data aggregation node, wherein all nodes are in close vicinity. Nodes alternate between sleep and wake cycles and uniform energy drain among nodes would be ideal. This is to avoid hot spots in the network; meaning all nodes in a certain spatial location have failed leaving a hole in the region being sensed. Also, task balancing helps in achieving increased network lifetime.

1.3.6 Quality of Service (QoS) Requirements

The primary focus on routing protocol design has been in achieving energy efficiency and increased network lifetime. However, the quality of data cannot be compromised in certain critical applications, though energy is also of prime importance in those applications. Sensor networks do not have a definite path for an end-to-end delivery, but the QoS focus is on an end-to-end delivery in the present setup with minimum time delay and bandwidth, yet retaining the energy efficiency paradigm.

1.4 Contribution

This thesis work details on a cross layer routing strategy for wireless sensor networks; proposed a network layer protocol where in the application layer information and the capabilities of the physical layer influence the network layer decisions. The protocol considers volume of data has an important criterion for determining the next hop node and suggests switching transmitter power levels as an energy efficient strategy for routing packets. The thesis also suggests a method of switching OFF unintended receivers based on the radio signal strength at the receiver end. The thesis is aimed at increasing the lifetime of the wireless sensor network and reducing the end-to-end delay in delivering the data, from the proposed algorithm.

1.5 Thesis Outline

Chapter 1 was aimed on introducing sensor networks and the network layer for sensor networks, also outlined the design challenges for an efficient routing protocol for sensor networks. Chapter 2 presents a literature review of existing routing protocols developed for sensor networks, with an insight into the pros and cons of each protocol. Chapter 3 details the proposed algorithm, arriving at a cost function and differentiated service, based on the volume of the data to be routed. Chapter 4 details on the implementation of the protocol in ns2, an event simulator. Chapter 5 draws a comparison of the proposed protocol with the existing protocol and results are analyzed. Chapters 6 concludes with the authors contribution towards the thesis and further scope of development.

Chapter 2

Routing Protocols for Wireless Sensor Networks - A Review

With innumerable applications of wireless sensor networks and limited in terms of energy availability, computational power and wireless connectivity; a number of protocols have been proposed specific to a genre of applications with optimal usage of available resources. One of the main objective in designing protocols was towards an extended network life time and also satisfying the design challenges, as detailed in the previous chapter. This chapter classifies routing protocols, followed by an elaborate discussion on the routing algorithms and current research focus in the design of efficient routing mechanisms [6], [4].

2.1 Classification of Routing Protocols

Several routing protocols have been proposed with different priorities on the design requirements and focus towards varied applications. This section is attempted on grouping protocols into a common genre based on their behavioral characteristics.

In general, routing protocols can be classified as *Proactive* or *Reactive*, based on the time the routing decisions are made. In proactive routing mechanisms, the network paths are devised on sensor deployment, irrespective of a sensed event or data availability for routing. As in the case of reactive routing, route path setup is triggered by an event. Reactive protocols have the disadvantage of a delayed information delivery since the routing decisions are triggered by events, but energy efficient compared to that of proactive, wherein active paths are maintained even in the absence of an event or data.

Routing protocols for wireless sensor networks can also be classified as *flat multi-hop, hierarchial* and *location-based*, a classification based on the communication architecture or interaction between sensor nodes. Flat multi-hop routing, a localized approach with communication restricted within neighbor nodes and distant neighbors are reached through multiple hops. In a flat schema all nodes are assumed to have the same functionality. In contrast to the flat schema, the hierarchial approach supports heterogeneity both in terms of node resources and functionality. Hierarchial routing model is a cluster based approach, wherein nodes in the neighborhood directly communicate to a more capable central node. Location based protocols are an extension to the cluster based approach, wherein the sensor nodes in a geographical region group and interact. This class of sensor network nodes are capable of identifying themselves in terms of location based attributes.

One other method of classification is based on the data aggregation capability of the nodes. While routing information, nodes fuse their data with that of the neighbors data before being routed, without processing the data. These protocols are referred to as *Non-Coherent Routing* protocols. *Coherent Routing* protocols process the data and fuse data before relaying, to the next hop node, thereby reducing data redundancy. Coherent protocols also have the advantage of reduced transmission overhead.

Routing protocols can also be classified as *Push* or *Pull* protocols, classified on how data is disseminated in the sensor network. In Push protocols the sensor nodes on identifying an event advertise it throughout the network. In the case of Pull protocols, user queries through the sensor network for information. Protocols may be Pull or Push based on the application the sensor network is deployed.

Most of the routing protocols proposed for sensor networks had energy efficiency and network lifetime as their performance measures. Adding on to these measures, applications required guaranteed data delivery models, such protocols where in general labeled *Quality of Service(QoS) Aware* protocols. The protocols addressed the issues of an end-to-end guaranteed data delivery, latency in acknowledging the data from the network, prioritizing the data and supporting real time data streams.

2.2 Routing Techniques

Having discussed on the grouping of sensor network protocols, this section details on individual protocols grouped as multi-hop, cluster based, location based and QoS aware routing techniques. Prior to the design of routing algorithms specifically for sensor networks, **Flooding** and **Gossiping** where the two classical methods of routing data through a sensor network. Flooding is a simple broadcast mechanism, wherein each sensor node broadcast received packet to its neighbors. The process continues until the packet reaches the destination or the maximum hop count of the packet is reached. In gossiping, a node picks up a neighbor in random and forwards the packet. Flooding has drawbacks of implosion, a node receiving multiple copies of the same data and has no consideration for energy utilized. Gossiping avoids the problem of implosion but adds to the delay in the packet reaching the destination and also there is a probability of nodes not receiving the data packet.

2.2.1 Multi-hop Routing Protocols

This subsection details routing protocols that use multiple paths rather than a single hop to reach the destination. The inherent advantage of these protocols is that they need not know the nodes other than their neighbor nodes. These set of protocols have a high fault tolerance as they are aware of or have a choice of multiple paths to reach a destination. Nodes periodically acknowledge the presence of their neighbors, which is an energy consuming process. However, the extent of neighborhood information a node maintains and the number of alternate paths setup by a node is protocol specific.

Sensor Protocols for Information via Negotiation(SPIN), a reactive push protocol [35]. SPIN compiled sensor nodes disseminate information as meta-data (short, high level descriptors of the sensed event) to other nodes in the network. Interested nodes on receiving the meta-data information query the node for more information or the data, as illustrated in fig. 2.1 [35]. SPIN protocol acknowledges the fact that neighbors do have the same information and distribute meta-data to far off nodes. SPIN protocol implements data exchange through three messages; ADV to advertise meta-data, REQ request for actual data on receiving the meta-data, DATA message the actual information. The semantics of the meta-data are application specific. The working group of SPIN proposed a family of SPIN protocols suiting varied network topologies and energy aware schemes. Adding on to the basic SPIN protocol, a family of SPIN protocols where proposed viewing energy awareness and network topologies. SPIN-2 nodes incorporated an energy threshold scheme, nodes below a set threshold would not participate in the meta-data cycle and would only sense for events. Other protocols of the SPIN family [20] are SPIN-BC, for broadcast channels, SPIN-PP for point to point communication (multi-hop), SPIN-EC for energy aware point to point communication and SPIN-RL accounting for lossy channel characteristics.

SPIN has advantages over flooding and gossiping by reducing redundancy in the information being transmitted and turns out to be energy conserving. However, SPIN can be viewed as a process of controlled flooding, relaying meta-data to nodes that would never require it, a source of energy drain. If the source and the destinations

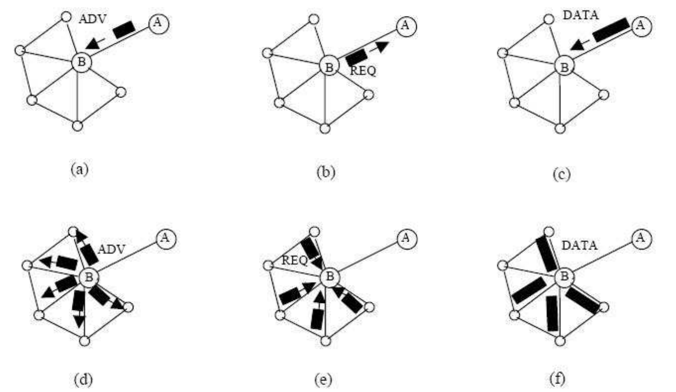


Figure 2.1: SPIN Protocol: (a) meta-data advertisement from A to B (b) Node B requests for DATA (c) Node A replies to B with DATA (d),(e),(f) the process repeats from Node B to its neighbors

nodes are farther apart all the intermediate nodes maintain state and information about the data being delivered across end entities. The meta-data mechanism does not guarantee data delivery to distant nodes, intermediate nodes might not find the information useful and may not advertise to its neighbors, resulting in events not being reported to the sink nodes. However, SPIN has the advantage of being localized to topological changes, since they maintain information on only there one hop neighbor. The concept of meta data helps in querying data at any node for relevant information on the network, rather than flooding interest to the network in search of events. SPIN turns out to be an adaptive and reliable data dissemination model.

Directed Diffusion a query based, on demand PULL protocol [11]. Directed diffusion supports a naming scheme for data identification and data is identified by an attribute value pair. Sensor node, referred to as the sink, query the sensor network with information of interest identified by a set of attributes and the interest message is propagated through the network, a controlled flooding mechanism. The propagated interest message are cached at all sensor nodes for a short time stamp. Sensor nodes with matching data attributes respond to the interest message, these nodes are referred to as the source nodes, illustrated in fig 2.2. Directed diffusion

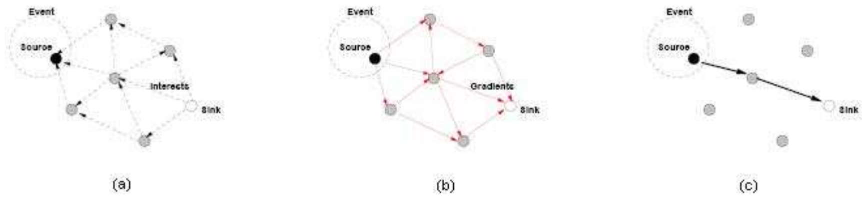


Figure 2.2: Directed Diffusion (a) Interest Propagation Phase (b) Gradient Setup Phase (c)Data Dessimination Phase.

operates in three phases, the interest propagation phase, followed by gradient setup phase and information dissemination phase. Gradients are setup for relaying back information to the sink node. The final phase of data dissemination, wherein paths are reinforcement and data is delivered from source to sink along the path established with the help of gradients. Path reinforcement also aids in data aggregation and setting up routes for further information querying and dissemination. The directed diffusion discussed is refereed to as the Two Phase Pull Diffusion, turns out to have lot of information exchange and inefficient for applications where in many interest are diffused through the sensor network. Two other variants of directed diffusion have been proposed [14] suiting various applications, the Push Diffusion and the One Phase Pull Diffusion. Push diffusion was designed to overcome the problem of maintaining gradients in applications, wherein information disseminated from the network is low and maintaining gradients is expensive in terms of energy. In push diffusion, the functionality of the source and the sink are reversed, the sink node becomes passive and source becomes active and publishes exploratory data messages. Gradients are established and paths are reinforced by exploratory data to the sink, avoiding the process of setting up interest gradients as in the case of two phase pull diffusion. When the exploratory data reaches the sink, reinforcement messages are sent back to the source, setting up gradients, followed by data on the gradient path to the sink. One Phase Pull Diffusion turns out to be more energy efficient than Push Diffusion, wherein data are sent to sink along preferred gradients identified by neighboring nodes minimum latency path. Neither interest reinforcement messages nor exploratory data messages are sent out in this schema.

Directed diffusion and SPIN were the first few protocols addressed specifically for sensor networks and had contrasting methods of information dissemination. Directed diffusion turned out to be more application oriented due to the attribute naming characteristics of the sensor network. Directed Diffusion has the advantages of restricting to local topology dependence and the inherent data aggregation capability is highly energy efficient. The attribute matching at the nodes requires comparatively higher intelligence at the sensor nodes incorporating directed diffusion. Since interests are cached for short time interval, periodically interest needs to be broadcasted into the network. On the other hand, caching interest for a long period of time questions the buffer requirements at the sensor nodes. Directed diffusion is one of the successful routing protocols for sensor Networks and many real world functioning models have incorporated directed diffusion as there routing technique. Also, most routing protocols are designed on top of directed diffusion and compared with directed diffusion as a bench mark for performance.

Rumor Routing [7], identified as conservative flooding or a restricted diffusion mechanism. Rumor routing is a variant of directed diffusion and finds application where geographic routing mechanism is not feasible. The idea is to flood data to those nodes that have detected a similar event of interest rather than flooding the entire network. Event is flooded to other nodes with the help of long lived packets, called agents. When a node senses a event, stores it in its local event table, and generates an agent which carries event information to distant nodes in the network. Nodes on receiving an agent store the information on their event table and the agents path serve as reinforced path for routing information. Nodes respond to query based on the information stored in the event table.

Rumor routing outperforms directed diffusion with limited flooding, however rumor routing suits applications wherein the information through the network is less and the number of events is less. With higher number of events reported the memory buffer on the sensor nodes would be a limiting factor. The protocol agent based scheme limits only a single path of communication between the source and destination, as opposed to directed diffusion. Rumor route results in additional overhead associated in maintaining the state of the agent and the event tables.

Energy Aware Routing Network survivability or elongated network lifetime was the major design goal while sketching this protocol [32]. The protocol highlights the fact that solely relying on optimal paths would exhaust the nodes along the path and depreciate the network lifetime; highlighting the employment of suboptimal paths for routing. Each node maintains a list of paths to reach a particular destination with a probability measure based on an energy metric. The node chooses a path for transmission based on the probability distribution. The protocol has three phases of operation, the initial setup or interest propagation phase wherein localized flooding takes place to associate an energy metric for all the paths. The energy metric cost function is based on the transmission and reception energy and the residual energy in every node. The second phase - data communication phase, paths chosen from the node's forwarding table based on the probabilities. The final phase -route maintenance phase, localized flooding to maintain and acknowledge live paths between nodes.

Built over the directed diffusion paradigm with the notion of network survivability, the protocol was proven to be energy conserving compared to directed diffusion. However, the list of paths that needs to be maintained on the nodes demands greater capability from the sensor nodes. Though proved to be energy saving the setup and maintenance phase consume a lot of energy. The network is proven to be effective over a limited number of nodes, its efficiency and memory requirements would be questionable with larger number of nodes. Also increased protocol complexity, as the number of paths to be maintained and the number of nodes in the sensor network increase.

