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Maximizing the System Lifetime in Wireless Sensor Networks using Improved Routing Algorithm

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MAXIMIZING THE SYSTEM LIFETIME IN WIRELESS SENSOR NETWORKS USING IMPROVED ROUTING ALGORITHM

by

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B.E., Visvesvaraya Technological University, 2007

A Thesis
Submitted in Partial Fulfillment of the Requirements for the
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MAJOR PROFESSOR: Dr. Dimitrios Kagaris

In wireless sensor networks, the maximum lifetime routing problem has received increasing attention among researchers. There are several critical features that need to be considered while designing a wireless sensor networks such as cost, network lifetime and Quality of service. Due to the limitation on the energy of sensor nodes, energy efficient routing is a very important issue in sensor networks. Therefore, to prolong the lifetime of the sensor nodes, designing efficient routing protocols is critical. One solution is to formulate the routing problem as a linear programming problem by maximizing the time at which the first node runs out of battery. In this paper, with the notion of maximizing the system lifetime, we implemented a new heuristic and evaluated the performance of it with the existing algorithm called flow augmentation algorithm. Further, our experimental results demonstrate that the proposed algorithm significantly outperform FA algorithm, in terms of system lifetime.

ACKNOWLEDGMENTS

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INTRODUCTION

Like any sentient organism, the smart environment relies first and foremost on sensory data from the real world [1]. All these data comes from multiple sensors of different modalities from various sensors distributed across different locations. The challenges in the hierarchy of: detecting the relevant quantities, monitoring and collecting the data, assessing and evaluating the information, formulating meaningful user displays, and performing decision-making and alarm functions are enormous [1].

A Wireless Sensor Network (WSN) consists of spatially distributed autonomous sensors to *monitor* physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants [2]. The applications for WSNs are varied, WSNs can be deployed on a global scale for environmental monitoring and habitat study, over a battle field for military surveillance and reconnaissance, in emergent environments for search and rescue, in factories for condition based maintenance, in buildings for infrastructure health monitoring, in homes to realize smart homes, or even in bodies for patient monitoring. The emergence of wireless sensor networks (WSNs) is essentially due to the latest trend of Moore's Law toward the miniaturization and ubiquity of computing devices. The hardware basis of WSNs is driven by advances in several technologies. Notably, System-on-Chip (SoC) technology is capable of integrating complete systems on a single chip which makes it more cost efficient. The Figure 1.1 shows a simple illustration of wireless sensor networks (WSNs)

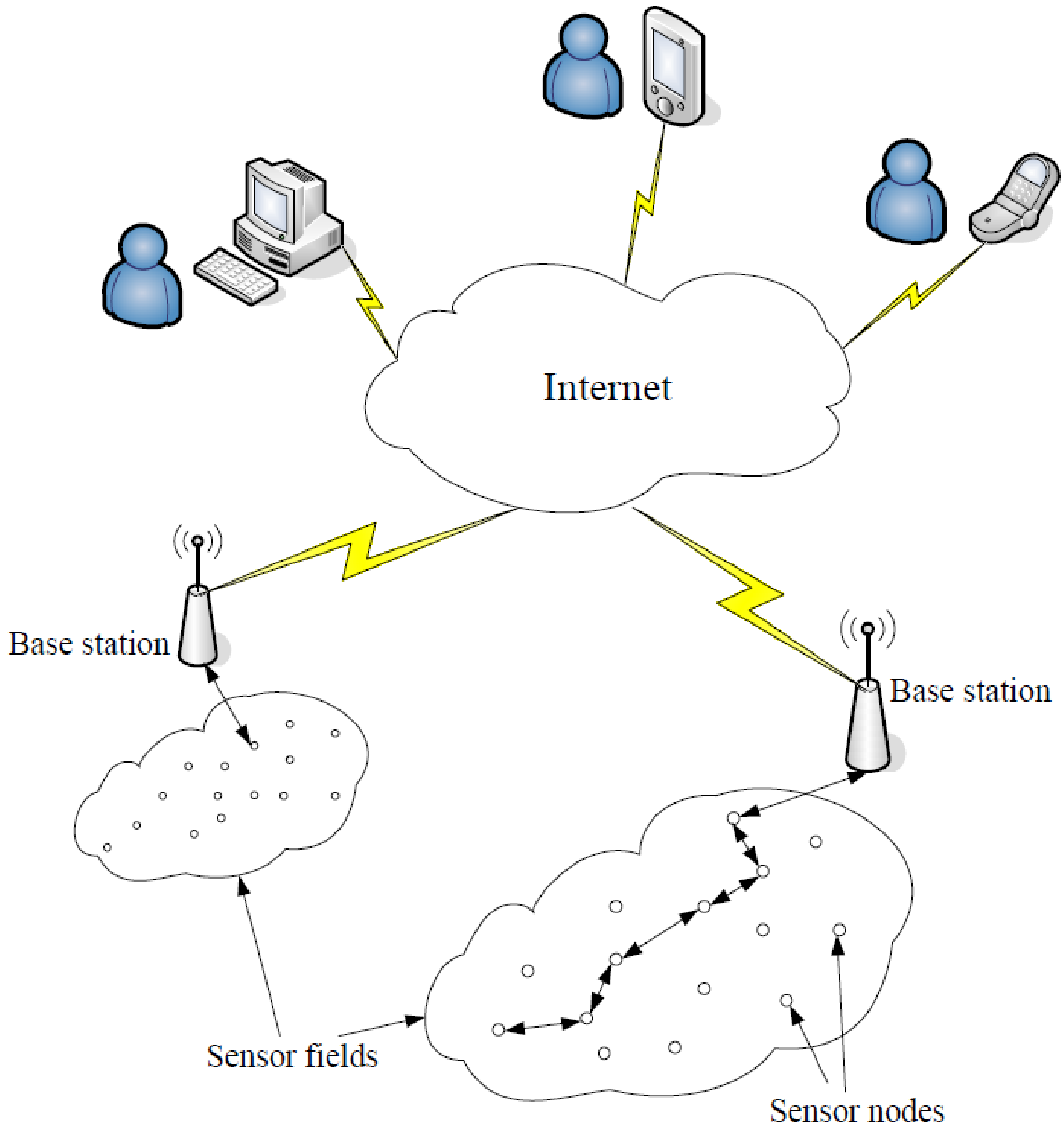
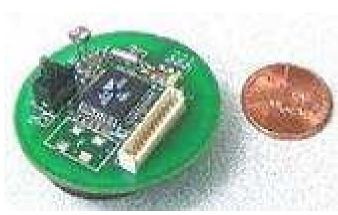


Figure 1.1 Simple illustration of WSN.

1.1 EVOLUTION OF WSNs

In 1996, UCLA and the Rockwell Science Center produced the Low Power Wireless Integrated Micro sensors (LWIMs). In 1998, the same team developed a second generation sensor node although relatively powerful processing and communication capabilities is offered by WINS, other research efforts focus on developing smaller and cheaper nodes with less power consumption. In 1999, UC Berkeley's Smart Dust project released the first node, WeC, in their product family of *motes* (Figure 1.3(a)). WeC was modeled with 8-bit, 4 MHz Atmel microcontroller (512 bytes RAM and 8 KB ash memory), consuming 15mW active power and 45 mW sleeping power. In 2001, Mica family was released along this line, which still used an 8-bit 4 MHz microcontroller (ATmega103L), in terms of memory and radio; it produced enhanced capabilities when compared with preceding products. In order to reduce the standby current, the sequence to Mica, Mica2 and Mica2Dot were built with an ATmega128 microcontroller in 2002. They provided improved radio modules with more selections for frequency range, and by using FSK modulation increased resilience to noise. The Figure 1.2 shows the WeC, Mica, Telos and Spec modules [3].



(a) WeC

(b) Mica Family

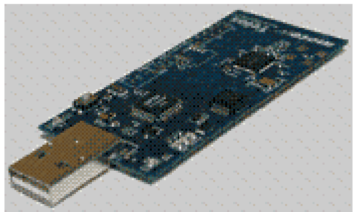
 (c) Telos	 (d) Spec Prototype

Figure 1.2 Wireless Integrated Micro Sensors

The architectures of all the above mentioned sensors are based on batteries. Techniques for energy scavenging from the environment have been an attractive research field due to the slow advancement in battery capacity. In 2003, the first radio transmitter, PicoBeacon (Figure 1.5), which is presented by the Berkeley Wireless Research Center (BWRC) is purely powered by solar and vibration energy sources [3].

1.1.1 Wireless Networking Technologies:

The development of WSNs relies also on wireless networking technologies apart from hardware technologies. In 1997, the first standard for wireless local area networks (WLANs), the 802.11 protocol was introduced. By increasing the data rate and CSMA/CA mechanisms for medium access control (MAC), it got upgraded to 802.11b. Routing techniques in wireless networks are another important research direction for WSNs above the physical and MAC layers.

Actually, the existing routing protocols for wireless ad hoc networks or wireless mobile networks are the early routing protocols in WSNs. Due to the high power consumption, these protocols, including DSR and AODV, are hardly applicable to WSNs [3]. Therefore scaling down the power consumption is another area where there are ample research opportunities. In the near future, the era of WSNs is highly anticipated.

1.2 APPLICATIONS

The applications in WSNs are generally classified into 2 categories, namely *Data Gathering Applications* and *Complex Computational Applications*.

1.2.1 Data Gathering Applications:

The primary goal of these applications is to gather information of a relatively simple form, such as temperature and humidity, from the operating environment. Environmental monitoring and habitat study applications also belong to this class [3].

1.2.1.1 Habitat Study:

One of the driving applications for WSNs is Habitat study. Sensing and gathering of bio-physical or bio-chemical information is usually required for such applications from the entities under study, such as Storm Petrels, Redwoods, Zebras, and Oysters. Habitat study needs relatively simple signal processing, such as data collection using minimum, maximum, or average operations in many scenarios. Hence for such applications, motes are ideal platforms [3].

1.2.1.2 Environmental Monitoring:

Environment monitoring is another field where WSNs have been used to a greater extent, some of the best examples are, forest fire alarm, landscape flooding alarm, soil moisture monitoring, micro climate and solar radiation mapping, and environmental observation and forecasting in rivers [3]. All the above examples are mostly large scale applications, smart homes can be considered as a example of a small scale environmental monitoring. Driven by emerging standards, increasing energy costs, and advances with Wireless Sensor Networking, the “smart home” is becoming a reality for the mass market.

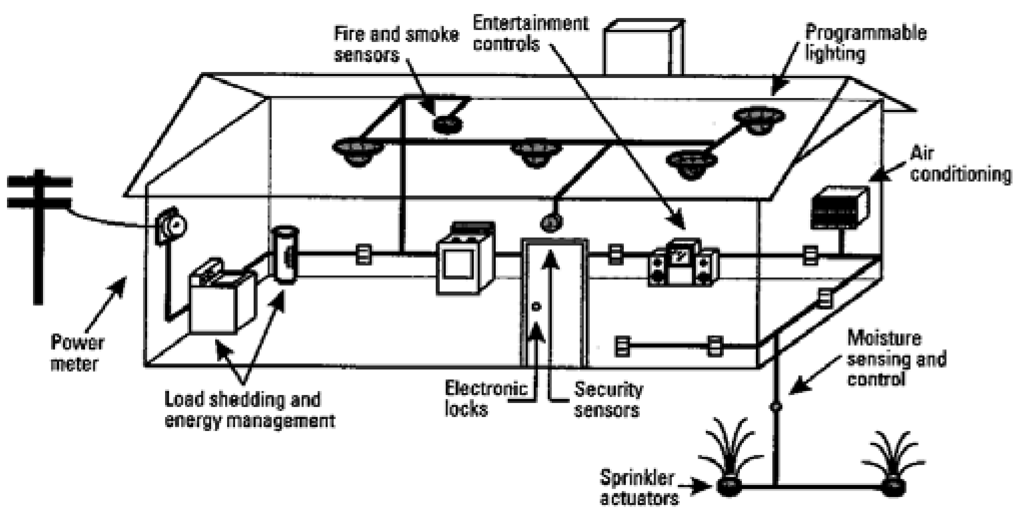


Figure 1.3 Smart Home Networks [4]

The Figure 1.3 shows how networks of various sorts might interact in the smart home environment. The BACnet protocol has been developed by the building automation industry to provide a standard for interconnecting networks for building sensing and control [1].