Gradient Based Routing (GBR) [31] a variant of directed diffusion wherein the focus is on data fusion and uniform traffic distribution through the network for optimal routing. When interest is diffused through the network, the hop count of the message is acknowledged and incremented at every node. Each node discovers the minimum number of hops required to reach a particular node. The hop count is referred to as the height of the node. The difference between the node's height and that of its neighbor is considered as gradient of the link. Node forwards packet on the link with the highest gradient. The paper details three data spreading techniques for uniform traffic distribution. Stochastic scheme, the node chooses to route to the next neighboring node randomly, when neighboring nodes have the same gradient. Energy based scheme, when a nodes energy falls below a threshold, it increases its height so that other sensors are discouraged from sending data to that node. Stream based scheme, nodes routing a stream of data increase their height thereby diverting new stream of data through other nodes.

The protocol is proved to have communication energy saving compared to that of directed diffusion. This can be attributed to the focus on data aggregation and uniform traffic distribution schemes. Data aggregation reduces the overhead in comparison to transmitting individual entities, effectively reduces the quantum of data communicated. Moreover, uniform traffic distribution splits the load evenly among nodes in neighborhood, energy consumption is also uniformly distributed among nodes, similar to the above discussed protocol. These factors attribute to the increased lifetime of the network.

ACtive QUery based forwarding In sensoR nEtworks (ACQUIRE), a data centric, distributed query based routing protocol [27]. The sensor network is seen as distributed data base and capable of answering complex queries, consisting of sub queries. A complex query is routed to a node in the sensor network, the node answers the sub queries based on the pre-cached information available at that node. Nodes unable to answer all the queries, forwards the query to the next node within 'd' hop counts. Where 'd' is referred as the look ahead parameter, which limits on the number of hop counts in handing over the query to the next node. When 'd' is large then the routing protocol would simulate flooding with smaller values of 'd' the query would have to hop among larger number of nodes. A mathematical model has been proposed to find out the optimal value of 'd', which was found out to be four. However, at a point when the query has been fully answered the node returns the packet to the central node along the reverse path or the shortest path. The basis of handing the query to the next node is random.

This process of iterative querying turns out to be energy efficient, but the delay incurred in solving a query would be high and does not suit time critical applications. If the query has been handed over to nodes far-off from the location where the event has been sensed, the protocol adds to the delay in solving the query. A knowledge of geographic aware routing or intelligently routing to nodes based on a probabilistic model or prior information exchange from the nodes, would fasten the process of querying.

Information Driven Sensor Query (IDSQ) and Constrained Anisotropic Diffusion Routing (CADR) [25], the protocol is based on an information utility measure on selecting which sensor to query and to dynamically route data. The information utility measure is a mathematical quantification of the amount of information gain that can be obtained by accessing a sensor node. IDSQ, works on selecting the optimal node to query while CADR defines on how to query a node and routing to the particular node. IDSQ works on electing a leader node among a group of nodes and the leader node has knowledge of the position of the sensors. This grouping of nodes with a leader node does not categorize this protocol as a cluster based routing scheme, since this is just a virtual group for co-ordination among nodes for information exchange, with no implication on the routing mechanism. The leader node establishes a belief state for every node in its cluster; based on the information it can process from the nodes. The belief state is function of the information utility measure, also depending on the application and the computational power of the node. If the belief state is satisfactory then the node is queried; if the belief state is not satisfactory the leader selects another node based on its position and information utility measure. The leader node updates the belief state of a node on every query to the node until a sufficient belief state has been reached. CADR, based on the decisions made by IDSQ device route path to the sensors. CADR resembles directed diffusion, with routing decisions made with or without the knowledge of position of the sensors. If the location of the sensors are know, route is addressed to the sensor, arriving at an optimal solution. The optimal solution is based on the evaluation of a composite objective function; a cost function on information transfer utility, depends on querying, routing, bandwidth and latency. In absence of information on the position of the sensor, local decisions are made at every node satisfying a composite objective function.

The protocol set maximizes information gain, with minimum latency and bandwidth. The algorithm was proven to be more energy efficient compared to directed diffusion, at the cost of increased protocol complexity. The protocol differentiates itself from existing protocols by considering information gain along with communication cost parameters. The computational complexity associated with the protocol raises high requirements on the nodes capability.

COUGAR, a data-centric protocol [39] views the sensor network as a distributed database system, using declarative queries to abstract information from the network. Declarative queries meaning query states what to look for in the network and not concerned on how to look for the data in the network. A query optimizer generates an efficient query plan for in-network query processing based on the users query. The author proposes an abstract query layer between the application and network layer to serve the purpose of efficient querying. The queries generated are independent of the network layer. COUGAR implements in-network data aggregation whereby one node is selected as the leader node which performs aggregation and transmits the data to the central node. The central node generates a query plan, which details the data flow, in-network data aggregation mechanism and selecting an optimal leader node, which in turn is processed at the query layer of the sensor nodes.

COUGAR's in-network aggregation reduces the overhead and ensures energy efficiency on transmission of aggregated information. Introducing a new abstract layer would turn out to be burdensome on the resource constrained nodes and adds extra overhead on the node in terms of energy consumption and storage capability. The process of in-network data aggregation from several nodes requires synchronization between nodes and relaying nodes wait for packets from neighboring nodes, before sending data to the leader node. Leader nodes are dynamically selected considering energy availability on the nodes.

2.2.2 Cluster Based Routing Protocols

The process of creating clusters and cluster head contribute to the overall system scalability, lifetime and energy efficiency. It supports heterogeneous sensor network by allowing powerful nodes to perform energy consuming tasks and the other nodes simply serve the purpose of sensing. The data delivery is in two stages, nodes communicate with a cluster head and the cluster head in turn needs to communicate with the base station. The cluster based architecture demands heavy functionality from the cluster head and the nodes highly rely on the cluster head. In heterogenous networks with failure of cluster heads, the nodes might turn out to be useless with no link to communicate with the base. In the case of homogenous sensor network, any node might be elected as the cluster head, also nodes alternate as cluster heads for even power drain among all nodes in the network. This subsection details a few hierarchial cluster-based algorithms.

Low Energy Adaptive Clustering Hierarchy (LEACH) cluster based energy efficient data aggregation mechanism; functioning as a self organizing adaptive dynamic protocol [36]. Nodes in spacial proximity group to form a cluster with one of them opted as a cluster head. Nodes directly communicate within the cluster to the cluster head, information within a cluster is aggregated at the cluster head and then the cluster head transmits a single aggregated message to the central node. On random intervals new cluster heads are elected and nodes join cluster heads in close spatial proximity. The periodic change in cluster head is for uniform energy dissipation among nodes in the sensor network. Within a cluster communication follows a Time Division Multiple Access (TDMA) schema, nodes communicate to the head at periodic time slots. The setting up of LEACH is a two phase operation, the setup phase and the steady state phase. The setup phase is when the clusters are organized and actual data transfer takes place at the steady state phase. The duration of the steady state phase is longer than the setup phase. The selection of the Cluster head is based on a probabilistic model, where each node opt itself as the cluster head and broadcasts it over the radio. Based on the received signal power nodes identify the closest head and join the network.

LEACH, the first of its kind, emphasizing grouping as an energy efficient technique, but limiting itself to a specific applications. The direct communication between the cluster head and the base is energy consuming. There is a possibility of a formation of hole in the network, wherein a node might not hear a cluster head's advertisement; also the possibility of two many cluster head's in close vicinity, as the decisions are on an independent basis. The cluster head communicates to the central node using Code Division Multiple Access (CDMA) technique. This demands the nodes participating in LEACH to be highly capable supporting two different Network, Medium Access Control (MAC) and Physical layers. The idea of cluster formation brings in overhead in communication and synchronization needs between the cluster head and the nodes belonging to the cluster. The protocol also assumes that all cluster heads consume the same amount of energy, which is not true, energy consumption varies on the location of the cluster head and number of nodes in the cluster. LEACH would not suit for sensor network deployment over large areas since the distance between the cluster head and central node would be far off for certain extreme nodes, demanding more energy for transmission, this in turn might result in faster energy drain in distant nodes. LEACH was found to be efficient and said to have an extended lifetime compared to that of SPIN and directed diffusion.

Power Efficient GAthering using Sensor Information System (PEGASIS) and Hierarchial PEGASIS, a data aggregation protocol wherein neighboring nodes communicate to form a chain link for the sole purpose of data fusion. Nodes exchange information only with their closest neighbor, node's sense closest neighbor based on the radio power and adjusts it radio power to reach the closest neighbor only. The formation of chain links is a greedy algorithm with nodes grouping to form a cluster head, the construction of chain starts from the farthest node within a cluster, since they have the least choice of neighbors. As a chain is formed and a node is fixed to co-operate with a neighbor, the setup process shall never be revisited until a neighbor dies. The chain link formed is the basis for data aggregation mechanism, the cluster head broadcasts to the base station and the nodes within a cluster alternate to act as cluster head, resulting in an uniform energy drain within nodes in a cluster.

The protocol was found to be energy efficient than LEACH. PEGASIS [22] aimed at an extended lifetime for the nodes, thereby increased the overall network lifetime, doubled in comparison with LEACH. The inherent disadvantage of this system is the excessive delay involved in data aggregation, which turns down PEGASIS from time critical applications. PEGASIS had an advantage of reduced communication overhead in comparision with LEACH.

Hierarchial PEGASIS [29] was proposed to overcome the delay involved in the PEGASIS model. The protocol proposed a shift from sequential data acquisition as in PEGASIS to a simultaneous data aggregation technique. Pairs of nodes in close proximity can communicate simulataneosly among themselves without causing disturbance. Pairs of nodes communicate and one of them inturn communincate with another node, this communication results in a tree hierarchy as shown in the fig 2.3 [29]. A protocol supported a CDMA scheme and a non-CDMA scheme of communication. The CDMA scheme supported communication among large pairs of nodes simultaneous and did not have any restrictions on the hierarchy level. The non-CDMA version had a restriction on the number of nodes that would communicate and limited to only three levels in the tree hierarchy. The hierarchial version had achieved significant reduction in delay involved in data fusion. The CDMA version had comparatively lesser delay than the non-CDMA version. The complexity of the protocol grew higher compared to that of its parent, communication overhead increased as the complexity of the topology increased and node failures needed to be sorted out more intelligently.

Threshold sensitive Energy Efficient (TEEN) and Adaptive Threshold sensitive Energy Efficient (APTEEN) Sensor Network Protocol, a hierarchial cluster based protocol responding to abnormality in measuring the attributes based on predetermined thresholds. Nodes group to form a cluster with a cluster head, similar to that of LEACH approach and cluster heads communicate on a multi-hop

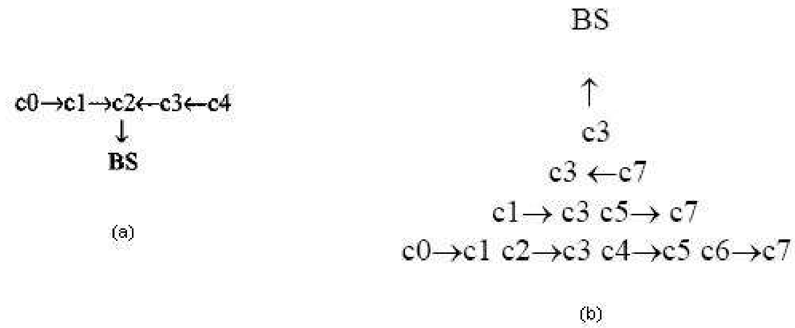


Figure 2.3: PEGASIS and Hierarchial PEGASIS (a) Data aggregation in PEGASIS (b) Data aggregation in Hierarchial PEGASIS.

fashion as illustrated in Fig 2.4 [2]. The protocol can be grouped as a reactive protocol as the nodes are responsive to events and data would be generated triggered by abnormality over thresholds. The algorithm works on two thresholds, a hard threshold and a soft threshold. Once the cluster based network topology is setup the threshold information is sent to the cluster heads, which in turn transmit to the nodes. When the sensed attribute changes by the hard threshold, the node reports to its cluster head. On sensing the hard threshold level, the next communication in the network would take place only after the sensed attribute changes by the soft threshold.

The threshold mechanism orients the protocol to be application specific. The soft threshold saves on the number of transmission that would have occurred when there was no change in the sensed attribute. The TEEN [2] protocol simply follows this threshold mechanism and achieves energy efficiency by reducing the number of communications. The drawback of the TEEN protocol is that when the sensed attributes remain unaltered no information is transmitted. This raises doubts on the existence of the nodes, alive or dead. Moreover, this technique is not suitable for end users wanting periodic updates on the sensed attributes. To overcome the limitations posed by TEEN, APTEEN [24] was proposed where in periodic updates of the sensed phenomenon are over the network. APTEEN turned out to be proactive and compromised on the energy efficient data delivery model of TEEN. The reactive

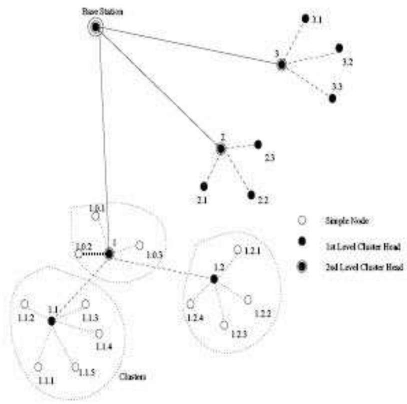


Figure 2.4: Hierarchial Clustering

property of TEEN was restored in APTEEN by responding to the threshold changes apart from periodic data delivery. TEEN and APTEEN turned out to be efficient for time critical applications and better performers than LEACH. It is also evident that TEEN is more energy efficient than APTEEN, absence of periodic data delivery in TEEN. However, the serious limitations of the set of protocols is in their application specific nature and setting up of multi-hop route among cluster heads, which change over random time intervals.

Energy Aware Routing in Cluster Based Sensor Networks [26], a routing protocol for heterogenous sensor network. This is a proactive routing mechanism, the cluster head is considered to be a powerful node, less constraint in terms of computational power or energy availability compared to the other node in the network. The cluster head also referred to as the gateway is aware of the location of all nodes in the network. The sensors nodes operate in either of the four states based on the instructions from the gateway node; sensing only, relaying only, sensing & relaying and inactive state; the functionality of each state is evident from their names. The gateway node decides on the route by instructing each node in the network to communicate with whom and when. The decisions are made to conserve energy based on a cost function. The cost function relies on the communication cost, energy availability at the node, energy consumption rate, node relaying cost, node sensing cost, maximum connections per relay, propagation delay and queuing cost. Node's communicate in a TDMA scheme, node's have a fixed assigned time slot for transmission and reception in the network. The gateway communicate's with other gateways and with the central base station.

The protocol was found to outperform other clustering protocols in energy metrics, network life time; and also in quality metrics, throughput and end-to-end delay. The route setup changes to accommodate the changing the network dynamics. The performance of this protocol is reliable and efficient; but the bottleneck is the powerful gateway module. The deployment of these nodes need to be organized; on random deployment nodes might be far apart from the gateway and would fail to be a part of the network.