1.2.2 Complex Computational Applications

The processing and transportation of large volumes of complex data is required by the second class of applications. The complicated signal processing algorithm is usually employed in this class and includes heavy industrial monitoring and video surveillance. These applications are referred to as computationally intensive applications [3]. For this class of sensors, a good example can be in the field of automobiles.

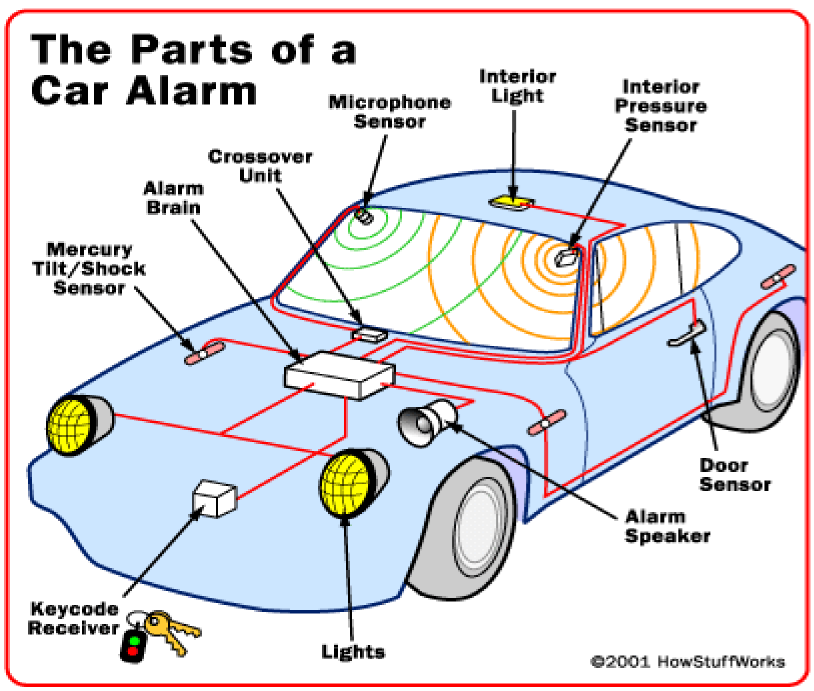


Figure 1.4 WSN in cars

The automobile application of wireless sensor networks comprises a challenge to be encountered in this endeavor; during an automobile journey, we believe a wireless sensor system is capable to collect process and supply several types of technical information to the user. Acceleration and fuel consumption, identification of wrong tires pressure value, acknowledgment of illumination failures (turn lights, brake lights, front lights, and register plate lights), and determination of the vital signals of the driver are few examples of it [5].

1.3 MARKET TRENDS

Wireless sensor networks market size was approximately $5billion in 2006 and $8billion in 2007, which according to the Wireless Research Group. More than 700 million units were expected to grow by 2007, catching up with the number of wireless handsets. More than half of the total market will be constituted by building and industrial automation, two of Dust Networks' primary application.

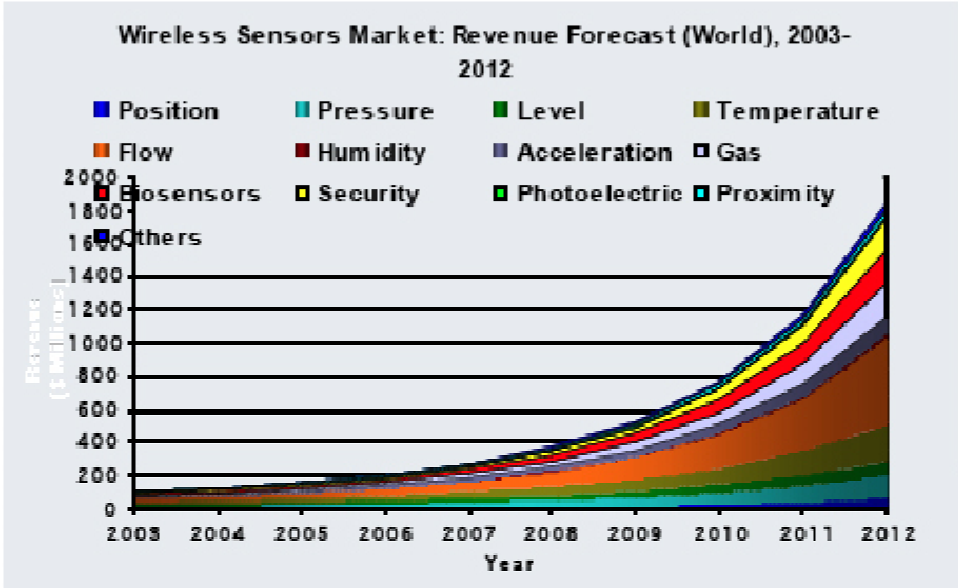
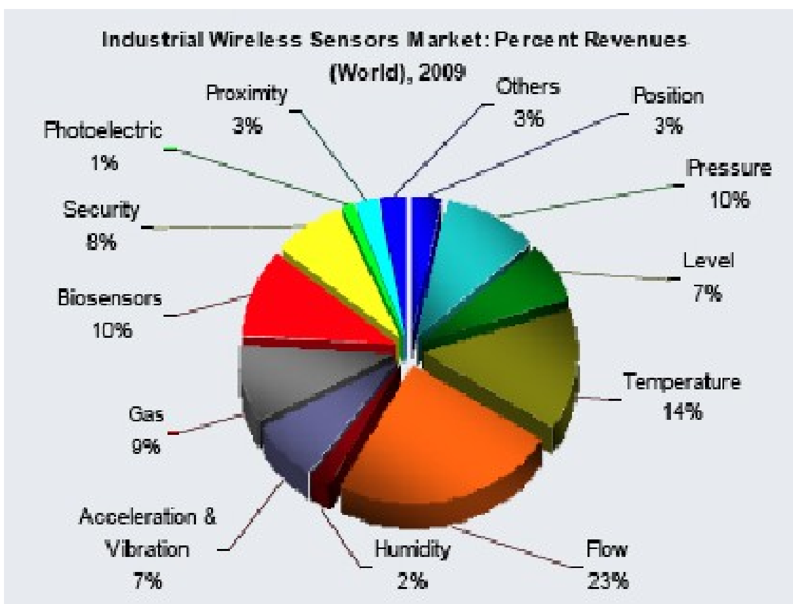


Figure 1.5 Wireless Sensors Market: Revenue Forecast, [6].



Source: Frost & Sullivan

Figure 1.6 Percent Revenues of Industrial Wireless Sensors, [6]

Figure 1.5 predicts the various types of sensors percent increase up to 2012. The residential sector is a vital target market for wireless sensing and control solutions, with a total potential market size of 6 billion cumulative WSN nodes worldwide. The percentage market shares held by various sensors is explained in figure 1.6. Lighting, energy management, security, entertainment control and home health are some of the largest and fastest growing smart home markets. In 2012, the Wireless Sensor Network (WSN) smart home market will be worth $2.8 billion worldwide, up from $470 million in 2007 [6].

1.4 CURRENT RESEARCH AND CHALLENGES

Considerable challenges in the field of WSNs range through network organization, topology discovery, communication scheduling, routing control, and signal processing. Also, tight energy budgets enforce energy efficient designs for hardware components, network stacks, and application algorithms.

There are 5 key challenges which require a great deal of research towards it. However, there many other research areas are very important including: localization, topology control, dependability, self-calibration, self-healing, data aggregation, group management, clock synchronization, query processing, sensor processing and fusion under limited capacities, and testing and debugging [7]. WSN are a fascinating area with great potential [7]. Here we would like to discuss briefly about the key challenges and our motivation towards this theses work.

1.4.1 Information Processing

In any Wireless Sensor Networks (WSNs), we have 2 fundamental processes, they are: Information processing and Information routing. Information processing typically deals with sensing data, fusing data, query processing and moving data. Information processing can be classified into three main categories, including energy aware information processing algorithms design, space time signal processing algorithms and networked information processing algorithms [8].

1.4.1.1 Energy aware information processing algorithms design

The sensor nodes in WSNs are energy constrained and has a finite lifetime. It would be highly desirable to carry out the information processing algorithms in an energy aware manner. In order to make energy efficient information processing the tradeoff between computational accuracy and energy requirement of the algorithm on a single node should be determined. Then to maximize the computational quality for a given energy constraint, we need break down the algorithm into multiple tasks and distribute it among a group of nodes, so that the energy consumption will be balanced among multiple nodes, and the overall lifetime will be prolonged. It is a major division in Information processing which opens a large area for research [8].

1.4.1.2 Space Time signal processing algorithms

An important aspect in the sensed region is that, always there exists a time varying, space-time signature field that may be sensed by multiple nodes. Individual nodes, however, only provide spatially local information. This necessitates collaboration between nodes to process the space-time signal to extract useful information such as the position of the moving object [8].

1.4.2 Information Routing

While information routing facilitates joint information compression (or data aggregation) by bringing together data from multiple sources, information processing helps reduce the data volume to be routed. However, analyzing and modeling the inter-relationship between information processing and routing is very significant. In many situations, the task of finding a routing scheme in association with joint compression for energy minimization turns out to be NP-hard [3]. Essential data between nodes in the region must be exchanged for information processing due to the limited communication and computational capability of each node. The routing of data should reduce the communication cost so as to save energy from the viewpoint of networking [3][8].

1.4.3 Network Management

In most cases, sensor data must be delivered within a specified time based on which appropriate observations can be made or actions can be taken.

One key challenge is to handle network dynamics during the process of network discovery and organization. These dynamics include fluctuation in channel quality, failure of sensor nodes, variations in sensor node capabilities, and mobility or diffusion of the monitored entity. Hence WSNs require autonomous adaptation of network discovery and organization protocols based on the network and situation, in order to deliver proper system functionality [3].

1.4.4 Security & Privacy

Ensuring the integrity and confidentiality of sensitive information is achieved by crucial security. To do so, intrusion and spoofing of the networks should be well protected. It is unsuitable to use the conventional encryption techniques as the sensor node is constrained of computation and communication capability. Lightweight and application-specific architectures are preferred instead [3]. By broadcasting a high-energy signal, an adversary attempts to disrupt the operation in case of denial-of service attack. The entire system could be jammed, if the transmission is strong enough. More sophisticated attacks are also possible: By violating the MAC protocol, the adversary can inhibit communication, for instance by continuously requesting channel access or by transmitting while a neighbor is also transmitting or with a RTS (request to- send) [7]. Since components designed without security can become a point of attack, every component must be integrated with security so as to achieve secure system [7].

1.4.5 Energy Conservation

In WSNs, it is often infeasible or undesirable to re-charge sensor nodes or replace their batteries once they are installed and configured. Thus, energy conservation of sensor network becomes crucial for sustaining a sufficiently long network lifetime [3]. The majority of current research focuses on ways to provide full or partial sensing coverage in the context of energy conservation. In such an approach, nodes are put into a dormant state as long as their neighbors can provide sensing coverage for them [7]. Energy conservation can also be achieved by employing smart routing algorithms that are generally referred to as energy aware information processing and routing algorithms. There are number of power reduction strategies for the sensor, some are listed below [9],

- Turn power on to sensor only when sampling.
- Turn power on to signal conditioning only when sampling sensor.
- Only sample sensor when an event occurs.
- Lower sensor sample rate to the minimum required by the application.
- Implement an event-driven transmission strategy; only transmit data when a sensor event occurs.

In spite of large number of existing strategies energy conservation still remains one of the major challenges for the industry.