Self Organizing Protocol (SOP) [33], a hierarchial routing protocol for heterogenous sensor network; stationary and mobile sensor nodes. The protocol relies on a set of fixed nodes, called routers, as the backbone of the sensor networks and the rest of the fixed or mobile sensor nodes probe in the neighborhood in search of router nodes; forwarding information to the router node. The routers in turn communicate among themselves and to the central querying base station. All sensing nodes, mobile or stationary, are networked with the router to be a part of the sensor network. The protocol supports an addressing scheme for identifying all nodes in the network and all nodes in the network are addressed based on the router node they are tied to. Mobile sensing modules report to the router in close spatial proximity. The hierarchial network frame is organized in four phases; Discovery phase, each node independently discovers its neighbors and fixes its maximum radius of data transmission. Organization phase, the node aggregates into a group and a hierarchy of group is formed in the network. Each node gets an address and a routing table is computed for every node in the network. Maintenance phase, nodes keep track of their stored energy and periodically broadcast to their neighbors; nodes periodically update their routing table and energy level information of their neighbor nodes. Finally, self reorganization phase, nodes detect failures and changes are reflected on the routing table of the nodes. In case of network partition due to node failures, group reorganizations are performed.

The hierarchial routing protocol has the benefits of good network connectivity, the addressing schemes help in querying individual nodes and energy saving by operating only on a subset of nodes. The cost of maintaining network routing table is minimum and broadcasting is less energy consuming due to the hierarchial structure of the network. The disadvantage is in the long organization phase and re-organization phase on a string of node failures. The protocol could be more efficient if it worked in an on-demand reactive basis, since a considerable amount of energy is utilized in maintaining the network while no event has occurred.

2.2.3 Location Aware Routing Protocols

Location aware routing protocols are also referred to as geometric or localized routing protocols. The nodes are identified based on a coordinate system, could be based on latitude/longitude or could be a user defined coordinate system. Global positioning system's (GPS) have been proposed to identify the system on a global scope, but its feasibility and cost is questioned. Simple localization techniques, like triangulation, have been employed which can be used to identify the position of a sensor node relative to the position of neighbor node. The routing protocols proposed have taken it for granted all nodes are position aware and feasible routing protocols have been proposed.

Geographic Energy Aware Routing (GEAR) [37] protocol proposes the use of geographic information for disseminating queries within a sensor network. The protocol works on energy aware and geographically-informed neighborhood selection heuristics to route packets towards a target destination. The protocol, acknowledged as an extension of directed diffusion, limits interest dissemination to appropriate regions. The energy efficiency paradigm is based on a set of cost function's; learning cost and estimated cost of reaching destination. The estimated cost is based on the residual energy at a node and distance to destination. The learned cost is the estimated cost of routing around a hole in the network. A hole occurs in the absence of a neighbor closer to the target region than itself. The node needs to find a route to get around the hole, the cost estimate is framed from the learned cost. In the absence of the hole, the learned cost equals the estimated cost and forwarding decisions are based on the estimated cost. The learned cost is propagated one hop back for reiterating route setup on the next packet. The protocol has a two phased operation; forwarding packets to a target region and forwarding packets within a region, as in fig 2.5. Forwarding packets to a target region is based on the cost function and determining the next hop neighbor closest to the target region. Once at the target region, forwarding packets within the region is through recursive geographic forwarding or restrictive flooding within the region. If the region is wide spread or high density of nodes, the region is split into sub regions, copies of the packet are created and are forwarded to the target regions.

With knowledge of geographic information GEAR has achieved better efficiency in comparison with directed diffusion. Also GEAR floods region faster by creating copies of data. GEAR can be grouped as a cluster based protocol wherein nodes belonging to a region form a cluster, but their operation is a multi-hop and non-hierarchial unlike the general group of cluster based protocol. GEAR is considered to be a development over GPSR, a protocol for adhoc wireless networks which used geographical information for routing with no emphasis on energy metric.

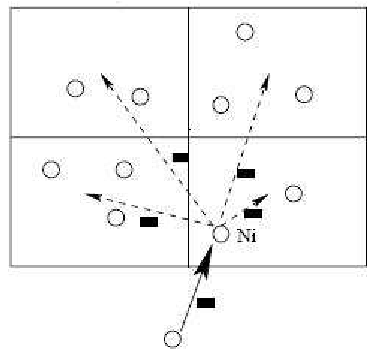
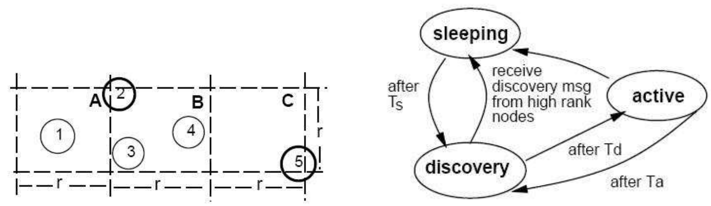


Figure 2.5: GEAR: Recursive Geographic Forwarding

Geographic Adaptive Fidelity(GAF) a location based energy aware routing protocol for wireless sensor networks though primarily designed for mobile ad-hoc networks. GAF [38] works on dividing the network into virtual grids and nodes identify themselves on the grid knowing their positions with the help of a global positioning system (GPS). Within a grid nodes are identified identically and nodes within a grid collaborate among themselves. Nodes within a grid elect one node to stay awake over a certain period of time and nodes alternate within a grid. The node awake acts as the cluster head reporting to the base station on happenings within the grid and also controls the nodes in the network. GAF programmed nodes operate in three states, as illustrated in fig 2.6 [38]; Discovery, Sleep and Active state. Nodes periodically get into the discovery phase, during the discovery state the node's look for neighbors, new mobile nodes might have moved into the grid and existing nodes might have died or moved to new grids. In the sleep state, the node is in the minimum energy consumption state with only their sensing modules ON and all other modules are switched OFF. Nodes are active when they act as the leader or when the nodes within a grid have sensed an event. Nodes utilize maximum energy in the active state. GAF supports multi-hop routing among clusters head in reaching the central base station, this identifies the protocol as a hierarchial protocol.



(a) (b)

Figure 2.6: GAF(a)Virtual Grids in GAF (b)State Transitions in GAF

GAF shows an increase in network lifetime as the density of nodes within a cluster increase. The fact that all nodes are identical within a grid and one node awake all the time, ensures network connectivity and contributes to the extended network lifetime. The high end assumption that all nodes identify themselves through a GPS, might not fit all category of sensor network applications where cost of the node is of great concern. Moreover, the power consumption on identifying nodes on a GPS system is not accounted for energy consumption. The leader node does not support any data aggregation or fusion mechanisms; this feature would have added up towards the efficiency of the protocol. GAF inherently supports mobility and its performance is comparable with ad-hoc networks in terms of latency and packet loss.

2.2.4 QoS Supportive Routing Protocols

In the above groups of routing protocols the emphasis was on energy efficiency and focused on increased network lifetime, with little concern on quality measures. This group of routing protocols in addition to the energy efficiency focus on QoS metrics such as latency, bandwidth and efficiency. QoS based protocols emphasize on acknowledging the data at the right time, differentiating data based on priorities and propose reliable routing algorithms. The protocols are concerned on the network fault tolerance and resilience of the network on node failures or node malfunctioning. Based on QoS metrics a few protocols have been elaborated.

Sequential Assignment Routing (SAR) [18] one of the first QoS based routing protocols for sensor networks. Routing decisions where made based on the energy consumption along the path, QoS metrics, such as delay and bandwidth, and priorities of each packet. A multi-path tree structure is formed from the source down to every sink or base stations in the network; every node in the network is a part of the tree structure. The network is resilient to node failures along a path as multiple paths exist between a source and the base station. The paths are void of nodes with low energy and unable to provide QoS guarantees. Each link in the path contributes towards the end-to-end cost metric as measure of resistance to the packet flow through that path; this information is used in framing an additive metric of the traffic flow through that path. A weighted QoS metric is calculated as the product of the additive QoS metric and a weighted coefficient associated with the priority of each packet. A node failure causes automatic path restoration locally. For dynamic sensor networks and to enforce path reliability, the base station initiates periodic re-computation of the path thereby accommodating changes in the network.

SAR turned out to be more energy efficient than protocols that considered only energy as a metric and ignored the priorities of packets. Having multiple paths between the source and the sink ensures guaranteed data delivery and fault tolerance. However, the protocol suffers from excessive overhead of maintaining tables and state at each sensor node especially when the number of nodes in the network is high. A recovery procedure is enforced when a node fails locally and periodic path reinforcement, maintaining routing path consistency between upstream and downstream nodes on each path. This proactive characteristics of the protocol turns out to be an energy consuming procedure for the network which has not detected any event. One nodes failure might result in a dramatic change in the network tree structure, as traffic through a node is a cost function metric.

SPEED, a stateless, localized QoS based routing protocol with minimum overhead and end-to-end guarantees. SPEED's QoS metric is the ability to maintain a desired delivery speed across the network, hence the name SPEED [34]. The protocol maintains information about neighbors and geographic information of the nodes in finding a quick route. The end-to-end delay estimate is made knowing the distance between the source and sink and the speed of the packet before route decisions are made at the nodes. Stateless Non-deterministic Geographic Forwarding Algorithm (SNGF) is the main routing module of SPEED, works on choosing the next hop nodes targeting a desired delivery speed and within a theoretical delay bound. SNGF co-ordinates with four other modules in making routing decisions. Neighbor beacon exchange module for periodic information exchange between nodes, gathering information about the nodes and their location. The rate at which neighborhood beacons are exchanged depends on the network dynamics; a static or slow moving nodes in the sensor network would have a low beacon rate. SPEED employs a single hop delay as a metric to approximate the load on the node. Assisted by the delay estimation module, the time elapsed to receive an acknowledgement in response to a packet sent to a neighbor gives the delay estimate. The delay estimated helps in selecting the next hop node. If a decision could not be made with the delay estimate, Neighborhood feedback loop module calculates the relay ratios of node. The relay ratio is calculated with respect to the neighbors of the node which could not provide the desired speed on earlier requests. The fourth module, Backpressure Rerouting module, alarms the source if packets are dropped at nodes unable to find the next hop neighbor, thereby initiating new routes at the source.

SPEED provides a reliable data delivery model with uniform speed for time critical real-time applications. The protocol has information of its immediate neighbors and does not maintain any routing table, thus described to be a stateless routing protocol. SPEED's congestion control mechanism dismissed the need for a QoS aware

MAC protocol. But this function of SPEED brushes off the advantages of a layered protocol architecture, burdening the network layer with too many functionalities. SPEED's SNGF module achieves load balancing by relaying the traffic across different paths, backing an energy efficient mechanism.

Maximum Life Time Routing in Wireless Sensor Networks [8], works on formulating the routing issue as an optimization problem with the goal of maximizing the sensor network lifetime; considering the fact that the communication circuitry consumes the maximum power in routing and making use of nodes with maximum residual energy for relaying information on the network. The protocol is intended for identifying the traffic pattern in the network for routing. Two traffic patterns are considered, fixed information generation and arbitrary information generation; and a flow augmentation algorithm is proposed which iteratively augments the flow along the shortest cost path. The routing issue is formulated as a linear programming problem, solvable in polynomial time. The objective was to find the best link cost function to maximize the network lifetime. The parameters that were considered for calculating the cost over the link are energy expenditure for unit data transmission over the link, the initial energy before transmission and the residual energy on the nodes. Importance is given to the residual energy in the node on transmission rather than the shortest path or minimum energy path. The least cost path solution is formulated using Bellman-Ford Algorithm, whose residual energy is largest among all paths.

The protocol emphasizes on the residual energy for increased lifetime compared to algorithms which considered the minimum transmission energy and the shortest path for routing. The tradeoff is the computational complexity in solving for the best cost path.

Maximum Life Time Data Gathering and Aggregation in Wireless Sensor Networks, the protocol [19] maximizes the network lifetime by information gathering and aggregation mechanisms. The QoS aware protocol works on maximizing the life time of the network as data gathering problem and is presented as polynomial time algorithm. The protocol defines network life time as the number of periodic data readings taken from the sensor before a node in the network fails. The proposed method solves the maximum lifetime data gathering problem for sensor networks, where in-network data aggregation is possible. The solution is in an optimal data gathering for routing data to the sink. The route path is a multi-hop tree structure from the source to the sink, and the schedule is followed for a designated time, called the system life time. The protocol aims in maximizing the system life thereby avoiding frequent change in schedules. The problem is formulated as a flow problem with linear objective functions and linear constraints. The linear objective function is computed over a polynomial time and a solution of real integer values is obtained. In the case where in-network data aggregation is not possible, for video streaming applications, then the problem is modeled as a network flow problem and energy constraints on the sensor also considered, arriving at a similar solution as in data aggregation case.

The protocol design increased the lifetime of the sensor network in comparison with hierarchial PEGASIS. However, the delay in delivering the data was greater compared to that of Hierarchial PEGASIS, this can be attributed to the data aggregation mechanism involving nodes along the route waiting for every other nodes data for information fusion. The computational complexity of the network is high for practical implementation in a constrained Wireless Sensor Network module.

Minimum Cost Forwarding Protocol [13], a simple and scalable protocol aimed at finding the minimum cost path in a large sensor network. A back-off timer based cost function algorithm that finds the optimal cost for data transfer from any node to the sink node with one single message overhead at each node. The cost function captures the effect of delay, throughput and energy consumption from any node to the sink. The protocol operates in two phases, in the first phase the cost values are calculated at every node. The calculation of cost starts from the sink message diffused to all nodes. Every node calculates its cost as a function of the cost of the node it received the message from and the cost of the link. The cost at every node is calculated based on a back-off based algorithm, every node on receiving a message backs-off and waits over a certain period of time to receive the minimum cost message. Then the node broadcasts only a single message to its neighbors with the minimum cost. In the second phase, the source broadcasts data to its neighbors. The nodes on receiving the broadcast message subtracts its transmission cost to the cost of the packet. If the remaining cost of the packet is not sufficient for forwarding the packet to the sink, the packet is dropped at that node else the packet is forwarded to its next set of neighbors.

The protocol does not remember the next hop neighbor node or its address for communication, as all cost function calculations are done independently at every node. Generally, cost field calculations are done by flooding the network, but has the inherent disadvantage of excessive advertisement messages as the node is unaware of the least cost path until receives all the packets. The back-off timer concept helps in overcoming the problem by delaying the broadcast until the node is sure of having received the least cost path message. Simulation results have proven that cost function calculated using flooding and back-off timer yield the same results, but the later has achieved the same with minimum advertisement messages. Nodes not maintaining information on their next hop neighbor ensures scalability of the protocol. The time for which the nodes defers transmission is critical and the back-off algorithm sets the deferral time proportional to the optimal cost at a node.