1.5 MY WORK

When we take a look at the existing challenges energy conservation of the Wireless Sensor Networks seems to be a major road block. This work focuses on addressing the energy conservation issues by coming up with a smart routing algorithm which is completely aware of the existing energy issues, thereby increasing the overall lifetime of the network. This work is split into 4 chapters; the crux of each chapter is as follows,

CHAPTER 1: This chapter will introduce the basic concepts about the Wireless Sensor Networks. It discusses the evolution of the WSN technology, its current technology, etc. It also briefs the market trends and the extent to which WSN plays a role in world economy. Finally here we discuss the challenges involved to design an optimized WSN.

CHAPTER 2: Routing characteristics, challenges and key issues of routing are discussed in this section. And a brief detail of different routing protocols are discussed here.

CHAPTER 3: In this section, linear programming formulation, existing algorithm and proposed algorithm is discussed. It is followed by examples to compare the proposed algorithm with existing algorithm. Then finally small window and large window information generation windows are analyzed.

CHAPTER 4: In this section we discuss the results obtained by using our algorithm and also we compare our results with the results from flow augmentation algorithm proposed in [21]. Finally we summarize our work and propose ways to extend our work in future in the conclusion part.

CHAPTER 2

ROUTING PRTOCOLS FOR SENSOR NETWORKS

Wireless sensors are small, inexpensive, low power devices which are deployed in large numbers over an area in an ad hoc fashion. Each sensor node has a limited battery life, limited gaze of the environment and limited processing power. A large number of such nodes which can co-ordinate amongst themselves give them huge advantage over centralized single sensor based techniques. Wireless Sensor networks have severe resource constraints, asymmetric many to one data flow and unreliable network nodes. Thus their primary objective is for energy conservation and prolonging network lifetime, which overlooks at performance, bandwidth and QoS to optimize the primary goals. Several current protocols are based on energy efficient routing.

Routing protocols, designed for sensor networks, must accomplish high reliability in the proximity of individual or patterned node. There has to be multiple paths to relay the data from source node to the destination node in order to achieve robustness. Sensor nodes are constrained in energy supply and recharging sensor nodes is normally impractical when they are out of power, therefore, energy saving is an important design issue in sensor networks. While the objective of traditional networks is to achieve high quality of service provisions, sensor network protocols must focus primarily on power conservation to maximize the network lifetime. Many recent research efforts are focused on how to improve energy efficiency of sensor networks. Flooding the network is a highly expensive operation with respect to energy consumption and should be avoided [10].

2.1 ROUTING CHARACTERISTICS

In the network, consumption of energy is mainly due to the Routing of data; efficient routing protocols can reduce the energy consumption drastically. In sensor networks, routing protocols can be classified based on number of criterions such as proactive vs. reactive routing, hierarchical vs. non-hierarchical routing, etc. In proactive routing, the data path is setup in advance and suitable routing table is maintained. While in reactive routing, the routing tables and paths are created on the fly as and when required. Either source or destination can initiate the routing. Below we discuss a few characteristics of a good routing protocol.

The important characteristics of a “good” routing protocol are as follows [11].

- ✓ *Simplicity:* due to the limited computation capabilities of nodes, the protocol used should not be too large or complex. Memory requirements and the amount of overhead it generates for routing should be reduced, which refers to minimizing the communication and state of the protocol.
- ✓ *Energy awareness:* the battery lifetime of sensor nodes is limited. For a

protocol to avoid nodes that are heavily depleted or use energy-rich nodes, it should have the knowledge of the current energy use and the battery charge.

- ✓ *Adaptability:* Sensor nodes are inherently unreliable. When there is a network change as a result of node failure, the system should be able to adapt to it.
- ✓ *Scalability:* Routing must scale gracefully when the sensor networks are scaled to hundreds and thousands of nodes. The size of the routing table that are maintained and how they scale with the number of nodes in the network is the key part.

2.2 ROUTING CHALLENGES AND KEY ISSUES

Despite enormous applications of WSNs, sensor nodes are constrained in bandwidth and energy supply. Such constraints combined with a typical deployment of large number of sensor nodes have posed many challenges to the design and management of sensor networks [12].

Sensor networks pose unique constraints in designing protocols and hardware for them. The major challenges faced are:

(a)Nature of deployment: Sensor networks are to be deployed in an Ad-hoc fashion with a little correlation in the nodes placement. The detection of network and its distribution is left to the nodes. In order to sustain the hardships of deployment in hostile conditions, the hardware should be rough enough.

(b)Self configuration: The system must be completely self configurable as the

nodes are deployed to work in an environment of unattended human intervention. *(c)Reliability:* A high reliability is expected on each link as the relayed data has to cross over multiple hops, or else the possibility of data reaching its destination is very low. *(d)Quality of Service:* Few applications demand packet delivery to be reached to its destination by specific time limit. Developing protocols for such applications is difficult and challenging one, as the degree of uncertainty in WSN is very high. *(e)Mobility:* Routing gets more difficult if either the message source or destination or both are moving. To solve this, the routing table has to be kept updating continuously or find proxy nodes which are responsible for keeping track of where nodes are. If a node moves away from its original location further, then the proxy node may also vary for a given node. *(f)Security:* Routing algorithms are susceptible to a variety of attacks, including selective forwarding, black hole, Sybil, replays, wormhole and denial of service attacks. *(g)Congestion:* In WSN, Packet losses and resending of data resulting from congestion cost precious energy and shorten the lifetime of sensor nodes. However, congestion is more dominant with larger systems that might process audio, video and have multiple base stations.

2.3 ROUTING TECHNIQUES

Many algorithms have been proposed for the problem of data routing in sensor networks. The characteristics of sensor nodes along with the application and architecture requirements have been considered in developing these routing mechanisms. Under the network flow model, the routing protocols are divided into flat-routing, hierarchical-based and location-based routing. In flat-based routing, no distinct roles of each node, all nodes are equal in functionality. In hierarchical-based routing, each node is distinct from one another and is of different functionality. In location-based routing, the locations of the nodes are manipulated to route the data.

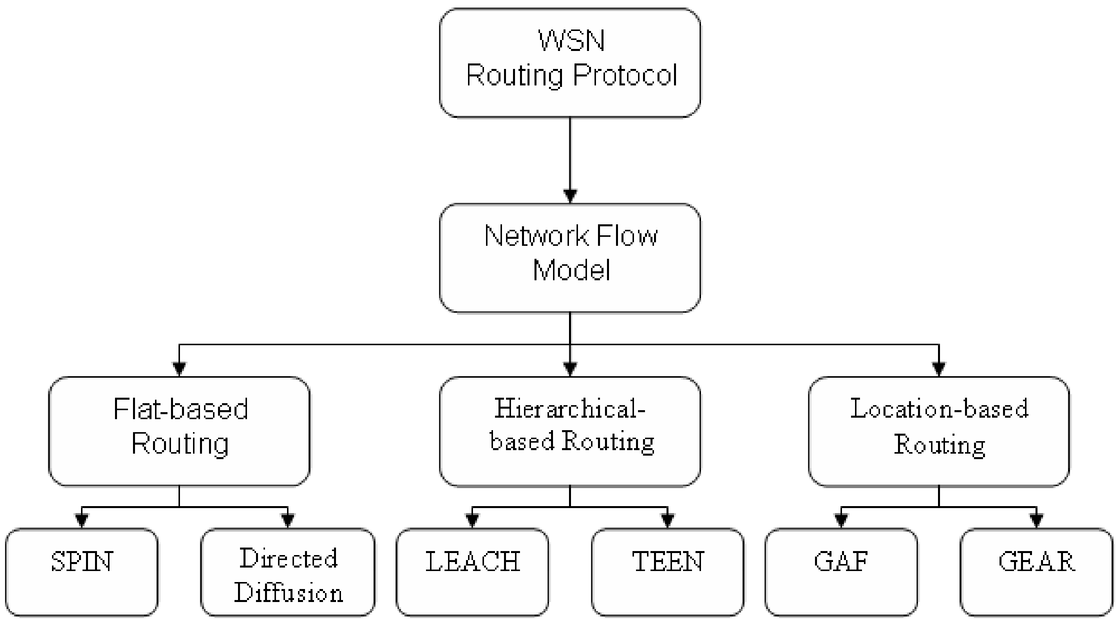


Figure 2.1 Flowchart of various routing techniques.

2.3.1 SPIN (Sensor Protocol for Information via Negotiation)

It is a negotiation based data dissemination protocol where unlike the other cases we want to send data to all nodes treating all nodes in the network as sink nodes. The design goal is to avoid the drawbacks of flooding protocols by utilizing data negotiation and resource-adaptive algorithms [13].

2.3.2 Drawbacks in classical flooding of networks

2.3.2.1 Implosion:

The network wastes resources by sending multiple packets of same data item i.e. node always sends a data packet to its entire neighbor without considering whether it has already transmitted the same packet earlier. The reason for this is lacking of mechanisms to uniquely identify a data item.

2.3.2.2 Overlap:

When more than one sensor monitor events, then the sensor network might form a geographically overlapping regions leading to situation when a common node receives multiple copies of a piece of data.

2.3.2.3 Resource Blindness:

Nodes do not adapt their behavior with change in energy level as it is unaware of the resource. By implementing negotiation based data transfer and resource-adaptation, SPIN overcomes these limitations. Before transmission, nodes negotiate to transfer unique data. This overcomes implosion. SPIN protocol name their data using high-level data descriptors, called meta-data. They use meta-data negotiations to discard the transmission of redundant data throughout the network. Inclusion of a resource manager which is polled before transmitting introduces resource awareness in the nodes.

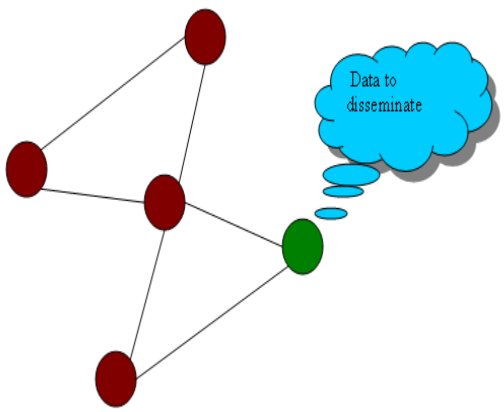


Figure 2.2 Receives data to disseminate.

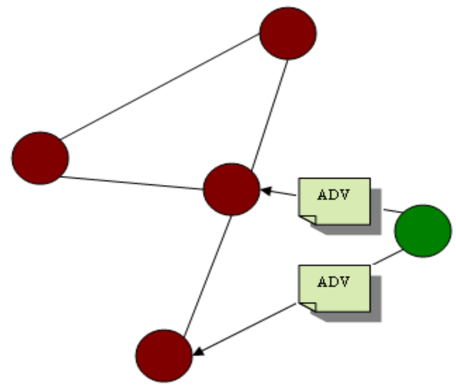


Figure 2.3 Creates ADV Packets.

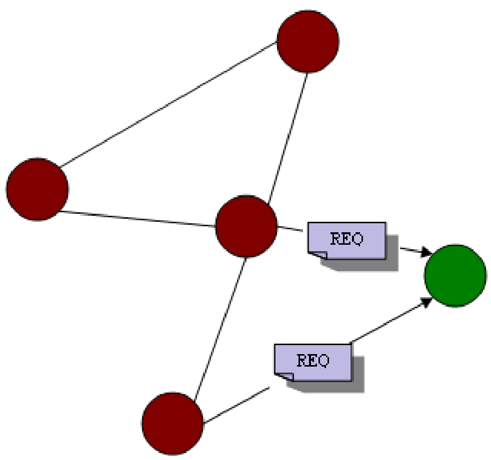


Figure 2.4 Requests to send data

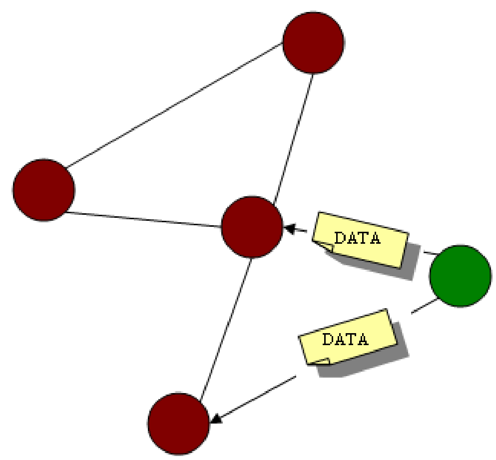


Figure 2.5 Transmits the data

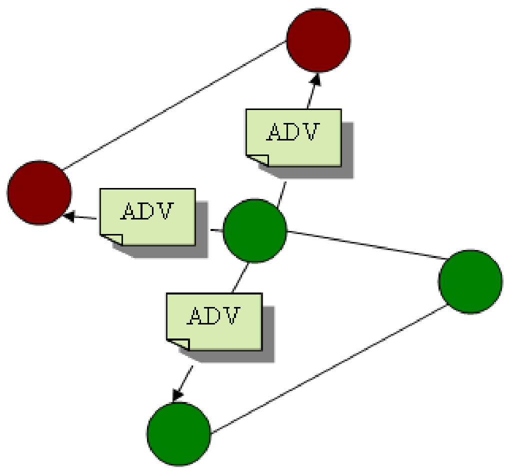


Figure 2.6(a)

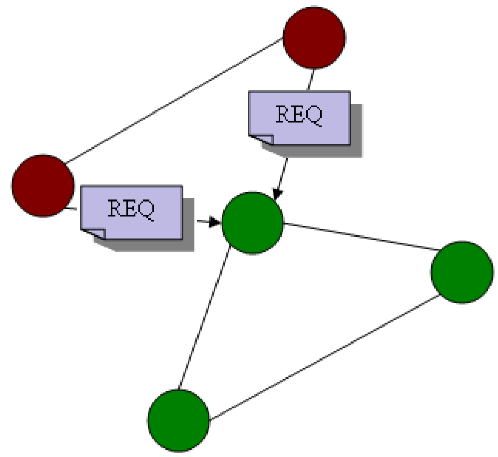


Figure 2.6(b)

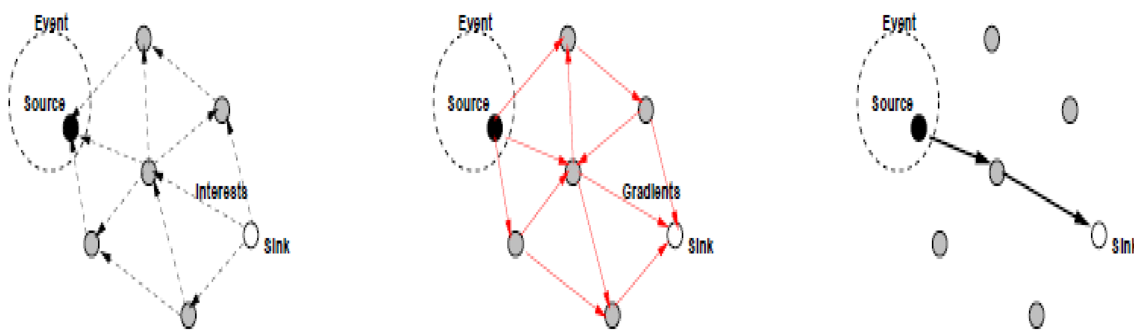
Figure 2.6(a) & 2.6(b) Next node repeating the same procedure

SPIN uses three types of messages for negotiations. When a node receives a new data to disseminate, it makes advertisement of the received data by creating an ADV packet with meta-data attached by transmitting to all its neighbors. The ADV packet contains only the metadata descriptor of the data. Node checks its cache on receiving the ADV packet. The node does not reply to ADV packet, if the metadata descriptor is already present in the cache. Otherwise it sends a REQUEST message, containing the metadata descriptor it received in ADV message of the data item it wants. The source node after receiving the REQUEST message dispatches a DATA message which has the data as the payload and a metadata descriptor as header which is used while constructing the ADV packets. It also has a resource manager which can poll all the resources of the node. If a node does not have sufficient energy to complete the process then resource manager stops the node from active participation. The node does not reply to ADV if it has no sufficient energy left in it.

The protocol have been compared with three standard protocols namely *(a)Classical flooding:* Each sensor on receiving data, forwards it to all its neighboring nodes without inspecting whether it has already transmitted a copy or not. *(b)Gossiping:* The node selects a random neighbor to transmit the received data, which picks another random neighbor to forward the data to and so on, instead of indiscriminately forwarding as in classical flooding to all its neighbors [12]. *(c)Ideal case:* Here data is sent to all the nodes on the shortest path from the source. For this purpose we can use IP level multicasting, etc. The result obtained indicates that SPIN gives much better performance then classical flooding and gossiping. In comparison to classical flooding and gossiping, the energy dissipation is low. For a simulation with fixed amount of energy the SPIN protocol was able to disseminate 73%, when ideal method did 85%, flooding did 53% and gossiping dissipated only 38% of data.

2.3.3 Directed Diffusion

Directed diffusion is another data dissemination protocol in which attributes value pairs name the data generated by the nodes. The routes are determined upon request as this is a destination-initiated reactive routing technique. Throughout the network, for named data a sensing task or *interest* is propagated by a node and data matching this interest is then sent towards this node. By exchanging messages between neighboring nodes within some distance helps in determining the propagation of data and its aggregation at intermediate nodes on the way to the request originating node. Tasks are described by the list of attribute-value pairs. This description is called an interest. In a similar way, naming is done for the response data to such an interest. The *sink* node which is the querying node broadcasts its interest message repeatedly to all of its neighbors. Each item of an *interest cache* of all the nodes corresponds to a different interest. No information about the sink node is contained in these entries [14][15].



(a) Interest propagation (b) Initial gradients set up (c) Data delivery along reinforced path

Figure 2.7 Schematic diagrams for directed diffusion [14].

An entry contains several fields - timestamp field, which has the last received matching interest, the gradient fields consists of the data rate specified by each neighbor, the duration field that contains the lifetime of the interest. Each node verifies its interest cache whenever it accepts an interest, to check if it has an entry. If there is no matching interest, creates one and also creates single gradient field towards the neighbor from which it received the interest. The timestamp and the duration fields are updated if already an interest exists. When a gradient is expired, it is removed from its interest entry. The data rate as well as the direction in which the event has to be transmitted is specified by a gradient. The nodes receiving interest from its neighbors think that node as the originating node but in fact it is transmitting the received interest. Hence, diffusion of interests occurs through the network. A node first examines its interest cache for a matching interest entry whenever it detects an event. If it finds one, then even samples are generated at the highest rate and which is computed from the event rates of outgoing gradients. All of its neighboring nodes which have gradients receive the event description. Hence, when an event is noticed, the sink starts receiving low data rate events, possibly along multiple paths. One particular neighbor is reinforced by the sink to receive the better quality events. This would probably lead to a multiple reinforced paths in which case, the better performing path is withhold and by timing out all the high data rate gradients in the network , the other paths are negatively reinforced while repeatedly reinforcing the selected path.

2.3.4 LEACH (Low-Energy Adaptive Clustering Hierarchy)

LEACH is an adaptive clustering-based protocol using randomized rotation of cluster-heads to evenly distribute the energy load among the sensor nodes in the network. The data will be collected by cluster heads from the nodes in the cluster and after processing and data aggregation forwards it to base station [16][17]. The three important features of LEACH are:

- ✓ Localized co-ordination and control for cluster setup.
- ✓ Randomized cluster head rotation.
- ✓ Local compression to reduce global data communication.

By forming clustering, the energy usage is low within the cluster but drains the energy resource for the cluster head. The cluster heads need to be more powerful than other common nodes of the networks of fixed cluster heads in order to perform maximum long distance communication [16][17].

LEACH’s operation is divided into rounds. Each round can be further divided into the following steps:

- ✓ *Advertisement phase:* With a certain probability, each node accepts to become a cluster head. The selected node advertises its cluster head status and depending on the signal quality, all the other nodes choose one of the clusters.
- ✓ *Cluster setup phase:* Each node informs a particular cluster head about its will to join. Out of multiple advertisement messages, a node selects one cluster head depending on criterions such as proximity, signal to noise ratio, etc.
- ✓ *Schedule creation:* For data transmission, each member of a cluster head follows the assigned TDMA scheduling. If nodes do not have any data to transmit then they can enter into sleep mode/close radio mode [16][17].

- ✓ *Data transmission:* The cluster head performs aggregation and compression of received data from all of its member nodes, which transmitted the data during allotted TDMA schedule [16][17].

The process starts once again at the end of the round. Based on the number of suggested cluster heads and the number of times a node has become cluster head before, decides the allocation of a cluster head to it. A random number is chosen by a node and if that number is less than the threshold value, the node becomes the cluster head [16][17]. The threshold value T_{thresh} is given by:

$$T_{thresh} = \begin{cases} \dfrac{P}{1 - P * (r * \bmod \dfrac{1}{P})} & if \quad n \in G \\ 0 & otherwise \end{cases} \tag{2.1}$$

Where P represents suggested number of cluster heads, current round and G is the set of nodes which were not cluster heads for 1/P rounds. Simulation results show that LEACH is able to maximize network life considerably when compared between direct transmission, multi-hop communication and fixed cluster head protocols. Also compared to other three, the nodes die in a random and distributed fashion [16][17].

2.3.5 Threshold-sensitive Energy Efficient sensor Network protocol [TEEN]

TEEN is a network protocol focused at reactive networks and proposed for time-critical applications. Once the cluster head is formed, it broadcasts attributes, hard and soft threshold parameters to its members [18]. *(a)Attributes:*

It is a set of physical parameters that the user is interested in obtaining [18].

(b)Hard Threshold (H_T): It is a threshold value for the sensed attribute [18].

(c)Soft Threshold (S_T): It is a small change in the value of the sensed attribute. The hard threshold parameter allows the nodes to transmit only when the sensed attribute is in the range of interest, which reduces the number of transmissions. Soft threshold parameter check on the sensed attribute value and if there is little or no vary in the sensed attribute, soft threshold parameter reduces the number of transmissions further by eliminating all the transmissions which might have occurred [18].

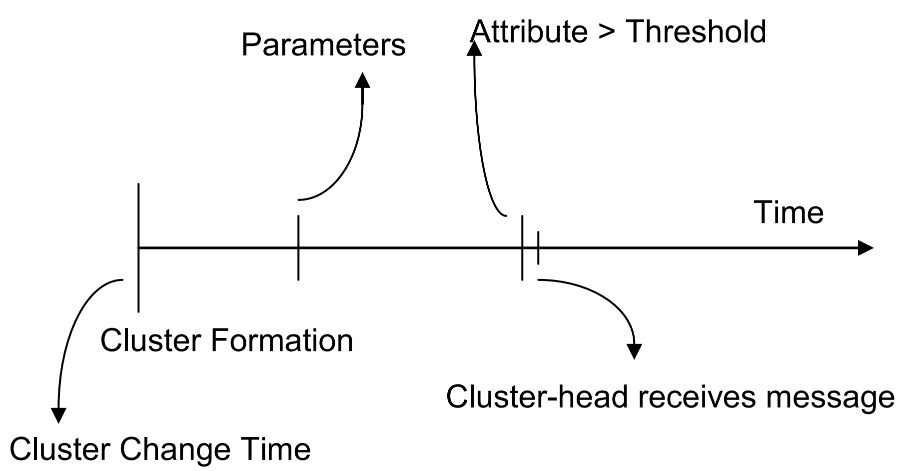


Figure 2.8 Time line for TEEN.

At each cluster change time, cluster formation occurs and after that parameters are broadcasted from cluster head to all its cluster members. Nodes on receiving the parameters start its job, which is to proctor the environment continuously.