Energy Aware QoS Routing [3] a class-based routing protocol supporting differentiated service for real-time and non real-time traffic. The protocol finds the least-cost, energy efficient path for data in terms of the link cost calculated based on nodes energy reserve, transmission energy, error rate and certain communication parameters. The class based queuing model is as shown in Fig. 2.7 [3] , wherein each node has a classifier and differentiates the realtime and non realtime traffic, servicing them through different queues. There is a scheduler which determines the order of the packets to be transmitted from the queues based on the bandwidth ratio 'r'. The bandwidth ratio is the initial value set by the gateway and represents the bandwidth allocation ratio to real time and non-real time traffic. The classes can borrow bandwidth from each other when either of the traffic types are non-existent or within limits. The queueing delay for the traffic is found with the help of the 'r' parameter. The cost function calculation takes place in two stages, first the candidate least cost paths are found and selects one that meets the end-to-end delay. An extended version of Dijkstra's algorithm is used in ascending the set of least cost path.

The protocol is consistent with respect to QoS and energy metrics. The assignment of 'r' value was uniformly set for all nodes, which does not provide flexible bandwidth sharing for different links. A later version of the protocol supported different values of 'r' for different links. The protocol supports both best effort and realtime traffic at the same time; best effort by means of the cost path and differentiation in bandwidth for real and non-real time traffic.

2.3 Open Issues in Sensor Network Routing

The inherent characteristic of sensor network is to operate in large numbers on several constraints yet yield satisfactory results. Many routing protocols for various applications, prioritize a few and trade-off a few constraints based on the application. A lot

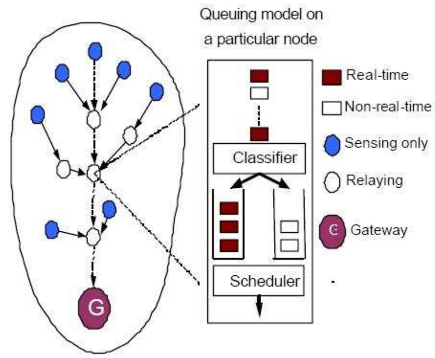


Figure 2.7: Queuing model for Energy Aware QoS Routing

more domains in this field are unexplored or await optimal solution, a few of them are identified and listed below.

- The protocols discussed in this chapter suited applications where the data was a few bytes of information. With end sensors like cameras wherein the information generated is large, the path meant for small data sizes is used for large data sets too, is this an efficient way is an unexplored area. The research focus would be to justify differentiated service for information based on the data size and find an optimal path, the present thesis focuses on this topic.

- The sensor network modules are being foreseen to be used by humans in everyday life. This calls for the integration of sensor network with the present IP based network or Wide Area Network (WAN). The focus is on developing a suitable architecture for networks to co-exist, retaining their functional characteristics.

- Nodes can collaboratively process and compute data, and reduce the amount of data communicated over the radio resulting in significant energy conservation on the nodes. The concept here is synonymous with grid computing, wherein a group of nodes share the computation burden, apart from data fusion mechanisms.

- Sensor nodes are deployed in random location and require a GPS to identify themselves in a global space. The GPS system can operate only in open spaces, also expensive and energy consuming for establishing its position. The alternative is the development of localized algorithm identifying itself with respective to its neighbor nodes and knowing the position of one node on the global space, one should be capable of mapping all the nodes on to the global space. Also using localized algorithm a new co-ordination system can be developed rather using the existing infrastructure.

- Sensor networks being applied in various military applications monitoring and collecting sensitive data, securing the data is of great importance. In sensor network an end-to-end security model is not of interest, as neighboring nodes would require access to the information. Current work has been on neighboring nodes acknowledging their true presence and nodes capable of distinguishing between friends and foe in a remote spatial distribution of sensor nodes.

Chapter 3

A Cross-Layer Routing Protocol for Wireless Sensor Networks

Having reviewed prevalent routing protocols for wireless sensor network in the previous chapter; wherein the emphasis was in arriving at efficient routing decisions banking on a set of network parameters; without comprising on the message that needs to be routed and focused on energy utilization. Decisions where made independent of other layers in the sensor network protocol stack, except that all layered protocols shared the knowledge of the energy availability on the sensor node in common. Apart from the network layer, the concept of energy efficiency was addressed in the application layer of wireless sensor networks for collaborative information processing and distributive task management; the Medium Access Control layer dealt with efficient channel allocation, synchronization and management of ON and OFF duty cycle's; and power control algorithms for energy efficient physical layer design. The layer specific protocols were optimized individually for best performance and eventually all layers addressed issues for extended sensor network lifetime. Evidently working towards a common goal, collaborative functioning and unified effort would help achieve better efficiency [30]. As detailed in [30], information from lower layers would help higher layer protocols function more efficiently and towards better usage of network resources. A cross layer protocol design helps achieve better performance by optimizing for an efficient co-existence in the protocol stack. The proposed network layer protocol, a cross layer design, is acquainted with application level information influencing routing decisions by tapping on the physical layer capabilities of the sensor node.

Real time low cost sensor modules, often referred to as motes in the sensor network community, are devices with limited capabilities and energy resources, designed to operate in large numbers in a networked fashion. The current generation of these motes developed for sensing applications such as the MicaZ, TelosB, Sun SPOT's and the Intel mote's physical layer are compliant with an IEEE 802.15.4 standard for the physical layer. The IEEE 802.15 group works towards the standardization of Wireless Personal Area Networks (WPAN) or short range wireless networks; one among them is IEEE 802.15.4 standard for low data-rate and long term battery operable sensor networks. In the current work, the proposed protocol relies on the capabilities of the 802.15.4 transceiver and details an energy efficient routing strategy, influenced by the volume of data thats needs to be routed and the energy availability in the nodes. The succeeding section in this chapter details on the pros and cons of a cross layer design, citing recent research on the cross layer design for sensor networks. The subsequent section details on the IEEE 802.15.4 physical layer specifications. The proposed cross layer routing protocol(XLRP) is elaborated in section 3.3, and finally in section 3.4 the factors influencing the decision making process are elaborated.

3.1 Cross-Layer Design for WSN

The concept of layered protocol architecture helped lay down a functional framework, wherein each layer had a well defined functionality and service definition, working independent of the other protocols in the stack. The model eased complex network design, supported heterogenous networked systems and inter-operable standard interfaces were designed. However, the layered architecture was best suited for general wired or wireless networks, wherein the Quality of Service(QoS) and inter-operability was of prime importance, however in wireless sensor networks the emphasis is towards energy efficiency and optimal usage of network resources. Moreover, sensor networks being application specific and built to serve a specific purpose, protocol design can be customized towards an application scenario. In line with this fact, cross layer protocols were proposed for wireless sensor networks [5, 9, 23, 28], wherein the layer functionalities are grouped to form a single entity.

Driven by the need for a cross layer design for efficient routing, in [23] and [28] the MAC layer and the network layer were unified. In [5], a resource efficient unified protocol was proposed combining the functionalities of all the layers into a single protocol, a complete alternative to traditional layered protocol architecture; the design complexity of the protocol increased as the number of factors influencing a decision making process was large; nevertheless the protocol proved to be efficient, in terms of energy and throughput. In [23], the lifetime of the sensor network was extended by uniting the functionalities of the network layer onto the MAC layer capabilities. The MAC layer organizes the network into a set of active and passive nodes, establishing connectivity through outthe network on a TDMA(Time Division Multiple Access) based scheme. The TDMA works on a multi-hop fashion, with nodes establishing connectivity with their neighbors based on the local information, setting up synchronized talk cycles; apparently shifting the route formation burden from the network layer to the MAC layer. The network route path is set through the connected system of active nodes, greatly relying on the information of the MAC layer; However, a small time sync disturbance in the MAC scheme or the death of an active node, would require the re-synchronization of the entire network, and need to devise new routes; the penalty of over dependence on the MAC layer.

In [28], efficient cross layer routing is achieved by combining the MAC functionality based on the routing decisions made at the network layer, reducing the overhead involved for medium access. The route path is setup by a stateless routing mechanism at the receiver node rather than the sender node, resulting in receiver contention rather than the sender contending to send information. The mechanism is based on geographic routing and is an end-to-end decision making process, between the origin node and the final destination node, making the protocol computationally complex as most protocols designed for sensor networks are based on localized information at the node. CoLaNet [9], an cross layer design of energy efficient wireless sensor networks, worked on collaborating on the characteristics and requirements of the application layer with the network layer in forming a route tree and the MAC layer scheduling algorithm. The network tree is based on data gathering from many to one sensors and the MAC was a TDMA based channel assignment algorithm. As discussed for [23], the problem of adaptability of the network to changing network dynamics because of a TDMA based media access.

The radio being one of the most energy consuming modules in the sensor node is predominantly controlled by the MAC layer, deciding on the radios ON/OFF cycle. When a sensor network is deployed the MAC is always active, irrespective of data being sensed keeps the network connected, however the above layers are reactive and act only on sensing events. The active state of MAC is unavoidable in the case of multi-hop sensor network for effective data communication across the network. And MAC functionality being software controlled, increasing the functionality of MAC by clubbing on network layer functionalities would tend to drain more energy when no event is being sensed, as suggest in above cross layer protocols. The cross layer routing protocol dealt with in this thesis, operates independent of the MAC layer but enhances power management, in addition to the MAC functionality, by controlling the radio modules based on application level information. Moreover, XLRP though relying on the information from the application and physical layer operates independent of the layer specifications and functionalities.

3.2 The 802.15.4/ZigBee Physical Layer

The IEEE 802.15.4 standard , a Wireless Personal Area Network (WPAN) Standard, proposed for low cost self-organizing mesh networks, especially for applications demanding low data rates and low power consumption. ZigBee is a multi-vendor consortium, an industry alliance for manufacturing IEEE 802.15.4 compliant radio modules. The standard operates in the Industrial, Scientific and Medical(ISM) band, 2450 MHz and the 915/868 MHz band, and supports a maximum data-rate of 250 kbps. The objective of the standard was towards a design of a reliable, short range communication interface with minimum operating cost and relaxed throughput requirements, ideally suited for sensor network applications. The 802.15.4 standard details the MAC and the Physical layer specifications, defining simple message exchange formats and operating characteristics for the transmitter and the receiver. Currently a few 802.15.4 compliant radio modules are being manufactured, Chipcon's CC2420 is a widely used 802.15.4 compliant radio module which is being integrated into Berkeley (Micaz, Telosb) and Intel motes. The proposed algorithm is simulated in NS2 with Chipcon's CC2420 radio module specifications, as a reference model for the physical layer. However, using a manufacturer specific data-sheet does not confine the working of the algorithm to the specific product; only that relying on a real-time radio model aids in accurate energy modeling of the system and utilizing those parameters helps in prototyping real time scenarios through simulations.

The CC2420 is a single chip programmable 802.15.4 compliant radio module operating in the 2.4 GHz unlicensed ISM band. The transceiver is operable at low voltage levels of 2.1 - 3.6 Volts and are low current consuming devices, with a receiver sensitivity of -90 dbm the current consumed is 18.8 mA and for transmission at the maximum power level of 0 dbm is 17.4 mA, the transmitter is capable of switching eight power levels from -25 to 0 dBm. The transmitter power switching capabilities is of significant importance for sensor nodes operating in large numbers, as this feature confines interference to smaller regions when multiple nodes would need to communicate at the same time and also giving the flexibility to communicate with relatively distant nodes. CC2420 is a Direct Sequence Spread Spectrum Transceiver supporting a data rate of 250 kbps modulated using O-QPSK (Orthogonal-Quadrature Phase Shift Keying) technique.

The transmitter and the receiver capabilities are of significant importance for the proposed cross-layer routing mechanism. Reiterating the fact that transceiver operation are the most energy expensive functions in the sensor network and with network layer dependence, the knowledge of energy consumption in each of the radio states is of prime importance. Capable of operating in five different states, the Idle state with oscillator ON is the when the receiver circuitry is ON and sensing the channel, when radio signals are detected it triggers receiver hardware functional and is in the higher power consuming receive state. The difference in current consumption between the Idle state with oscillator OFF and power down state is because of the voltage regulator, the voltage regulator is turned OFF in the latter state and thereby the entire radio module is powered down. Table 3.1 details the current consumed in each of the radio states, the energy is calculated with knowledge of the supply voltage and the time period for which the radio is ON.

Radio state	Max. Current Consumption
Transmitting at 0 dbm	17.4 mA
Receiving	19.7 mA
Idle Mode, Oscillator ON	365 μA
Idle Mode, Oscillator OFF	20 μA
Power Down Mode	1 μA

Table 3.1: Radio States and their current consumption.

Transmitter Power (dBm)	Current Consumption (mA)
0	17.4
-1	16.5
-3	15.2
-5	13.9
-7	12.5
-10	11.2
-15	9.9
-25	8.5

Table 3.2: Radio Transmitter Power Levels and the current drawn.

The radio module is powered by a 3 volt supply, the product of voltage and current gives the power; times the period the radio is ON in a particular state gives the energy consumed over the time interval. Table 3.2 lists the eight transmission states as per the 802.15.4 standard specifications and the current consumption in the corresponding states is tabled for the CC2420 module. In the present case of WPAN communication modules, the radio operations consumes few tens of micro amps for transmitting and receiving and the maximum transmitting powers being 0 dBm, draining only a few micro amps; thereby the energy consumed in switching between radio states is appreciable. As in [17], the author has calculated the energy consumed in switching from one state to another for the CC2420 radio module, the information is reproduced in table 3.3 for switching between eights levels of transmitting, receiving and idle states. From the data presented, the protocol iterates that for short transmit or receive cycles, the energy consumed in switching is of concern and of significant importance in determining the cost of the communication.

Transition	Energy Consumption (μJoules)	Transition	Energy Consumption (μJoules)
Rx - Tx(0dBm)	6.92	Tx(0dBm) - Rx	6.16
Rx - Tx(-1dBm)	6.62	Tx(-1dBm) - Rx	6.13
Rx - Tx(-3dBm)	6.31	Tx(-3dBm) - Rx	6.14
Rx - Tx(-5dBm)	5.90	Tx(-5dBm) - Rx	6.08
Rx - Tx(-7dBm)	5.53	Tx(-7dBm) - Rx	6.02
Rx - Tx(-10dBm)	4.94	Tx(-10dBm) - Rx	5.95
Rx - Tx(-15dBm)	4.16	Tx(-15dBm) - Rx	5.82
Rx - Tx(-25dBm)	3.77	Tx(-25dBm) - Rx	5.70
Idle - Tx(0dBm)	3.13	Idle - Tx(-10dBm)	2.52
Idle - Tx(-1dBm)	2.99	Idle - Tx(-15dBm)	2.39
Idle - Tx(-3dBm)	2.90	Idle - Tx(-25dBm)	2.24
Idle - Tx(-5dBm)	2.73	Idle - Rx	5.92
Idle - Tx(-7dBm)	2.67	Rx - Idle	3.35

Table 3.3: Radio Transmit and Receive Transition Energy Consumption.

3.3 The Cross-layer Routing Protocol (XLRP)

One of the characteristic feature that distinguishes wireless sensor network from an Ad-Hoc Network, is the knowledge of information that would be generated in the network. Sensor networks being deployed for a specific application, one is aware of the information that would be generated from the sensor and the volume of data the sensor network would render, based on the sensors in the network. As an example, a temperature sensor would give out one or two bytes of data, an acoustic sensor would generate a few hundred bytes, an image sensor would generate images of few kilobytes of information; and also in the case of a heterogenous sensor networks the volume of information that would be generated can be scaled. The XLRP algorithm explores an efficient routing strategy based on the volume of data exchanged in the network. The protocol relies on the fact that any information transmitted from source to sink (destination) is complete when received in its entirety; as the process of transmission may involve fragmenting the data into packets based on the maximum transmission units supported by the network.

On the physical layer, sensor node radio modules are programmed to operate at low transmitting power reaching their closet neighbor causing less interference, aspiring for minimum energy drain and extended network lifetime. In general, sensor nodes switch to higher transmitting powers to reach farther nodes, where in the importance is in rendering information of high priority with minimum latency; a tradeoff between energy and latency. However, the current protocol establishes the fact that resorting to low transmitter power levels is not always the energy efficient strategy. The proposed routing algorithm corroborates on switching transmission power levels based on the volume of the data being transmitted as an energy conserving mechanism for protracted network lifetime. Supported by the fact that for smaller volume of data, the transmitter is on for a shorter period, so transmitting at low power levels would be more efficient in comparison to switching power levels at the expense of energy consumed. However, for larger volume of data the transmitter would need to transmit for a relatively longer time, and the energy consumed in switching to higher transmitter power level would be negligible, moreover hoping over a few intermediate nodes would save on energy and reduced delay. Nevertheless, transmitting at high power levels results in increased transmission radius and increase in the number of unintended receivers, eventually resulting in an energy drain. The proposed XLRP algorithm saves energy by switching OFF unintended receivers based on the power of the received radio signal. Also, the routing decision are based on the energy availability, the local communication cost and node connectivity, the details of which are elaborated in the subsequent section. Though XLRP nodes are capable of switching transmission powers, nodes are interested in information about their immediate neighbors, meaning neighbor nodes that can be reached with the least transmission power level, for decision making process.

In most energy aware routing protocols and were neighborhood information is of importance, nodes exchange beacon messages with their neighbor nodes in a periodic fashion. Though the neighbor messages are broadcasted only when active subscriptions are present, energy is drained during this process. The proposed XLRP protocol is suggestive for reduced energy consumption by piggy backing node information on its transmissions and also evokes unintended receivers who had received the packet to process and extract information from the received data. For example consider a random distribution of nodes as shown in Fig. 3.1, for the highlighted node in the center the radius of transmission with the least power level is the highlighted region, the highlighted node is interested on the energy levels of the nodes within the region. Also, any node communicating within this region would be heard by the nodes within its transmission, thereby nodes on receiving the packets, process the header to find if it was addressed to it and the packets are dropped, as in any conventional network. However, XLRP is suggestive of nodes process the packet to extract information about the sender node if it is within its region of interest, neighborhood table. Iterating the fact that receiving consumes lot more energy than processing, and thereby extract information from the received information rather than dropping the packet after receiving, however do not react (respond) to the received packet. This methods saves energy by avoiding periodic beacon messages for marking neighbor node presence. In XLRP, nodes broadcast information identifying themselves to their neighbor nodes at different operational transmitter power levels and also respond to new identification messages received from new neighbor node, with a set delay between identification messages being transmitted.

3.4 Criterions for Routing Decision

This section details the controlling and contributing factors in determining the next hop neighbor, enroute for communication through the wireless sensor network.

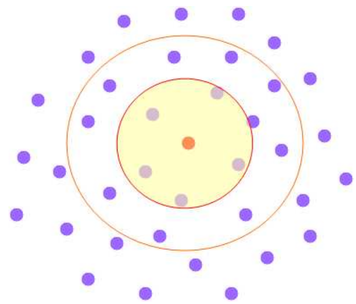


Figure 3.1: Node and its neighborhood region of interest

3.4.1 Switching Transmission based on Volume of Data

Information disseminated though the network vary from a simple interest message or sensor data; to a control or an acknowledgement/reinforcement message. Apart from the messages being unique in functionality; the messages can be classified by their size in terms of the number of bytes. This application layer information, size of the data, made available at the network level helps determines the next hop neighbor and accordingly switches the transmit power level at the physical level. As stated in the previous section, most sensor deployments and algorithms prefer operating the radio transmitter in the minimum power level state to avoid interference, reducing the burden on the MAC layer design. However, the current proposed algorithm tries to explore the energy saving possibilities in switch transmitting powers based on the size of the data, moreover, it adds to the MAC layer functionality of switching radio states and conserving energy. The XLRP switches to high transmission power levels for large volume of data and remains in lower power levels for small packet transmission. Larger packet size implies larger transmission and reception time, meaning the radio is in high power consumption state for a longer time. Transmission of a larger packet at low transmitter power levels results in an increase in number of hops, delayed reception and multiple nodes draining minimal energy but collectively energy consumed would be higher; whereas switching to higher transmitter levels reduce the number of hops and reduced delay in data reaching the destination. However, an individual node would have drained lot more energy than it would have if transmitted at lower power levels. Nevertheless, the collective energy drain would be less as we have reduced the number of transmitter and if only we could reduce the number of unintended receivers, detailed in the subsequent section. Moreover, this does not exhaust the energy reserve on a single node, has energy in the node is also considered in decision making process.

Also in sensor networks, the setting up of path and routing is more towards circuit switching than packet switching, unlike in conventional wireless networks; as maintaining multiple paths for routing is at the cost of a node's energy. When a few kilobytes of information needs to be routed between two nodes, the information is broken into packets and the route path is established to transmit these packets through a single established path, rather than sending through multiple paths. an increased burden of sequencing the packets at the receiver end and expensive in terms of energy in maintaining multiple paths. Thereby switching to higher transmit state and switching off intermediate nodes from receiving would help reduce the number of transmission and receptions.

3.4.2 Signal Strength based Decision Making

The CC2420 radio module has the capability of measuring the signal strength of the received radio signals. This feature has been explored in localization algorithms in determining near and far neighbors, wherein nodes are programmed to operate at fixed power levels and based on the received signal strength the proximity of the sensor nodes can be determined, modeling the propagation losses. With nodes capable of operating at different power levels and knowledge of the received signal, the proposed model conceptualizes on a back-off mechanism for unintended receiver nodes to switch their radio modules, saving on energy.

The number of unintended receivers increase on switching to higher transmission power levels, nevertheless they can be limited by switching of the receiver based on the received signal strength. For example, if a node wants to talk to distant node it would switch to a higher transmitter power level sufficient for the desired node to receive (the transmitter node has prior knowledge of the required transmission power level); meaning the signal strength of the receiver node would be close to the radio modules receive threshold. Also nodes within the transmission range of the sender would receive the signal, however the signal strength of the node adjacent to the transmitter node would be different from that received by a farther away node. Truly the sender would not transmit at a very high power level to reach its adjacent neighbor node, capable of being reached at a lesser transmitter power level and the viceversa also holds true. Thereby, setting up a maximum signal strength threshold value, receiver modules sensing signals above the set threshold consider themselves unintentional receivers and turn OFF their radio modules. This is an iterative learning process wherein nodes learn from messages received (during the neighbor discovery phase) and set their threshold values.

A limitation on the effective functioning of this mechanism is the size of the packets being transmitted. The process involves the radio module listening to the radio signal, determining the signal strength of the received signal, then rendering the value (RSSI) to the microcontroller module in the sensor node, which makes the decision on turning OFF the receiver and finally switching OFF the receiver if required. If the packets being transmitted is only a few bytes of data, the time taken to make a decision and enforce it would be longer, for the packet would have been received over the period; however, for lengthier packets this mechanism would be effective in terms of energy conservation. The time involved in this process helps determining if a message is short or long, and helps opting for the right power level.

This further restates the need for switching to higher power levels based on the volume of the data that needs to be transmitted.

3.4.3 Energy in the Node

Energy availability in node is of great concern in determining the operations the node would need to perform and also the overall network lifetime. The node functionality is based on a relative measure of the energy with respect to its peer neighbor nodes. Also, nodes with limited energy would not take part in energy expensive operations, such has switching to higher transmission power levels and acting as relays for multihop communication. Restating the definition of network lifetime, the time taken for the first node in the network to fail; an ideal protocol design would drain energy uniformly among all the nodes, eventually leading to the death of all nodes at the same time or near close intervals.

The strategy of switching to higher transmission power based on data volume and switching OFF the radio to save on energy, as discussed in the above sections, would not convince one on uniform energy drain among the nodes. However, decisions planned on considering energy as a relative quantity and the circle of neighborhood under consideration would connotate uniform energy drain. When a node transmits at an higher power level, the nodes immediately surrounding the transmitting node would turn off their radio sensing very high radio signals, assuming large packet sizes transmissions, resulting in large difference in energy availability among neighbor nodes. The measure of the difference in energy levels can be calculated as a ratio of the nodes energy to the average energy of its neighbors. If the ratio is greater than one implies that the node being considered is more resourceful compared to its neighbors and less than one would push the node to operate in energy conserving state; transmitting at lower transmitting power levels and excuse itself from network route relay paths. The ratio would also vary based on the neighbor nodes being considered, if the ratio is with respect to the first tier neighbors, meaning nodes that can be reached with the least transmitting power; the energy ratio would vary even for small difference in work load on nodes but more uniform energy drain, however considering larger subset of neighbors would average out the high difference and lessen the regulations on the node. XLRP algorithm restricts its neighborhood region to nodes within its least transmission range.

3.4.4 Communication Cost

The communication cost parameter is analyzed in terms of the energy consumed by the node for that specific radio communication. The cost calculation is based on the energy availability, the energy consumed for the operation and the energy consumed in switching nodes to the required states. In the case of large volume of messages to be relayed by a node, the node needs to switch to higher power state, the decision to choose a power level is based on the energy consumed for the node to transmit in that state and what would be the energy ratio after the node as transmitted in that state with respect to their neighbors current energy availability. As ideal energy ratio is one, the decision made on selecting the particular energy state should'nt bring in large changes to the energy ratio. For large messages, being transmitted as a sequence of packets, nodes can switch to lower power states after transmitting a series of packets, thereby avoiding any possible large variation in energy with that of its peer nodes. This is suggestive of nodes changing network paths after a sequence of transmissions.

3.4.5 Node Connectivity

The position of the node relative to the nodes in the network is of prime importance in deciding the node participation for efficient routing and extended network lifetime. In scenarios were the density of the nodes is high, meaning a node has larger number of neighbors to choose from, the nodes have high connectivity and the network load can be effectively shared among the nodes. With lesser node density implies poor node connectivity, the nodes functionality is seriously limited; as in worst cases scenario the death of a few nodes might part the sensor network. The node connectivity parameter would determine the functionalities of the node; with poor connectivity the node would not switch to high transmitting powers and would be less engaged as a relay node, excusing itself from energy depleting processes. The dependence of node functionality on the node connectivity parameter can be attributed to the collaborative functioning of sensor network and energy as a collective measure of a region, and not just a nodes energy. In addition the node connectivity parameter can be also be used to determine the next hop neighbor, data could be forwarded via nodes which have a higher count of neighbors; in cases of two promising next hop neighbors with equal energy levels or proximity to the final destination, the node with higher connectivity would be a better choice.

Quality of Service for sensor networks can be categorized into Application specific and Network based QoS, as identified in [10]. The application specific QoS in unique to sensor networks, which deals with sensing area coverage, exposure, positioning of sensors, functions of sensor and sensor measurements, details relevant and specific to the application scenario [10]. The Network QoS is applicable for any networked system, dealing with network resource allocation, service guarantees in terms of delay, throughput, data delivery, to name a few; and for sensor networks all the QoS guarantees are addressed in terms of energy consumption and efficient network utilization. XLRP reduces the delay in message transmissions by switching to higher transmission power levels. The application layer based switching characteristic of XLRP would reduce the transmit/receive time by limiting the number of intermediate nodes along the route, reducing the delivery time from sender and receiver and also saves on energy. Having identified strategies and constraints for efficient routing, the proposed cross layer protocol is being implemented in Network Simulator (NS2), detailed in the following chapter. The effectiveness of the protocol is being proved though the simulations in comparison with that of directed diffusion implementation in NS2.

Chapter 4

Implementation In Network Simulator (NS2)

Having discussed the cross layer routing protocol in the previous chapter, this chapter details on modeling of the proposed algorithm in network simulator. The first subsection details on the simulator, followed by the implementation details of directed diffusion in the network simulator, which forms the basis of the current implementation. Section 4.3 details on the implementation of the proposed cross layer routing in ns2. The final section details on the energy model in ns2 for calculating the energy consumed during the routing process.

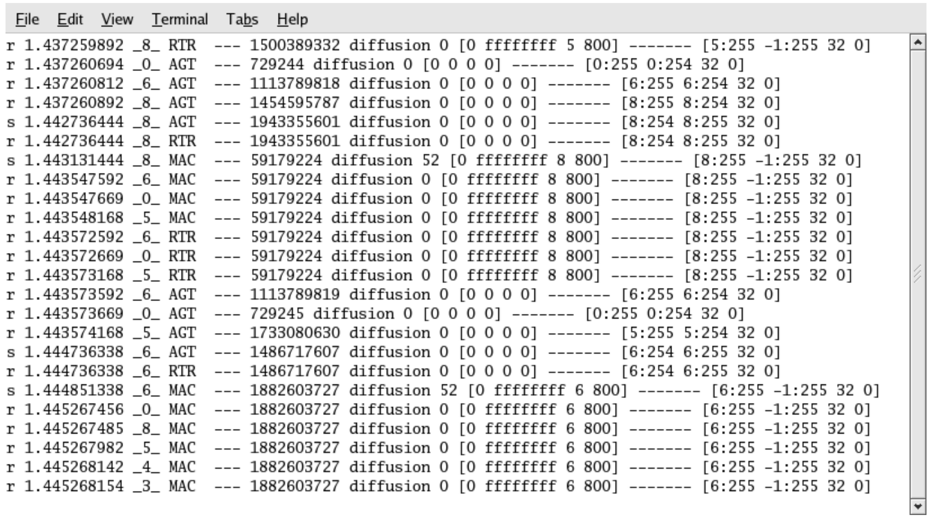
4.1 Introduction to Network Simulator

Network simulator(ns, better know as ns2) is a discrete, event simulator for modeling wired and wireless network scenarios. In the presented work, network simulator version 2.29 is being used. The simulator is written in objected oriented C++, for implementation of core algorithms and OTcl (object Tcl) shell scripts as a frontend tool, for testing and simulating the performance of protocols implemented in C++

[1]. The C++ and OTcl have mirror implementations with an one-to-one correspondence; network models are developed by creating instances in tcl (tool command language) that are linked to the corresponding C++ object modules. C++ is used for detailed protocol implementations has it provides a higher level of control and flexibility on data handling, packet format and exchanges. Also, C++ executes faster compared to that of tcl scripts, thereby reduced run time for complex algorithms running over large data sets. On the other hand, tcl is easier to program and modify compared to that of C++, thereby helpful in creating test scenarios and instances of protocol implementations in C++ [1]. For example, both TCP (Transmission Control Protocol) and UDP (User Datagram Protocol) have implementations in c++, however the choice of a node adopting TCP or UDP schema is opted at the tcl level. Tcl helps design network topologies with nodes as the hardware entities in a network and nodes are configured to a set of protocols as agents, representing the software entities. Packets are the fundamental unit of data exchange between agents in the simulator. The simulator supports protocol implementations for unicast, multicast and broadcast packet exchanges.