If the sensed attribute is greater than the obtained hard threshold parameter, the node switch on its transmitter and transmits the sensed data to its cluster head for the first time. Sensed attribute is stored in an internal variable in the node, known as sensed value (SV). After that in order for a node to transmit its sensed data, the following conditions have to be met:

- ✓ Current value of the sensed attribute should be greater than the hard threshold.
- ✓ Current value of the sensed attribute should differ from SV by an amount equal to or greater than the soft threshold.

The key features of TEEN include its ability of transmitting data almost instantaneously for time critical applications. Message transmission consumes more energy than data sensing, so the energy consumption in this scheme is potentially less than the proactive networks. The user can vary the attributes as required, as it is broadcasted afresh at every cluster change time. And also, soft threshold can be changed. The main drawback of this scheme is that, the nodes will never communicate to the user, if the thresholds are not reached.

2.3.6 Geographic Adaptive Fidelity (GAF)

GAF is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to sensor networks as well. The network area is divided into fixed zones to form a virtual grid, and nodes inside each zone work together to perform different roles. For example, out of many nodes, one node will be elected to stay awake for a certain period of time, responsible for monitoring and reporting data to the BS on behalf of the nodes in the zone and after that this node will go to sleep. By turning of unnecessary nodes in the network without affecting the level of fidelity, GAF conserves energy. To associate itself with a point in the virtual grid, each node uses its GPS-indicated location. If nodes are associated with the same point on the grid then it is considered as equivalent in terms of the cost of packet routing. Such equivalence is exploited in keeping some nodes located in a particular grid area in sleeping state in order to save energy. Hence GAF prolongs the lifetime of the network as the number of nodes increases [19].

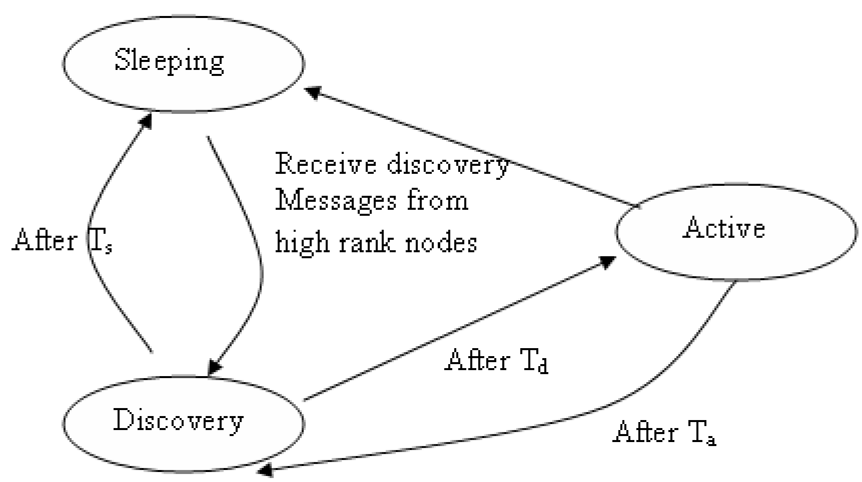


Figure 2.9 State transitions in GAF.

There are three transition states defined in GAF as shown in figure 9, which is redrawn from [19]. These states are *discovery*, for determining the neighbors in the grid, *active* reflecting participation in routing and *sleep* when the radio is turned on. Each node in the grid estimates the leaving time of grid and sends this to its neighbors to handle the mobility. In order to keep the routing fidelity, sleeping neighbors adjust their sleeping time accordingly. One of the sleeping nodes becomes active much before the leaving time of the active node expires. GAF is implemented both for non-mobility (GAF-basic) and mobility (GAF-mobility adaptation) of nodes. GAF always keeps a representative node in active mode for each region on its virtual grid to ensure network connectivity. Simulation results show that GAF performs at least as well as a normal ad hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy [19].

2.3.7 Geographic and Energy Aware Routing (GEAR)

The GEAR protocol uses energy aware and geographically-informed neighbor selection heuristics to route a packet towards the targeted region. The key idea in this scheme is to consider only a certain region to transmit the interests rather than sending the interests to the whole network as in directed diffusion. GEAR can conserve more energy than directed diffusion with this idea [20].

In this scheme, each node keeps an estimated cost and a learning cost of reaching the destination through its neighbors. The combination of residual energy and distance to destination is the estimated cost. The learned cost is a refinement of the estimated cost that accounts for routing around holes in the network. If a node does not have any nearby neighbor to the targeted region than itself, a hole appears. When there are no holes, the estimated cost is equal to the learned cost. The learned cost is propagated one hop back every time a packet reaches the destination so that route setup for next packet will be adjusted. There are two phases in the algorithm [20]:

- ✓ Forwarding packets towards the target region: A node checks its neighbors on receiving a packet to see if there is a neighbor that is closer to the targeted region than itself. The nearest neighbor to the targeted region is selected as the next hop, if there is more than one neighbor. If they are all further than the node itself, then there is a hole. In this case, one of the neighbors is picked to forward the packet based on the learning cost function. This choice can then be updated according to the convergence of the learned cost during the delivery of packets.
- ✓ Forwarding the packets within the region: If the packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or restricted flooding. Restricted flooding is better, if the sensors are not densely deployed. Recursive geographic flooding is more energy efficient than restricted flooding when the sensors are densely deployed.

CHAPTER 3

METHODOLOGY

In this section, we first summarize the maximum lifetime routing problem, which is formulated as a linear programming problem. It is followed by a discussion on the flow augmentation algorithm and proposed heuristic in this paper with examples. Then a comparison is made between smaller windows against larger windows.

3.1 MAXIMUM LIFETIME ROUTING PROBLEM

Consider a wireless sensor network with N nodes. Let K_i represent the set of immediate neighbors of node i ∈ N, e_{ij}^{t} indicates the average power consumed for data transmission from node i to node j and E_i be the initial battery level of node i. Let there be multiple commodities, where a set of source node and destination node forms a commodity. We have, for each commodity c ∈ C, a set of origin nodes $O^{(c)}$ where information is generated at node i with rate $Q_i^{(c)}$ and a set of destination nodes $D^{(c)}$ among which any node can be reached in order for the information transfer of commodity c to be considered done. Let $S_{ij}^{(c)}$ be the traffic generated at node i and destined for node j and Y_{ij} be the amount of data that needs to be transmitted from node i to node j.

The main objective is to maximize the system lifetime which is by definition the time of the first node death and is equivalent to maximizing the total amount of information transmission under a fixed information generation rates. The above problem can be shown as a linear programming problem. Given the amount of information generated $S_{ij}^{(c)}$ at each origin nodes $O^{(c)}$ for each commodity c, the problem of maximizing the system lifetime is analogous to linear programming problem which is as shown below:

Maximize : $\sum_{ij} S_{ij}$

s.t. ∀i ∈ N, ∀j ∈ k_i, ∀c ∈ C,

$$e_{ij}^{t} * Y_{ij} \leq E_i \quad (3.1)$$

$$\sum_j Y_{ji} = S_{ij} + \sum_j Y_{ij} \quad (3.2)$$

From equation (3.2), we can see that the total amount of data that node i sends is the amount of data that this node generates plus the amount of data it has received from its predecessor nodes.

3.2 FLOW AUGMENTATION ALGORITHM

The authors in [21] proposed a heuristic called the flow augmentation algorithm for fixed information generation rates and arbitrary information generation rates, which aims at maximizing the system lifetime of a wireless sensor networks. In this paper, we concentrate only on fixed information generation rates and the description of the algorithm is as given below.

Algorithm FA(x_1 , x_2, x_3)

At each iteration,

1. Calculate the shortest cost path for each commodity c with cost of link (i, j) given by

$$cost_{ij} = (e_{ij}^{t})^{x_1}\ R_i^{-x_2}\ E_i^{x_3} + (e_{ij}^{r})^{x_1}\ R_j^{-x_2}\ E_j^{x_3} \qquad (3.3)$$

If there is enough residual energy for a packet, i.e., if E_i- e_{ij}^{t}>0. The path cost is given by the sum of the link costs.

2. If any of the commodities cannot find a path to its destination then stop. Otherwise continue.
3. Augment $\lambda Q_i^{(c)}$ on each shortest cost path of its commodity and update the residual energy accordingly.
4. Goto 1.

In the above description, λ is the augmentation step size which is equivalent to the amount of information routed between routing information updates and the cost function for each link described above in the algorithm will be defined in the following section.

3.3 COST FUNCTION

The main objective is to ensure that node and network life is prolonged by properly managing the power conservation of a node and sharing the cost of routing packets carefully [23].

The process of choosing a path demands the knowledge about flow requirements, characteristics, availability of resources in networks and evaluating the quantity of resources that needs to be assigned to encourage the new flow [24].

To achieve our objective of “maximum lifetime”, we should give importance to all the nodes and ensure that no node must be penalized more than any of the others, which is equivalent to the nodes with depleted energy resources do not lie on many paths [23].

To implement this, several power-aware metrics that does result in energy-efficient routes has been presented in [23] separately. The authors [21] combined all these metrics into one and proposed a new link metric, which will lead to the maximization of the system lifetime. The link cost function $cost_{ij}$for a link (i, j) is proposed to be

$$cost_{ij} = (e_{ij}^{t})^{x_1}\ R_i^{-x_2}\ E_i^{x_3} + (e_{ij}^{r})^{x_1}\ R_j^{-x_2}\ E_j^{x_3} \tag{3.4}$$

The metrics represents e_{ij}^{t}, the energy expenditure for unit data transmission over the link (i , j), the initial battery level E_i and E_j and residual energy R_i and R_j. The parameters x_1, x_2 and x_3 are nonnegative weighting factors for each quantity and the value of x_1 is either zero or one. The significance of the parameters is abbreviated in Table 3.1 for reference.

Table 3.1 Meanings of the parameters in the Algorithm FA [21]

$FA(x_1, x_2, x_3)$	Meaning
$FA(0,0,0)$	Minimum hop (MH) routing
$FA(1,0,0)$	Minimum total energy (MTE) routing
$FA(\cdot, x, x)$	Normalized residual energy is used
$FA(\cdot, \cdot, 0)$	Absolute residual energy is used

The above link cost, $cost_{ij}$ has been put up taking into consideration that flow augmenting path should consider minimum total consumed energy path when the network is new, should use up less resource and should stay away from nodes with small residual energy [21].

Each link cost add up to form a path cost and out of many available paths from source node to destination node of a commodity c ∈ C, the shortest cost path is computed by the execution of shortest path algorithm. Distributed Bellman-Ford algorithm is used in Flow augmentation algorithm and Dijkstra's shortest path algorithm is used in this proposed algorithm.

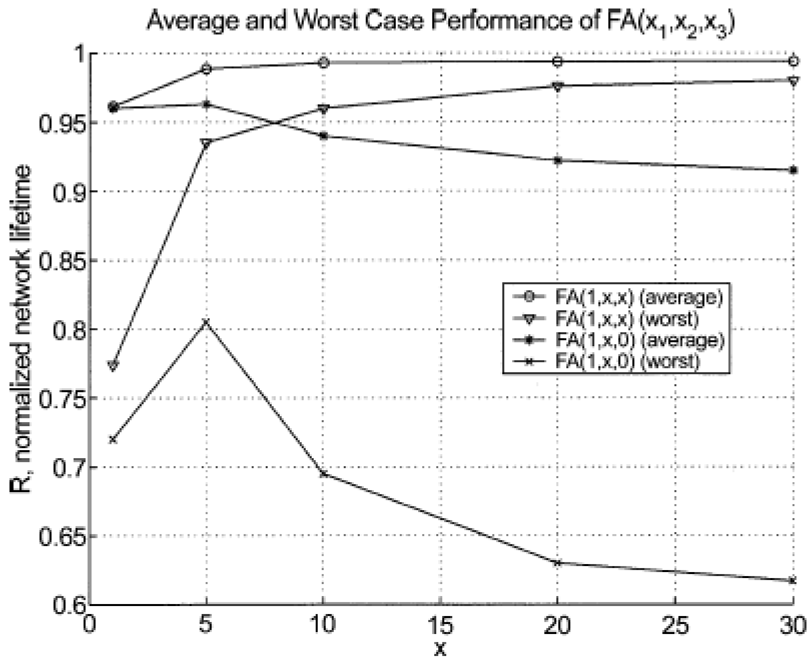


Figure 3.1 Performance comparision of FA(1, x, x) with FA(1, x, 0) [21].