All events in the simulator are queued based on time, a scheduler executes the next earliest event in the queue, completes the current event execution before executing the next event in queue, also adds event's dynamically as a result of executed events. The tcl interface allows user to schedule events. The results of simulation on the execution of tcl scripts are in the form of trace files which detail on the various events such as packet arrival, departure or packet drop. Every event in the trace file is timed precisely to a nano second. The trace file can be formatted based on the fields of interest, the file that needs to be modified is located at ns-2.29/trace/trace.{h,cc}. To track events and generate trace files, a common header is included in every packet, uniquely identifying the packet. The common header includes a set of field's for handling packets during simulation and are not accounted towards performance evaluation of protocols. Fig 4.1 is snapshot of a sample trace file, wherein the first row indicates if a packet is being sent or received, represented by 's' and 'r' respectively; 'D' indicates a packet is dropped. The second column indicates the time in seconds at which the event had occurred. The subsequent column indicates the node id, defined in tcl scripts, followed by 'AGT' indicating agent generated message, 'RTR' indicating router or network layer generated message or 'MAC' indicating message generated by the media access layer. The next column, a long series of number, is a unique identifier for every packet generated, this is a field in the common header; followed by the word 'diffusion' indicating the message is generated by the directed diffusion agent. The subsequent field indicates the packet size, in the trace file snapshot packet size is displayed only for packets communicated over the radio, received or sent by the MAC layer. The four values within the square braces, indicate the time to send, source MAC address, destination MAC address and the packet type (ARP or IP or AODV) in hexadecimal; however, these fields are not applicable to our current simulation. The final column also enclosed within square braces are applicable for IP based simulation, the first two pairs separated by semicolon indicate the source IP address, source port address and destination IP address, destination port address. The last two fields indicate the time to live (TTL) value of the packet and the next hop node information, if any.

The network simulator does not support any GUI (Graphical User Interface), however the simulator does support a visualization tool, nam (network animator); helps picturise the network setup with nodes and node movements, if mobility enabled. Also, help visualize packet transfer between wired nodes and wireless node transmissions with their region of coverage. To run nam, a specific nam trace file needs to be generated while executing tcl scripts, nam trace file is different from the trace file discussed earlier. The tool animates the network operations as timed events



```
File  Edit  View  Terminal  Tabs  Help
r 1.437259892 _8_ RTR  --- 1500389332 diffusion 0 [0 ffffffff 5 800] ------- [5:255 -1:255 32 0]
r 1.437260694 _0_ AGT  --- 729244 diffusion 0 [0 0 0 0] ------- [0:255 0:254 32 0]
r 1.437260812 _6_ AGT  --- 1113789818 diffusion 0 [0 0 0 0] ------- [6:255 6:254 32 0]
r 1.437260892 _8_ AGT  --- 1454595787 diffusion 0 [0 0 0 0] ------- [8:255 8:254 32 0]
s 1.442736444 _8_ AGT  --- 1943355601 diffusion 0 [0 0 0 0] ------- [8:254 8:255 32 0]
r 1.442736444 _8_ RTR  --- 1943355601 diffusion 0 [0 0 0 0] ------- [8:254 8:255 32 0]
s 1.443131444 _8_ MAC  --- 59179224 diffusion 52 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443547592 _6_ MAC  --- 59179224 diffusion 0 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443547669 _0_ MAC  --- 59179224 diffusion 0 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443548168 _5_ MAC  --- 59179224 diffusion 0 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443572592 _6_ RTR  --- 59179224 diffusion 0 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443572669 _0_ RTR  --- 59179224 diffusion 0 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443573168 _5_ RTR  --- 59179224 diffusion 0 [0 ffffffff 8 800] ------- [8:255 -1:255 32 0]
r 1.443573592 _6_ AGT  --- 1113789819 diffusion 0 [0 0 0 0] ------- [6:255 6:254 32 0]
r 1.443573669 _0_ AGT  --- 729245 diffusion 0 [0 0 0 0] ------- [0:255 0:254 32 0]
r 1.443574168 _5_ AGT  --- 1733080630 diffusion 0 [0 0 0 0] ------- [5:255 5:254 32 0]
s 1.444736338 _6_ AGT  --- 1486717607 diffusion 0 [0 0 0 0] ------- [6:254 6:255 32 0]
r 1.444736338 _6_ RTR  --- 1486717607 diffusion 0 [0 0 0 0] ------- [6:254 6:255 32 0]
s 1.444851338 _6_ MAC  --- 1882603727 diffusion 52 [0 ffffffff 6 800] ------- [6:255 -1:255 32 0]
r 1.445267456 _0_ MAC  --- 1882603727 diffusion 0 [0 ffffffff 6 800] ------- [6:255 -1:255 32 0]
r 1.445267485 _8_ MAC  --- 1882603727 diffusion 0 [0 ffffffff 6 800] ------- [6:255 -1:255 32 0]
r 1.445267982 _5_ MAC  --- 1882603727 diffusion 0 [0 ffffffff 6 800] ------- [6:255 -1:255 32 0]
r 1.445268142 _4_ MAC  --- 1882603727 diffusion 0 [0 ffffffff 6 800] ------- [6:255 -1:255 32 0]
r 1.445268154 _3_ MAC  --- 1882603727 diffusion 0 [0 ffffffff 6 800] ------- [6:255 -1:255 32 0]
```

Figure 4.1: Snapshot of a trace file

for the entire length of the simulation period; the time step can be changed with the help of the controls provided on the GUI. Fig 4.2 is a snapshot of the nam GUI with a few wireless nodes represented as black dots and the circles centered around a node indicating the radio signal reach at that instant of time, if continued over time the radio signals might propagate further or diminish. Nam tool is useful for visualizing simple network scenarios with a few tens of nodes, however with a few hundred nodes interpreting network activities in nam would be cumbersome.

4.2 Directed Diffusion

Directed diffusion was one of the first protocols for wireless sensor networks to be implemented in ns2. The simulator supports all variations of directed diffusion, the two-phase pull, one-phase pull, one-phase push(or simply push) and GEAR implementations. The control flow for directed diffusion implementation in NS2 is as represented in Fig 4.3 [1]. The directed diffusion core(the core diffusion agent) helps integrate the protocol into the network simulator suite, as a wrapper class for sending and receiving packets to and from the network. The different variations of

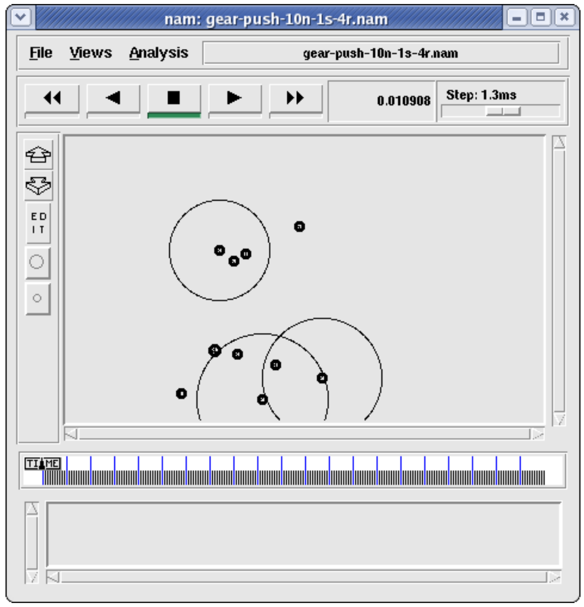


Figure 4.2: Nam user interface

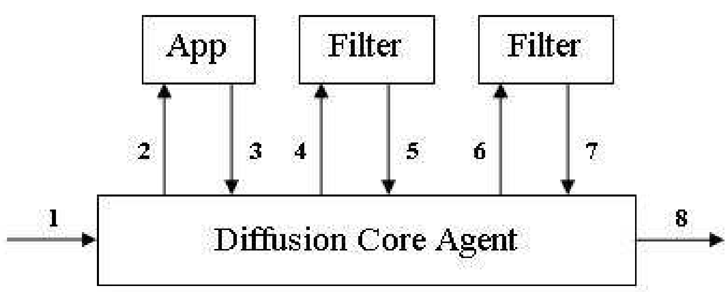


Figure 4.3: Message flow in Directed Diffusion (redrawn from [1])

directed diffusion are implemented as filters communicating with the core diffusion agent. This has the advantage of testing diffusion algorithms individually or in combinations, for example GEAR implementation with two phase pull can be compared with that of GEAR with push algorithm. The decision making process and the flow of packets within directed diffusion is controlled by the core diffusion agent. Every filter included in the current simulation has a predefined priority, a packet arriving at the core agent is directed to the filter with the highest priority and subsequently to filters with lower priorities. The core diffusion agent in addition to encapsulating diffusion packets in the NS2 module, stores information that are in common for the apps and filters. The apps block in the figure provides interface for source and sink applications, that invokes the publish and subscribe interfaces for interest dissemination and data exchange between nodes. All these modules have equivalent tcl instances, the core agent needs to be initiated first by selecting the routing protocol as `Directed_Diffusion`, and the diffusion algorithms are initiated as filters, `GradientFilter` for the two phase algorithm and `GeoRoutingFilter` for invoking the geographic routing algorithm in tcl scripts.

The diffusion header implemented in ns2 includes a twenty four byte constant header and message attributes of varying length based on the message type. The first field identifies the diffusion packet with a version number, if a packet other than the specified version is received, the packet is dropped by the diffusion agent. Followed by the message type field, identifying a beacon request, data, interest or a subscription message. The next three fields are two bytes long identifying the source port, length of the message and the number of attributes in the message. Diffusion also generates a thirty two bit packet number for uniquely identifying every packet generated by the diffusion layer and followed by a thirty two bit random id for every node; and the last field indicates the address of the next hop node.

Attributes in directed diffusion are represented using attribute-value-operator tuples; serves for comparing interest messages and specifying node properties such has longitude, latitude and energy. Moreover, the tuples help in matching interest and subscriptions using simple logical operations. For example, longitude, latitude, information specific to node or sensor capabilities, like temperature form the attributes, the values correspond to attribute type can be string, integer or float data type. Finally operator details on interpreting and comparing the attribute values, operators are IS, GE (greater than or equal to), GT (greater than), LT, LE, to name a few. In diffusion implementation every subscription and publisher message is identified by a unique hexadecimal number, helps in associating subscriptions with a source node.

4.3 XLRP Implementation

The proposed cross layer routing protocol is being implemented in ns2 identical to directed diffusion implementation in ns2. Initial implementation attempts where for XLRP to be part of directed diffusion as one other filter, however the difference in packet header information and the programming complexity in adding a protocol as filter to directed diffusion led to the implementation of XLRP as a stand alone module.

4.3.1 Message Types

The protocol implementation handles three different messages for communication among node; subscription, data and identity messages. In our implementation the publish message is local to node, a node is identified as a publisher by creating a tcl instance and the message is local to the node created by the apps agent and not broadcasted. The subscription message is an interest message broadcasted by sink node to the network, includes an unique interest identity. When matching publication identities exist a data message of varying size based on the interest is directed towards the sink node.

Identity message's are broadcasted by nodes during the initial setup phase, when the node joins the network and also when a new node joins the neighborhood. Initially, identity messages are transmitted at all power levels. When a new node joins the neighborhood, the identity message is transmitted in the power level as that of the new node's transmission, this information is included in the node identity message. The node identity message also includes the nodes current energy level. One other instance when the node transmits its identity message is when the node can no longer support relaying of messages and serves only the purpose of sensing in the network. The message is not flooded as in the case of subscription and is intended only for nodes within its neighborhood. This message is flooded locally, at the least transmission power, within the region wherein the node information is present in the receiver nodes neighborhood table. If the message is received by a node for which the information is not useful, no entry in the neighborhood table, the packet is dropped and message is not broadcasted any further.

The XLRP protocol switches transmitter power level based on the number of bytes of information thats needs to be transmitted, which is applicable only to data messages because of varying data volume based on the publisher (source) node information. Node identity messages which are also transmitted at different transmitter power levels but are not subjected to check on data size for choosing the power level. In other words, the protocol's check for switching power level is applicable only for unicast data messages. As subscription messages are of minimal bytes and needs to be broadcasted among all the nodes in the network, the power level for subscription message is never switched. By default the transmitter operates at its least power level.

4.3.2 Message Header

Figure 4.4 details the basic header format of the proposed XLRP algorithm. In addition to the header information used in diffusion implementation XLRP relies on few other parameters for its functioning. The first eight bit version field identifies XLRP message, if message other than XLRP message arrives at the node the packet is dropped. The second eight bit type field identifies the message as an identity, subscription or data message. The two byte agent field is useful in routing information to the appropriate agent, distinguishing between the filters and the application agent. The header also includes a four byte randomly generated packet number uniquely identifying the packet generated, this is in sync with the directed diffusion implementation. All nodes in the simulation are addressed by a two byte node id generated in a random fashion, which is also a part of the header. Followed by the next hop and the last hop node id's which are also two bytes long. All the above mentioned fields are also a part of the directed diffusion implementation. Energy of the current node is also included in the header field, which is two bytes in length and length field indicating the size of the packet in two bytes. Unlike the current implementation, energy is broadcasted only in beacon messages of directed diffusion implementation and represented as a tuple. Two other fields that have been included in the common header is the current node's transmitter power level and the node connectivity parameter. The transmitter power level as decided by the cross layer protocol is included in the header, thereby the receiver would in turn know the transmission power level to reach the transmitter node. In the neighborhood learning process this of great importance since it determines the power level by which the neighbor node can be reached, this is under the assumption that the channel is symmetric; meaning if a node can reach another node with a specific transmission power level, the viceversa is also true.

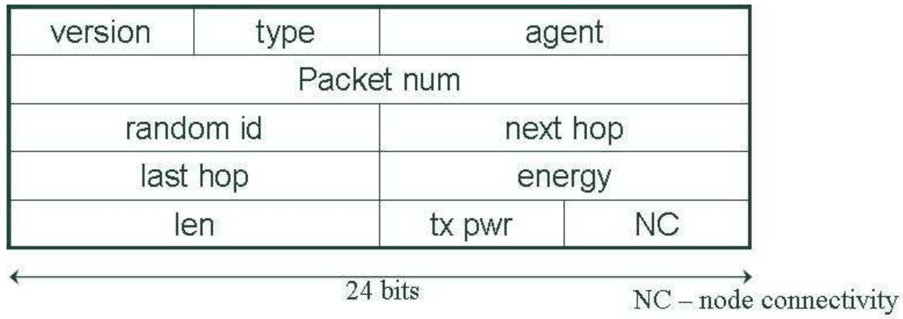


Figure 4.4: XLRP Header Format

One other information included in the header of the subscription message is the path traversed by the subscription message, which includes information on the last two hops in addition to current transmitting node details as key-value-operator tuples. For example, consider five nodes A,B,C,D and E; where node A sends a subscription message to B, similarly B to C and C to D. Node D receives the subscription message from C and the message includes information that node B was the previous hop and node A was prior to it. Similarly, if node D forwards the message to E, node E is aware from the received message that C and B are the prior hops. This information is vital for the node to switch power levels for transmission of data messages, when an entry of the node exits in its neighborhood. If this information is not available transmission would take place at least power levels only; as transmitting at higher power levels with a broadcast address would lead to multiple transmission of messages along the same paths and nodes might receive and process multiple copies of the same message. However, an intermediate node might not be interested or lack of resources might restrict it from relaying data messages, the node notifies its decision in the subscription message by not including its id in the header message or locally floods an identity message indicating its restrictive behavior of only sensing events and not relay messages.

4.3.3 XLRP Phased Operation

The working of the XLRP protocol can be detailed as a three phase operation; Neighbor Discovery Phase, Interest Dissemination Phase and Data Delivery Phase.

Neighbor Discovery phase is the initial phase of sensor network setup wherein nodes broadcast their identity. For the first time when nodes are activated, they broadcast their identity message at different operable transmitter power levels. During this phase nodes learn about their neighbor nodes and the power level the respective nodes can be reached based on the header information. Nodes retransmit identity message only when a new nodes join the network and the identity message is transmitted at the power level required to reach the new node. Also identity messages are broadcasted when there is an appreciable change in the energy level of the node in comparison with neighbor nodes energy level. During which nodes advertise and locally flood at the least transmitting power level and indicate that the node can only sense indicated as a tuple attribute.

Interest Dissemination phase, the interest message is broadcasted at the least transmitter power level and flooded through the network. In the interest dissemination phase apart from the common header, the last two hop information and the interest id is also included in the message being broadcasted. The interest identifier helps in reinforcing paths with minimum latency, based on the latency with which the subscription messages are being received.

Data Delivery phase, occurs when an event is sensed and information is routed from the sink node to the source node. Data messages are unicast messages, messages are directed to the neighbor node with matching subscription. In a general IP based wireless network data routing is an end to end model, wherein the sink node is aware of the final destination node or the source node, however this is not the case in wireless sensor networks, the sink node is only aware of the neighbor node it needs to direct the data message and has no knowledge of the final destination node.

4.3.4 Physical Layer Characteristics

The zigbee radio module has discussed in the previous chapter, has the capability to switch between eight different transmission power levels. However in the simulation we are opting for three transmission power levels; as the emphasis in this thesis is to implement the idea of routing by switching transmitter power levels for which three power levels would be sufficient. The three transmitter power levels opted are -15, -7 and 0 dBm and their corresponding transition energy measurements are taken to account. The receiver sensitivity or receiver capture threshold has been opted as -90dBm and the carrier sense threshold has been chosen to be -100 dBm. When the received signal strength is within the receiver sensitivity limits then signal is captured and can be decoded to receive the entire packet, however when the signal strength is between the receiver capture threshold and the carrier sense threshold then a part of the signal can be received and the packet cannot be decoded completely; equivalent to packet not being received in simulation environment but the channel is busy for transmission. The carrier sense threshold is used to sense if the channel is free before attempting for transmission.

The RSSI (Received Signal Strength Indicator) is a part of the radio module, a registry in the CC2420 radio module. The received signal strength is calculated every eight symbol periods of the received signal strength. For the node to decide in turning OFF the receiver or not it needs to communicate with the micro-controller, the micro-controller compares it with the threshold value and turns of the receiver. The process of switching OFF the radio module takes place in few tens of microseconds, the entire operations is assumed to last for a few tens of milliseconds. In the current simulation we have turned OFF the radio on satisfying two measures, if the receive signal strength exceeds the software receive threshold as set by the network layer and reception time exceeds the time required to receive the node identity message. This aids in identification of new nodes joining the network.

Two ray ground propagation model is used in our simulation, wherein the receiver and transmitter antenna gain are set to one and frequency of operation is the 2.4GHz band at a transmission bandwidth of 250 kbps (kilobits per second).

4.4 Energy Modeling

Energy model in ns2 helps simulation of energy efficient protocols, by modeling the energy consumption when the radio is in receive, transmit, sleep or idle mode's. In addition, the energy model accounts for energy consumption during transition from idle to sleep mode and viceversa. The energy monitoring feature is implemented as part of the wireless physical layer interface (ns-2.29/mac/wireless-phy.{h,cc}) and accesses the energy model implementation at ns-2.29/mobile/energy-model.{h,cc}. The wireless physical layer simulates the transmission and reception of the packets through the physical channel, thereby triggers energy calculations when there is a change in the radio state. Also periodic energy calculations are initiated for nodes which are in the sleep state. The energy model does not have information of the radio states, but maintains information on the residual energy in the node and calculates energy exhausted and residual energy based on the time and the power consumption information provided by the wireless physical channel; the product of power in watts and time in seconds is the measure of energy consumed in joules.

The wireless physical layer interface details on the transmitter power and receiver sensitivity. For the current implementation, decisions made at the network layer are made available at the physical layer interface and also the physical layer data is rendered to the network layer to aid in the decision making process. The transmitter power level and the dynamic receive threshold set by the XLRP algorithm are passed on to the physical layer. Based on the information received the transmitter power level is switched and the packet is transmitted, corresponding transmission energy and radio state transition energy calculations are triggered. Based on the receiver threshold information from the above layer, the radio is switched OFF and the packet is dropped. Also, information on the signal strength for the received packet is made available at the network layer, to aid in decision making processes.

The current energy model has been modified to accommodate the energy calculation as required by the proposed cross layer routing protocol. In the original energy model, transition energy between sleep and idle states where only accounted, the same was extended for any state change in the radio model. As discussed in the previous subsection, the common header is required for ns2 simulations and generation of trace files, moreover the common header is unique has the packet traverses towards the various layers (application, network, mac and physical layers) of a node, maintaining its unique identity. In the current implementation, the common header is being used to share information across layers within a node.

The proposed cross layer routing protocol has been implemented in the network simulator; with tcl instances for instantiating the core filter agent and the XLRP filter, in similar grounds as that of the directed diffusion implementation. Also the subscribe and publish instances have mirrored tcl instances. Various test scenarios have been generated and the effectiveness of the protocol has been proven in the subsequent chapter.

Chapter 5

Simulation Results and Discussions

The preceding chapter detailed on the protocol and the implementation of the algorithm in network simulator. The current chapter demonstrates the efficiency of the algorithm by simulating a wireless sensor network and generating test scenarios using tcl in ns2. The chapter is organized into three sections; the first section details on the simulation model, briefing on the network setup, assumptions and the mac layer protocol used. The subsequent section details on the performance metrics used for evaluating the protocol. The final section details on the simulation results and an analysis of the results.

5.1 Simulation Model

Having understood the functionalities of network simulator the core algorithm was implemented in C++ and tcl scripts were used to generate test scenarios. In simulation, nodes are deployed randomly within a specified area, with the density of the nodes chosen such that nodes can talk to each other in their least transmitter power levels. The minimum transmitter power level assumed in the current simulation is -15dm with a receiver sensitivity of -94dbm, this leaves a node with a neighborhood radius of 6 meters; meaning adjacent nodes are spatially separated with maximum distance of six meters. The nodes are configured with XLRP as the network layer agent and the wireless interface of ns2 with CC2420 radio module specifications as the physical layer agent. For the MAC (media access layer) layer, 802.11 interface was used. To reduce the overhead and making 802.11 MAC more viable for sensor networks, the RTS (Ready To Send), CTS (Clear To Send) and ACK (Acknowledgment) controlled messages have been nullified. Though SMAC (Sensor MAC) and TMAC (Timeout MAC) have implementations in ns2, the operation of the protocols suites sensor network layer protocols operating in single fixed transmitter power levels. Most MAC layer protocol implementations in NS2 for wireless sensor networks are developed to operate in fixed transmitter power levels, has the protocol design needs neighbor nodes to synchronize and have identical sleep and wakeup cycles for communication. Extending these MAC protocols to operate in varied power levels would increase the complexity of the protocol and extensively need to test the efficiency of the modified protocols. Moreover, the emphasis in this thesis being network layer design for sensor networks, a viable MAC schema has been opted to test the effectiveness of the proposed cross layer design.

To prove the effectiveness of the current proposed work, directed diffusion with geographic information has been used for comparison. Directed Diffusion is one of simple and efficient routing protocols designed for sensor networks which found its applicability in real time sensor network test beds. GEAR (Geographic and Energy Aware Routing) a variant of directed diffusion is being used for comparison, however only the location aware routing has been implemented in ns2, the energy aware version awaits implementation. Many network layer protocols have also been proposed, detailed in chapter 2, wherein most multi-hop routing protocols were a development over the diffusion paradigm, however the increased complexity of the algorithm's and the feasibility of implementation on low cost sensor network modules is questioned.

However, the current work tries to identify factors that could help in efficient routing without appreciable increase in complexity of the routing mechanism.

5.2 Performance Metrics

This section details on a few performance metric's used to evaluate the performance of network layer protocols in wireless sensor networks.

Energy Consumption is one of the prime metric determining the utility of the protocols designed for wireless sensor networks. Low cost sensor network modules are developed and built for remote deployment wherein the cost of recovering or replenishing the batteries is higher than replacing the sensor network with new modules. The rate of energy consumption in the network determines **Sensor Network Lifetime**. Lifetime of the sensor network has many definitions, the simplest is the time taken for the first node to die in the sensor network. A uniform drain of energy if coordinated among all nodes prolongs the lifetime of the sensor network. One other definition of sensor network lifetime is the time at which the energy drain in a sensor node parts the sensors network or creates a hollow in the region being sensed. Energy consumption and network lifetime are closely related, a uniform energy drain among the nodes in the network results in maximum sensor network lifetime. However, other application layer characteristics also determine the network lifetime, as in case when event is detected in one part of the network, a relatively higher energy drain in the sensed region is unavoidable. For network layer test of energy consumption and sensor network lifetime, events are uniformly distributed throughout the network.

Latency, the time taken for information to reach the sink node from the source node. The ideal delay for information to be transferred between two nodes would be a direct transmission, however not always possible in real time. As in the case of a multi-hop routing protocol increasing the number of hops adds to the delay, nevertheless switching to higher power levels would help reduce the number of hops resulting in faster delivery of information at the node. However, all these performance parameters are related, for a speedy reception of data energy consumed might be higher, a tradeoff between energy consumption and latency.

Throughput, a ratio of the number of packets received to that of the packets transmitted at the network. At the MAC, throughput is an important performance measure on the MAC layers channel arbitration capability in avoiding data loss due to collision. However, at the network layer it is based on the successful receipt of information by intended receivers irrespective of the number of retransmission. In general TCP/IP based networks throughout is high because of the acknowledgment message exchanged between nodes, requiring retransmission of packets if not received correctly. However, in wireless sensor network this would account to huge amount of information exchange and a source of energy drain in the network. In general in sensor networks messages are not addressed to nodes rather messages are identified by their content and forwarded. For example, a data message from source to sink, the message would be forwarded based on the nodes subscription information.

5.3 Simulation Results

Based on the simulation model elaborated in section 5.1, the effectiveness of the proposed cross layer routing protocol is being evaluated in reference to the above discussed performance metrics.

5.3.1 Energy Efficiency

To test the energy efficiency of the protocol a sensor network of 50 nodes was created, bearing the assumption that nodes are placed such that they have at least one neighbor node that can be reached through its minimum transmitter power level. The

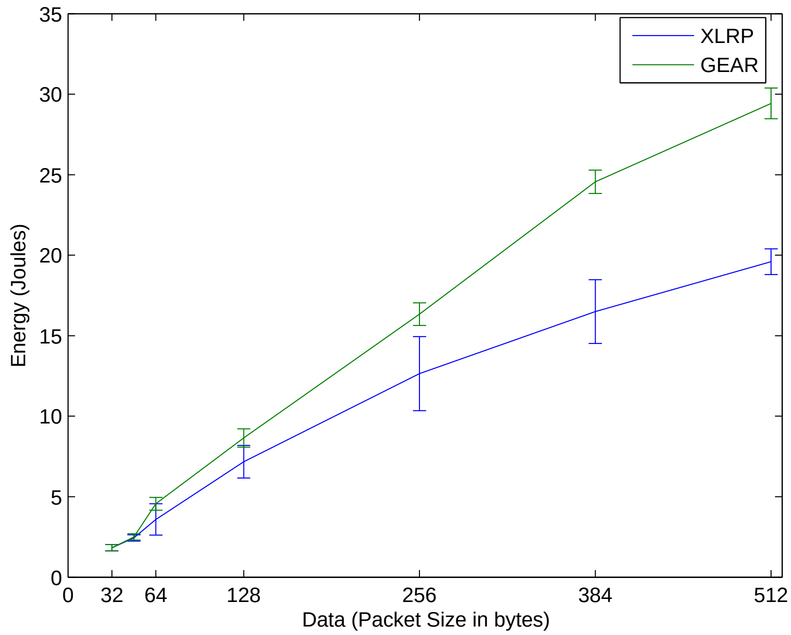


Figure 5.1: Energy consumption with varying data size

data size was varied and the energy consumed for data transmission between nodes farther apart, requiring a multi-hop communication, was calculated. Identical network topology was used for comparing XLRP and GEAR. The results of simulation are shown in fig 5.1. For small packet sizes of 32 or 48 bytes, the energy consumed was identical for both the protocols, however for increasing packet size XLRP proved to be consume lesser power compared to that of geographic aware routing. The energy saving is attributed to the reduction in number of transmitters and controlled switching OFF of receivers. The high standard deviation in energy for packet sizes around 256 bytes is because of the higher influence of the communication cost factor in the decision making process of switching to higher transmitter power levels.