In [21], the authors performed simulations of FA algorithm with one hundred randomly generated networks to encounter the best parameters of x_1, x_2 and x_3 . Then a comparison is made between FA(1, x, x) and FA(1, x, 0) to figure out whether Normalized residual energy or the absolute residual energy to be used. From the Figure 3.1, one can observe that FA(1, x , x) obtains better result than FA(1, x, 0) for both average and worst case performance. Therefore, only Normalized residual energy is used in Flow augmentation algorithm and as well as in our algorithm for comparison.

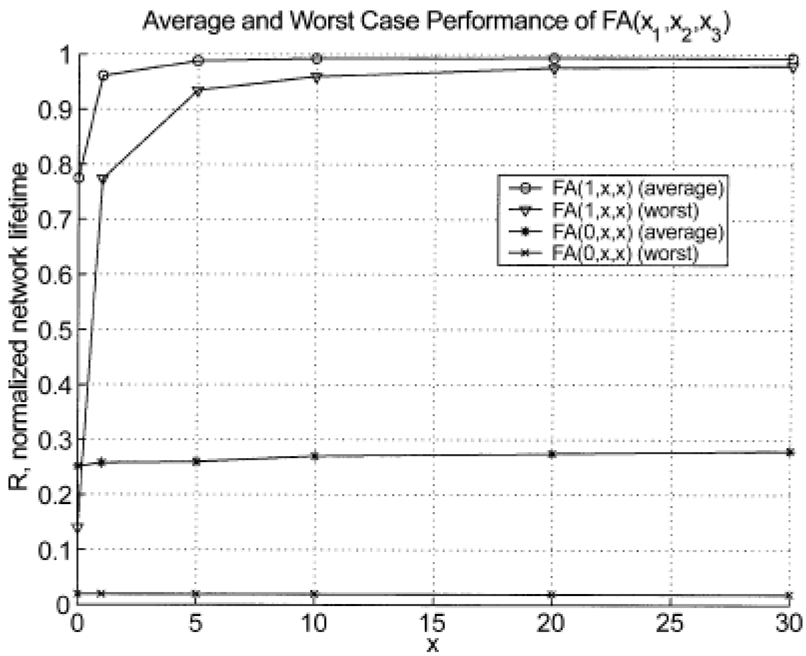


Figure 3.2 Performance comparison of FA (1, x , x) with FA(0, x , x) [21].

After determining the importance of normal residual energy, the authors [21] investigated whether communication energy consumption should be added in the link cost or not. So a distinction is made between FA (1, x, x) and FA (0, x, x) and the obtained result is a shown in Figure 3.2. From the figure it is very clear that whether the communication energy consumption is included or not, it doesn't have much impact on the network lifetime. Hence only FA (1, x, x) term is used in the rest of the paper.

3.4 PROPOSED ALGORITHM

In this paper, we aim at designing a heuristic that achieves the goal of maximizing network lifetime. We then provide examples to demonstrate how our algorithm contribute better outcome compared to flow augmentation algorithm.

The algorithm is depicted for fixed information–generation rates.

We have come up with a heuristic, which targets to improve a heuristic scheme proposed in [21]. Similarly to flow augmentation algorithm, at each iteration our algorithm determine the shortest cost path from a source node o ∈ $O^{(c)}$ to its corresponding destination node $D^{(c)}$ for a commodity c ∈ C. The cost function is same as that of the flow augmentation algorithm, but reception metric is not included here since it is very negligible. Then information is relayed on the calculated shortest cost path between source node o and destination node $D^{(c)}$ by a magnitude of $\lambda Q^{(c)}$, where λ is augmentation step size which is equivalent to the amount of information routed between routing information updates [21].

Routing information update is carried out after the residual energy is updated at each node, which will vary the link costs. The defined method is repeated until the time network partition occurs because of node failure. However in our algorithm, the nodes are not mobile and the topology of the network is static.

Hence obtained result is applicable for static networks. The energy consumption at unintended receiver nodes and at the receivers during reception is not included in the algorithm. Also energy consumption due to routing control packets is not included in the model assuming that energy consumption is dominated by the data packets.

Algorithm

1) For a commodity c ∈ C, calculate the shortest cost path with link cost (i, j) given by

$$cost_{ij} = (e_{ij}^{t})^{x_1}\ R_i^{-x_2}\ E_i^{x_3} \tag{3.5}$$

If and only if E_i- e_{ij}^{t}>0. Summation of the each link cost will obtain the path cost.

2) If a commodity c ∈ C cannot find a path to its destination then stop. Else continue.

3) Augment $\lambda Q^{(c)}$ on the calculated shortest cost path of a commodity and update the residual energy accordingly.

4) Goto 1.

3.5 COMPARISON OF FA ALGORITHM AND PROPOSED ALGORITHM

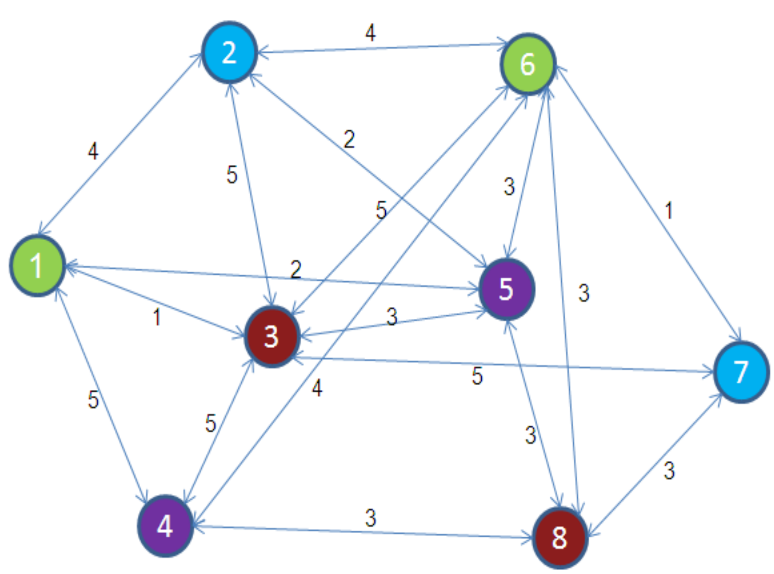


Figure 3.3 Example to compare FA algorithm and proposed algorithm

Consider a wireless sensor network of N = 8 nodes distributed randomly as shown in the Figure 3.3. Let each node i have an initial battery level of E_i = 12 J. The origin nodes O = {1, 2, 3, 4} and its corresponding destination nodes D = {6, 7, 8, 5} form a multi-commodity case with each commodity c ∈ C where C = {1, 2, 3, 4}. The information-generation rate at each origin node is Q_o = 1 and augmentation step size λ is of unit measurement. The energy required to cross each link is as depicted in the Figure 3.3. The total amount of information generated at each origin node is as given below.

Table 3.2 Information generated for every origin node.

Origin node	Information generated
1	12
2	6
3	12
4	3

Let us simulate this problem with FA algorithm followed by our heuristic.

3.5.1 FA Algorithm

Let us simulate the problem according to the algorithm described. Table 3.3 has been set up as a reference for residual energy update, which would be updated at the end of the each iteration.

Table 3.3 Reference table for residual energy update

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	12	12	12	12	12	12	12	12

3.5.1.1 First Iteration:

Step 1: The shortest cost path of each commodity is calculated.

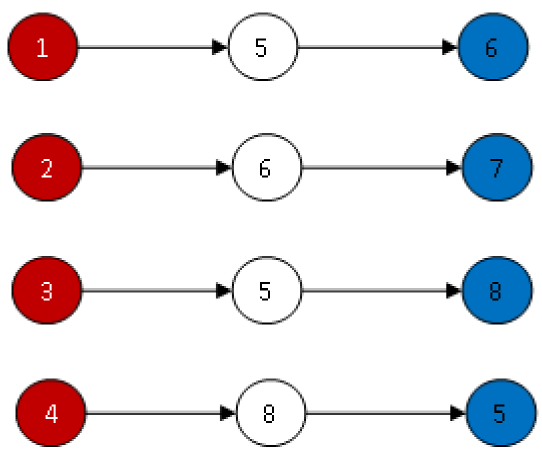


Figure 3.4 Calculated commodity paths

Step 2: Here, all the commodities has found a path to its destination. Hence continue.

Step 3: Now $\lambda Q^{(c)}$ is augmented on each calculated shortest cost path i.e. information is transmitted from source node to its corresponding destination node via the calculated shortest cost path. Now update the residual energy accordingly.

Table 3.4 Residual energy update after first iteration

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	10	8	9	9	6	11	12	9

Step 4: Continue to step 1.

3.5.1.2 Second Iteration

Step 1: Again the shortest cost path of each commodity is calculated:

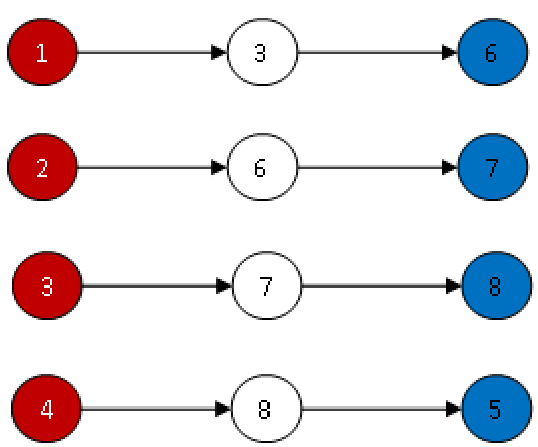


Figure 3.5 Calculated commodity paths

Step 2: There is a path for all the commodities to its corresponding destination. Hence continue.

Step 3: Augmenting $\lambda Q^{(c)}$ on the calculated paths and Update the residual energy accordingly.

Table 3.5 Residual energy update after second iteration.

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	9	4	X	6	6	10	9	6

While augmenting $\lambda Q^{(c)}$ on each shortest cost path, source node 1 transmits the assigned packet to its destination node (node 6) successfully. Similarly, node 2 delivers its packet to node 7 with ease. A *real problem* occurred on transmitting data from node 3 to node 8 as it could not make through in transmitting data as calculated in step 1.The packet got dropped due to inadequate energy at node 3.

Then how did step 2 pass over declaring all commodities has found a path? After first iteration, node 3 had a residual energy of 9 J. Node 1 selected node 3 as via node to node 6. It requires 5 J of energy for node 3 to relay the received packet from node 1 to node 6 as depicted in Figure 3.3, which made the residual energy of node 3 to 4 J although the residual energy update happens only after all the commodities complete their data transmission. Since node 3 unaware of being via node to some other node, would have calculated a shortest cost path in step 1 for its own data. When node 3 turn appear and tries to send the data which it has, it eventually leads to dropping up of packet due to the deficient of energy. According to step 2 of algorithm, if any of the commodities cannot find a path to its destination then the process is halted. Even though the prior commodities can conveniently transmit the data, it is considered as undone and will be dropped.

The algorithm takes into account only when all the commodities of the network effectively transmit the data packet to its respective destinations. Therefore total number of packets transmitted is only from the first iteration and which is equal to 4 packets.

Total Packets Transmitted = 4

3.6 PROPOSED ALGORITHM

3.6.1 First Iteration

Step 1: Shortest cost path of commodity c is calculated.

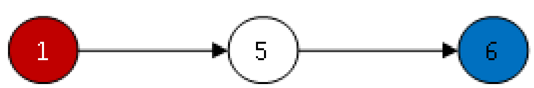


Figure 3.6 Calculated commodity paths - 1

Step 2: Commodity has found a path.Hence continue.

Step 3: Augmenting $\lambda Q^{(c)}$on the calculated shortest path and update the residual energy.