XLRP also had the benefit of switching between neighbor nodes at different transmitter power along the subscription path, thereby supporting uniform energy drain along the path. Meaning, though a single path is reinforced with data all the nodes along the path are not active as nodes alternate radio state by switching transmitter power levels. However, in the case of diffusion based algorithms the energy drain would be higher for nodes along the path, since in sensor network protocols the cost of maintaining multiple paths is high.

5.3.2 Reduced Latency

In real time systems, the timely delivery of information is as important as the data itself. Delay's beyond a certain bound might no longer be useful at the user end. The plot in figure 5.2 compares the delay in information being delivered across the network from a source node to a sink node, the simulation setup is identical to that discussed in the previous subsection for energy calculations. It is evident from the plot that XLRP has fifty percent lesser delay compared to that of the directed diffusion paradigm for the maximum packet size is 512 bytes, this is because of the reduced number of hops along the transmission path. 512 bytes is set as the maximum physical unit that can be communicated over the radio by zigbee consortium, detailed in chapter 2. However, for smaller packet sizes the delay in both the protocols are the same as it is preferred to remain in lower power transmission mode's for lower energy consumption.

5.3.3 Scalability

Wireless sensor networked are deemed to operate in large numbers deployed in no particular fashion. Protocols need to be efficient and prove to be independent of the network size. Scalability of the protocol has been addressed in terms of increasing network size with no change in the density of the nodes and increase in node density by increasing the number of nodes within a region. Scalability of the protocol has been addressed in terms of the network lifetime, also can be addressed in terms of the throughput of the sensor network as discussed in the subsequent subsection.

XLRP and GEAR do not have a huge difference in terms of the network lifetime, however XLRP outperforms GEAR. GEAR has high extended network life time

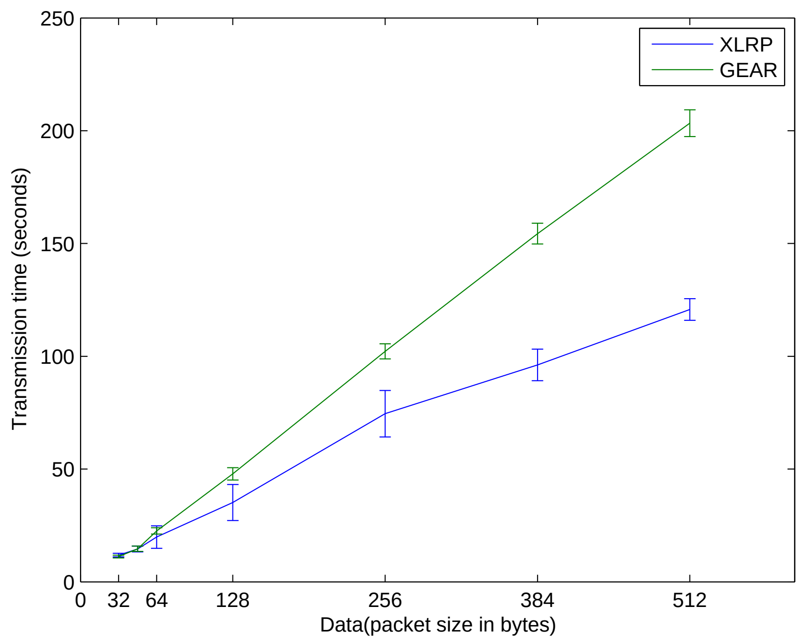


Figure 5.2: Latency Measure with respect to data size

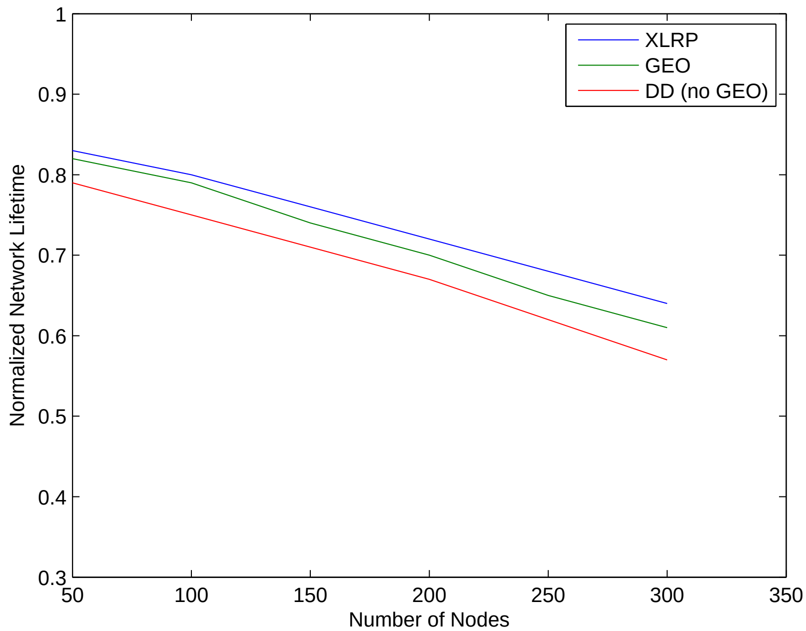


Figure 5.3: Lifetime of the sensor network with increasing network size

because of the knowledge of the location information, as seen in the plot in fig 5.3 compared to that of directed diffusion paradigm with no location information. The presence of geographic information has the benefits of controlled flooding thereby saving on energy. However, XLRP outperforms GEAR because of the lesser control information for the operation of the protocol, GEAR has periodic beacon message exchange between neighbor node, XLRP does not support any periodic beacons as in GEAR. However, similar functionalities are achieved by piggy backing information and gathering information from packets received even though not destined to the node. Moreover, controlled forwarding is used only for communicating sink messages, thereby not very beneficial for unicast data messages. In the sensor network lifetime plots, y axis is labeled normalized network lifetime, calculated as a ratio of energy exhausted to the total energy available at the instant when the first node is exhausted of its energy resource.

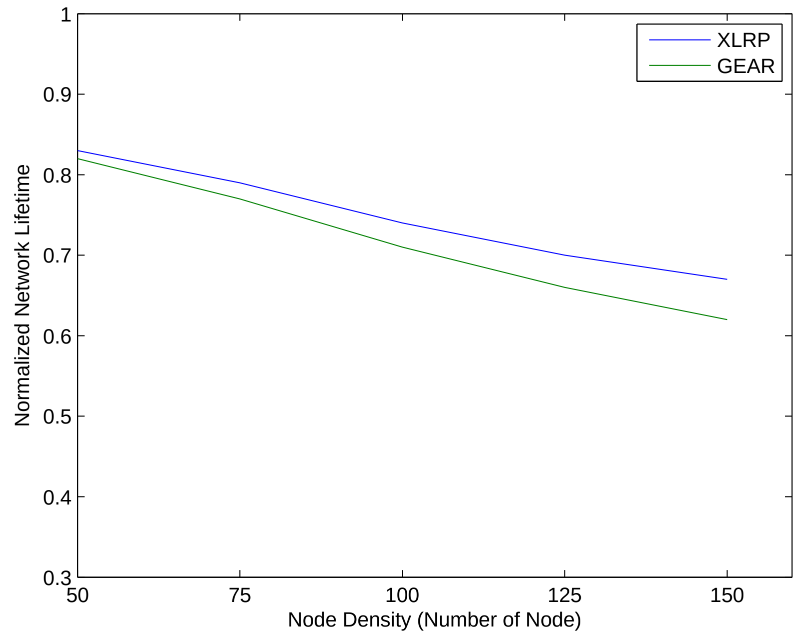


Figure 5.4: Lifetime of the sensor network with increasing network density

Also the network lifetime is evaluated with respect to varying node density. As in fig 5.4, along the x axis the number of nodes increase within a fixed region thereby increasing on the node density. XLRP shows better performance compared to that geographic based routing technique, though location information is available, the information would not be of great help within a specific closed region. XLRP's effectiveness is greatly due to the receiver switching characteristic, as a larger number of unintended receiver nodes can turned OFF. Moreover reduced number of transmission adds to the external network life time of XLRP.

5.3.4 Throughput

Throughput determines the number of packets lost in transmission and that never reached the intended receiver. Throughput analysis is not confined to data messages, node identity messages and subscription messages are being accounted for throughput analysis. Transmission at larger power levels implies larger number of nodes contend

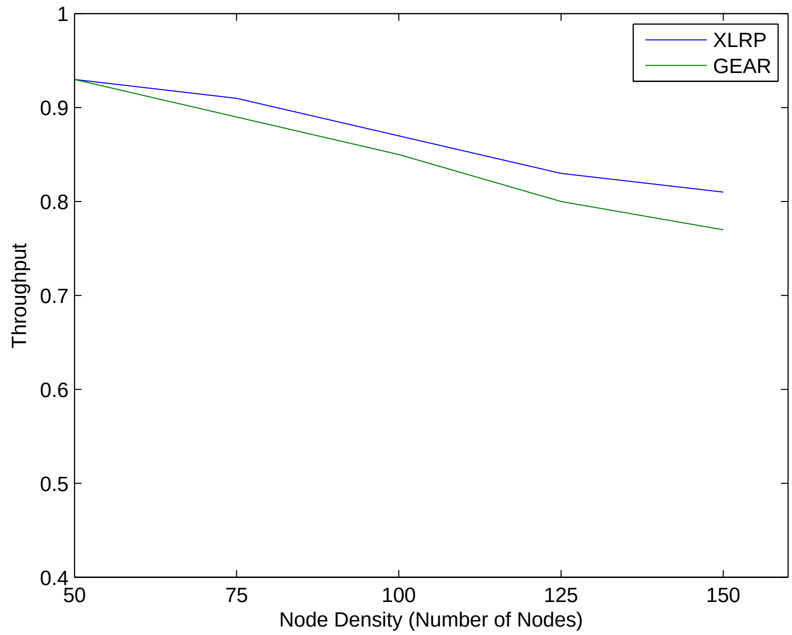


Figure 5.5: Throughput of the network with increasing node density

to send resulting in larger transmissions, however in the present case only unicast messages are broadcasted at higher power levels, this reduces the number of nodes that might want to retransmit. Moreover, our concern is in evaluating the performance of the network layer protocol where in the collision while transmission are not accounted for, as they are dependent on the MAC layer. In the present case, the reception of the message is only accounted irrespective of the number of hops or path the message would take to reach the destination node.

From the plot shown in fig 5.5 with increasing node density the throughput for the sensor network drops, however gear has a greater slope for drop in throughput compared to that of XLRP. This is again due to the fact that number of control message exchange in GEAR is higher compared to that of XLRP where no periodic control message exchange takes place.

Chapter 6

Conclusion and Future Work

This thesis was aimed at identifying and proposing a cross layer routing strategy for wireless sensors networks, which has been proven efficient in comparison with that of directed diffusion paradigm in the previous chapter. The concept of using data size as a feature for routing is uniquely applicable to content aware networked systems, as in the case of wireless sensor networks deployed for specific applications. Switching transmitter power levels and dropping packets based on the received signal strength proves to be an energy efficient and a delay tolerant method for information dissemination in wireless sensor networks. To conclude with, this chapter details on the applications and future developments to the proposed work.

6.0.5 Applications

The proposed algorithms finds it's application in wireless sensor network systems wherein messages of varied size needs to be exchanged among nodes. Also, for networked sensing systems wherein the volume of information exchange is high and data needs to be exchanged with specific nodes. Typical application would involve a heterogenous sensor network system, wherein the nodes have a wide range of sensing capabilities and generate data varying from a few bytes to a few hundred kilobytes.

For example, a temperature sensor would generate a byte or two bytes of information, an acoustic sensor would generate a few tens of bytes of data and an image sensor would generate few hundred bytes of information. Sensor networks being application specific, built to sense a certain event, one has prior knowledge on what information would be available from the sensor network. This unique characteristic of sensor network supports size of the data has an unique parameter for routing information and its unique applicability to sensor networks.

Plans are underway to implement the proposed routing algorithm in a geophone based wireless sensor network system. Telosb motes are being used as the wireless sensor network module integrated to a geophone. The network consists of a group of twenty four or forty eight geophones arranged in an linear fashion, with a master telosb node attached to a high end computing system like a laptop. The master node helps logging information generated from the geophones and synchronizing the geophones for data acquisition. The sensor modules are triggered by an external source generating seismic signals and the data is acquired by the sensor modules for a few seconds, 2 to 5 seconds. The motes have a built in ADC (Analog to Digital Converter) with a resolution of 12 bits, however not built to acquire data has the negative reference pins for the ADC have been grounded. An external ADC is being built to acquire the entire peak-to-peak seismic signal and is interfaced to the telosb motes via serial programmable interface (SPI). Moreover, the application requires higher data resolution thereby ADS1211 from Texas Instruments is being used as external ADC which has a maximum bit resolution of 24 bits. With a resolution of 24 bytes and sampling rate in hundreds of microseconds, the data collected would be around a few hundred kilobytes. This effectively tests the protocol to switch to higher transmitter power levels for reduced delay and as energy efficient strategy for data acquisition.

The geophone sensor network finds its applicability in structural health monitoring, oil explorations, mapping geological features in the earth's crust, to name a few. The current setup is a wired network wherein all geophones are spatially separated and are wired to a data acquisition box capable of acquiring 48 channels of data simultaneously. Changing the current setup into an wireless sensing system saves on time for setting the network and reduces the cost in comparison to the current wired setup.

6.0.6 Future Work

Having suggested and analyzed the cross layer protocol in detail, possible grounds for improved performance of the protocol have been identified and are as listed below.

- **Node Failures**, the advantage of transmission of periodic beacon messages helps nodes figure out neighbor node loss, however at the expense of energy. The proposed XLRP algorithm helps acknowledge node loss as a result of energy exhaustion, however loss due to node malfunction is not accounted for. This affects the network functionality and data is lost only when messages are unicast messages. To overcome the problem active nodes on receiving unintended unicast messages of their one hop neighbor nodes, wait for the intended receiver node to react within a time limit, else the message is locally broadcasted by the neighbor nodes. Though initially multiple copies of the same message would be generated as the messages is being forwarded to the source, redundant messages are further not broadcasted.

- **Support for Mobility**, the radio signal strength parameter has been widely used for localization in mobile systems, with the received signal strength parameter being used in the proposed work, its applicability can be extended to support mobility in network modules. In the proposed work nodes are identified based on the transmitter power level used for communication. In the case of a mobile node, which can send out a identity message at periodic intervals and based on the information received nodes can suitably make changes to their routing table.

- **Include Location Information**, the proposed protocol was found to have an extended network lifetime in comparison with that of location aware diffusion paradigm. Adding location information to proposed cross layer design would enhance the network lifetime by limiting interest flooded to geographic regions. However, this would require specific hardware on the motes to identify themselves on the network in a global scale. Nevertheless, using simple radio based technique to localize node information serves as a low cost alternative but would increase the complexity of the protocol.

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