Table 3.6 Residual energy update after first iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	10	12	12	12	9	12	12	12

Step 4: Continue to Step 1.

3.6.2 Second Iteration

Step 1: Calculate the shortest cost path for the next commodity i.e. commodity 2.

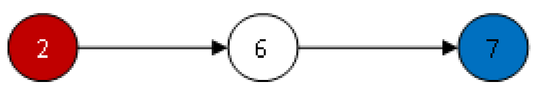


Figure 3.7 Calculated commodity paths - 2

Step 2: Path found.

Step 3: Data transmission and residual energy update.

Table 3.7 Residual energy update after second iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8

Energy	10	8	12	12	9	11	12	12

Step 4: Continue to Step 1.

3.6.3 Third Iteration

Step 1: Calculate the shortest cost path for commodity 3:

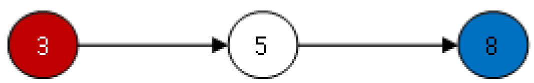


Figure 3.8 Calculated commodity paths - 3

Step 2: Path found.

Step 3: Data augmentation and residual energy update.

Table 3.8 Residual energy update after third iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	10	8	9	12	6	11	12	12

Step 4: Continue to Step 1.

3.6.4 Fourth Iteration

Step 1: Calculate the shortest cost path for commodity 4.

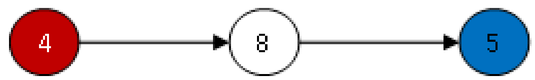


Figure 3.9 Calculated commodity paths - 4

Step 2: Path found.

Step 3: Data augmentation and residual energy update.

Table 3.9 Residual energy update after fourth iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	10	8	9	9	6	11	12	9

Step 4: Continue to step 1.

3.6.5 Fifth Iteration

Step 1: Calculate the shortest cost path for commodity 1 again.

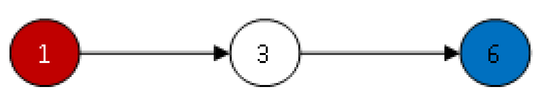


Figure 3.10 Calculated commodity paths - 5

Step 2: Path found.

Step 3: Data augmentation and residual energy update.

Table 3.10 Residual energy update after fifth iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	9	8	4	9	6	11	12	9

Step 4: Continue to step 1.

3.6.6 Sixth Iteration

Step 1: Calculate the shortest cost path for commodity 2.

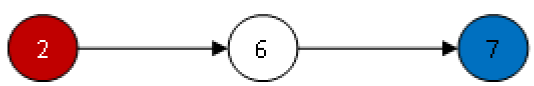


Figure 3.11 Calculated commodity paths - 6

Step 2: Path found. Continue to Step 3.

Step 3: Data augmentation and residual energy update.

Table 3.11 Residual energy update after sixth iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8

Energy	9	4	4	9	6	10	12	9

Step 4: Continue to step 1.

3.6.7 Seventh Iteration

Step 1: Calculate the shortest cost path for commodity 3.

Figure 3.12 Calculated commodity paths - 7

Step 2: Path found . Continue to step 3.

Step 3: Data augmentation and residual energy update.

Table 3.12 Residual energy update after seventh iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
Energy	7	4	3	9	6	10	12	9

Step 4: Continue to step 1.

3.6.8 Eighth Iteration

Step 1: Calculate the shortest cost path for commodity 4.

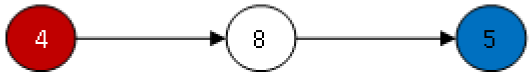


Figure 3.13 Calculated commodity paths - 8

Step 2: Path found. Hence continue to step 3.

Step 3: Data augmentation and residual energy update.

Table 3.13 Residual energy update after eighth iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	7	4	3	6	3	10	12	6

Step 4: Continue to step 1.

3.6.9 Ninth Iteration

Step 1: Calculate the shortest cost path for commodity 1.

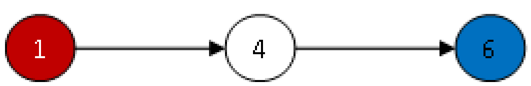


Figure 3.14 Calculated commodity paths -9

Step 2: Path found. Hence continue to step 3.

Step 3: Data augmentation and residual energy update.

Table 3.14 Residual energy update after ninth iteration (Our Algorithm).

Initial Energy	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
	12	12	12	12	12	12	12	12
Residual Energy	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
	2	4	3	2	3	10	12	6

Step 4: Continue to step 1.

3.6.10 Tenth Iteration

Step 1: Calculate the shortest cost path for commodity 2.

Path could not be found for commodity 2 due to the inadequate energy.

Figure 3.15 Calculated commodity paths - 10

Step 2: Path not found. Hence stop.

Therefore total number of packets transmitted is all the packets delivered from first iteration through ninth iteration, which is equal to 9 packets.

Total Packets Transmitted = 9

3.7 KEY FEATURE

A difference of 5 packets is a big accomplishment for this small network. If we look at the residual energy table at the end of the simulation, it is very clear that nodes are more widely spread in our algorithm compared to the flow augmentation algorithm, excelling in prolonging the system lifetime.

The serious drawback of FA algorithm is updating the residual energy, which takes place after all the commodities complete their productive data transmission i.e. at the end of the iteration. By doing this, it encourages nodes to assume energy falsely and try to communicate with other nodes, which ultimately accompany in depletion of data.

Unlike in FA algorithm, our algorithm routes the packets through paths that may be longer but that pass through nodes that have excess of energy resource, leading to maximize the node lifetime. Importantly there is a zero probability of node being placed in false assumption of energy thus avoiding the packet drop.

3.8 COMPETENCE OF SMALLER WINDOW AGAINST LARGE WINDOW

Here the lifetime achieved for large window is compared with lifetime of the small window, where a *large window* is defined as the amount of information generated for a time period of T_L seconds and *small window* is defined as the amount of information generated at each sub-divided intervals of T_L seconds. Figure 3.16(a) and (b) shows the pictorial representation of large window and small window respectively.

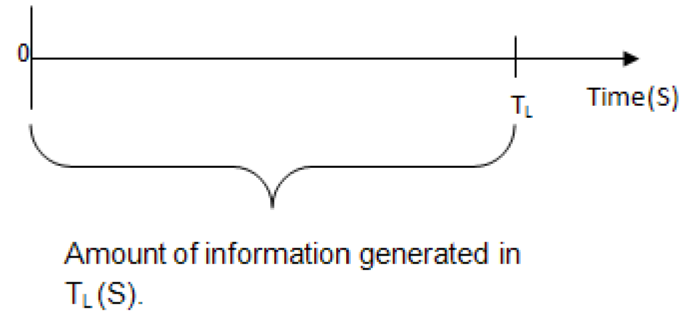


Figure 3.16(a) Large window time period

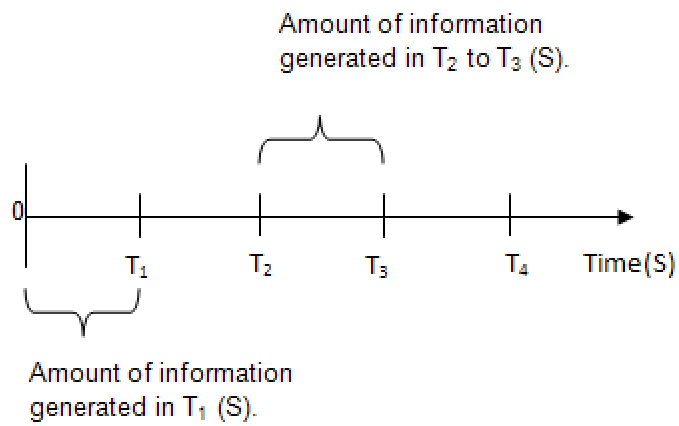


Figure 3.16(b) Small window time periods.

From Figure 3.16(a) and 3.16(b),

$$T_L = T_1 + T_2 + T_3 + T_4 \tag{3.6}$$

In general,

$$T_L = \sum_{k=1}^{n} T_k \tag{3.7}$$

Let us consider an example and try to prove improvement achieved by small window compared to large window.

3.9 COMPARISON OF LARGE AND SMALL WINDOW

Consider a wireless sensor network of N = 6 nodes. Let each node i have an initial energy of E_i = 8 J. The origin nodes O = {1, 2} and its corresponding destination nodes D = {6} form a multi-commodity case with each commodity c ∈ C where C = {1, 2}. The augmentation step size λ is of unit measurement. The energy required to cross each link is as depicted in the Figure 3.17. Let us simulate this problem with the proposed algorithm for both large window and small window.

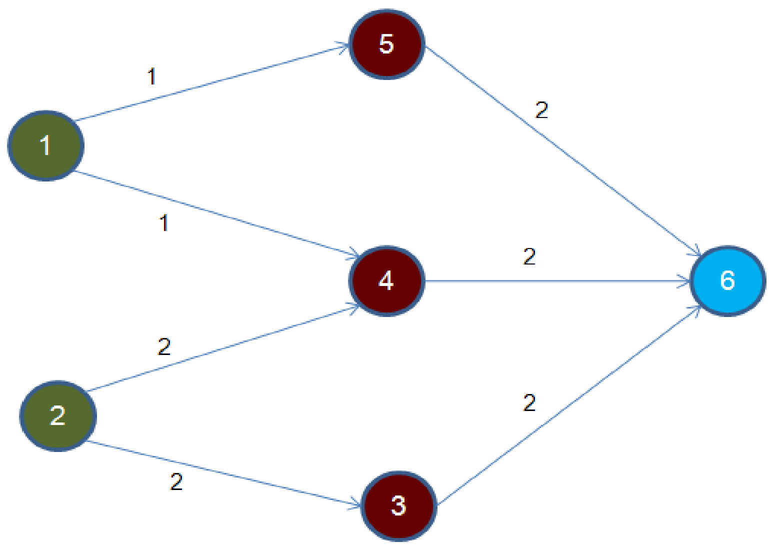


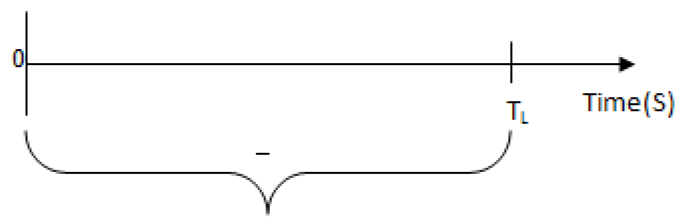
Figure 3.17 Example to compare the large window with small window using the proposed algorithm

3.9.1 Large Window

Let's say, the information generated at each origin nodes O = {1, 2} is 8 & 4 respectively for a period of T_L seconds. The initial and residual energy of all the nodes before the simulation is given below.

Table 3.15 Reference table before simulation (Large window).

Initial Energy	E_1	E_2	E_3	E_4	E_5
	8	8	8	8	8
Residual Energy	R_1	R_2	R_3	R_4	R_5
	8	8	8	8	8



Origin node	Information generated
1	8
2	4

Figure 3.18 Timing diagram of Large window with information generated.

When the above information run through the proposed algorithm , the following output were obtained and which is as shown in the Figure 3.19.

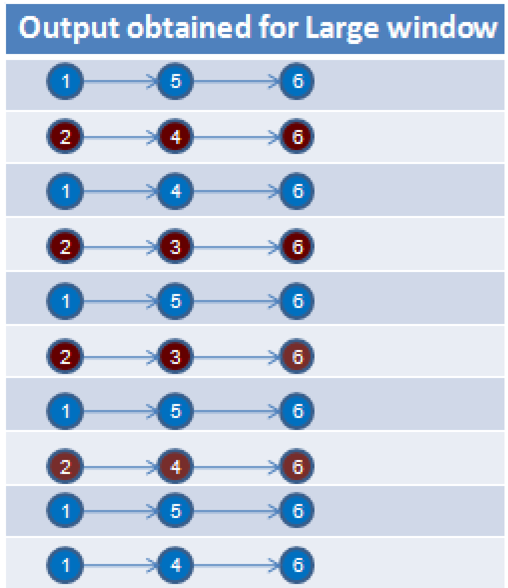


Figure 3.19 Output obtained for Large Window

Table 3.16 Reference table after simulation(Large window).

Initial Energy	E_1	E_2	E_3	E_4	E_5
	8	8	8	8	8
Residual Energy	R_1	R_2	R_3	R_4	R_5
	2	0	4	0	0

Total packet's transmitted = 10

3.9.2 Small Window

Let's say, T_L is sub-divided into four equal intervals. The information generated at each sub-divided period is as given below:

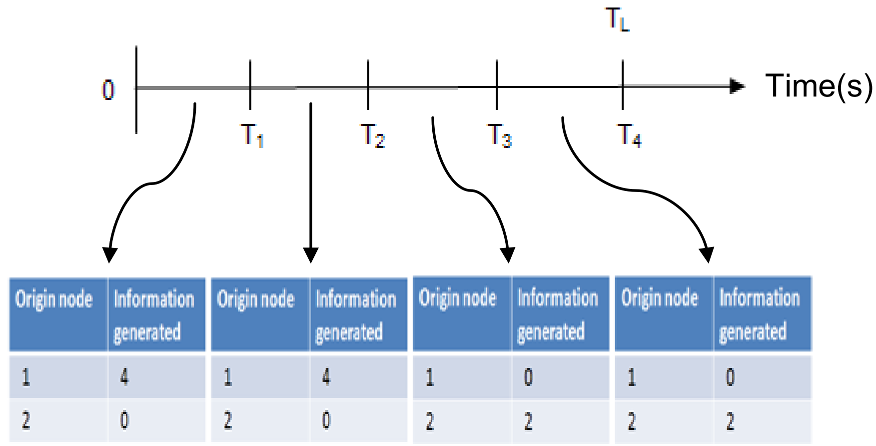


Figure 3.20 Timing diagram of Small window with information generated.

The initial and residual energy of all the nodes before the simulation is given below.

Table 3.17 Reference table before simulation(Small window).

Initial Energy	E_1	E_2	E_3	E_4	E_5
	8	8	8	8	8
Residual Energy	R_1	R_2	R_3	R_4	R_5
	2	0	4	0	0

When the above input is given to the proposed algorithm, it gives the following output.

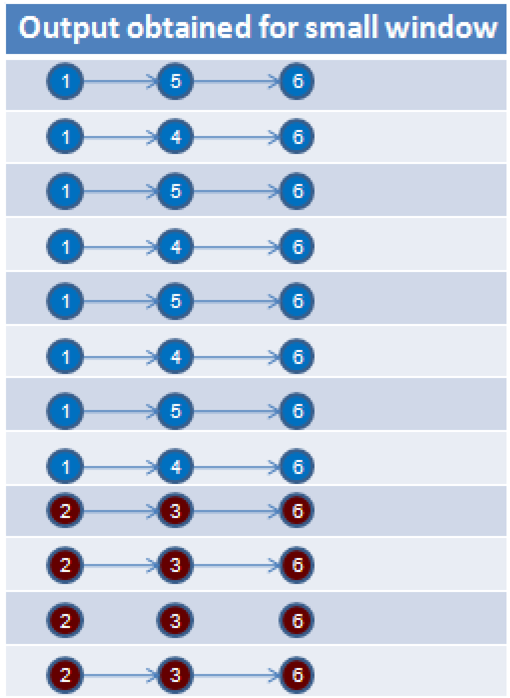


Figure 3.21 Output obtained for small Window

Table 3.18 Reference table after simulation(Small window) .

Initial Energy	E_1	E_2	E_3	E_4	E_5
	8	8	8	8	8
Residual Energy	R_1	R_2	R_3	R_4	R_5
	0	0	0	0	0

Total packet's transmitted = 12

A gain of two packets achieved through this smaller window.

Key feature: In the above example, the information generated at each origin nodes (node 1 and 2) is 8 & 4 respectively(T_L seconds). From the obtained result, it demonstrates that there is a scarce for two packets of source 1 with large window as compared to the small window. The reason behind this is, source 2 utilizing the allocated resource of source 1 to transmit two of its data packet to its destination node (node 6). In doing this, source 2 made source 1 deficient of two packets.

In small window, the time period is sub-divided into 4 equal intervals

$$T_L = T_1 + T_2 + T_3 + T_4 \tag{3.8}$$

It is not the case in large window, where information generated is encountered at one shot which is after T_L seconds. At $T_{1,}$ the information generated at each origin nodes (node 1 and node 2) is 4 and 0 respectively. Now source 1 transmits the received packets to its destination node (node 6). At $T_{2,}$ the information generated is again 4 and 0 at respected nodes (node 1 and node 2). Source 1 relays the received packet to its corresponding destination. Hence, till T_2 there is no botheration from source 2 on allocated resource of source 1, which made source 1 in successful transmission . At T_3, the information generated at origin nodes (node 1 and node 2) are 0 and 2 respectively. And also at T_4, same amount of information is generated. Now source 2 transmits all of its received packets efficiently to its destination node (node 6) out of its solely allocated resource, leading to achieve the optimal solution of 12 packets.

CHAPTER 4

RESULTS AND CONCLUSION

In this section, we evaluate the performance of our heuristic and compare it to that proposed in [21]. In section 3.5, we saw how it is possible to maximize the system lifetime. In this section, we provide graphical results to support the conclusion made in section 3.5.

4.1 RESULTS TO SHOW INCREASE IN LIFETIME:

We use a static network of sensors for simulation purposes. The adjustable parameters are:

- N the number of sensor nodes. We vary this from 5 to 300.
- B the battery level of sensor nodes.
- By varying the number of commodities with fixed number of nodes and fixed battery level.
- By varying the load for fixed number of nodes N, fixed battery level and fixed commodity c.

In order to compare our results with [21], we use the constant information generation rates model defined by them. Let S_X denote the ratio between the system lifetime obtained by algorithm X and the optimal solution and be called the normalized network lifetime.

We will also evaluate the percentage gain P_{gain} of proposed algorithm to that of flow augmentation algorithm with following formulation.

$$P_{gain} = \frac{(Difference\ in\ amount\ of\ data\ sent\ by\ proposed\ algorithm\ over\ FA\ algorithm) * 100}{Data\ transmitted\ from\ FA\ Algorithm}$$

We have implemented our algorithm in C++ and run experiments on randomly generated graphs. For performance comparison, the optimal solution is obtained from the lp solver after solving the linear programming problem. Note that λ is of unit measurement.

4.2 RESULTS FOR VARYING NUMBER OF NODES

The comparison in terms of normalized lifetime is made in Table 4.2 and depicted in Figure 4.2. In table 4.2, the terms S_{PA} denotes the normalized lifetime of proposed algorithm, S_{FA} denotes normalized lifetime of flow augmentation algorithm and P_{gain} is the percentage gain of proposed algorithm over FA algorithm.

Table 4.2 Performance comparison of proposed algorithm and FA algorithm

No of Nodes N	No of commodities c	S_{PA}	S_{FA}	P_{gain}(%)
5	5	0.72	0.5	45.00
10	10	0.38	0.21	52.50
25	25	0.32	0.24	59.61
50	50	0.49	0.35	25.20
75	50	0.66	0.52	16.88
100	80	0.52	0.41	27.81
150	125	0.58	0.47	30.69
200	175	0.59	0.32	80.58
250	225	0.60	0.24	136.41

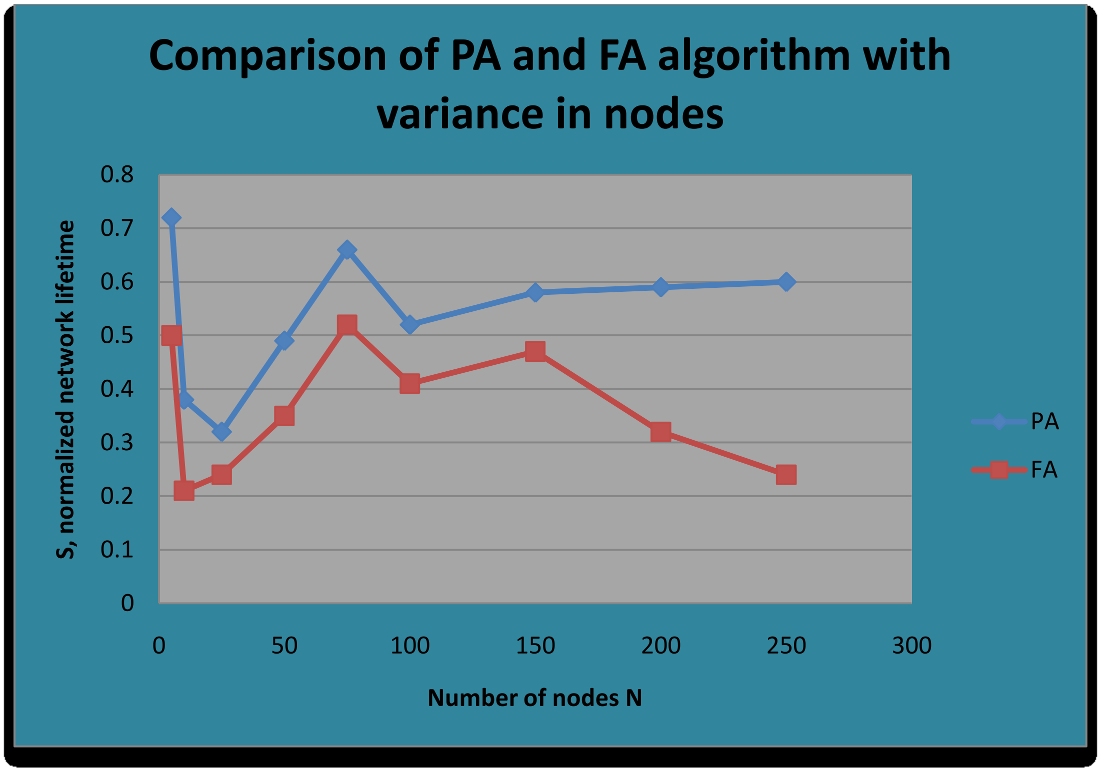


Figure 4.2 Comparison of proposed algorithm and FA algorithm

Figure 4.2 illustrates the case, where the initial battery level of each sensor node is of 25 units and the variation in the network lifetime is measured with an increase in the number of sensors. From the graph, we can observe that the performance of proposed algorithm is better than the FA algorithm and as the number of sensors increased, the network lifetime of proposed algorithm started to excel in comparison to it.

4.3 RESULTS FOR CHANGING BATTERY LEVEL:

Table 4.3 Performance comparison of proposed and FA algorithm with change in the battery level.

No of Nodes N	No of commodities c	S_{PA-15}	S_{FA-15}	$P_{gain}(\%)$
25	25	0.26	0.00	185.71*
50	50	0.29	0.12	132.00
75	50	0.34	0.21	65.00
100	80	0.27	0.17	54.375
150	125	0.33	0.14	131.19
200	175	0.35	0.14	143.03
250	225	0.34	0.11	201.19
300	275	0.33	0.09	259.46

Table 4.3 and Figure 4.3 show the performance of proposed heuristic and FA algorithm with change in the initial battery levels from 25 units to 15 units of previous example. As we can see, as the node increases, there is an increasing difference in network lifetime between our algorithm and FA algorithm.

Based on the obtained results, we can conclude that the proposed heuristic is very beneficial in finding a route of sensor networks. Because, the difference in battery consumption of various nodes is reduced, which ultimately prolong the system lifetime or node failure. It is to be noted that our results will hold true in networks where nodes are static.

* In the Table 4.3 denotes a data packet that is being sent from FA algorithm is void. According to the step 2 of the FA algorithm, if any of the commodity cannot find a path to its destination then it has to be halted or it is considered undone even though few of the commodities can find a path to its destination. Here for tabulation purpose, the ignored packets are taken into consideration for comparison and the obtained result is as shown.

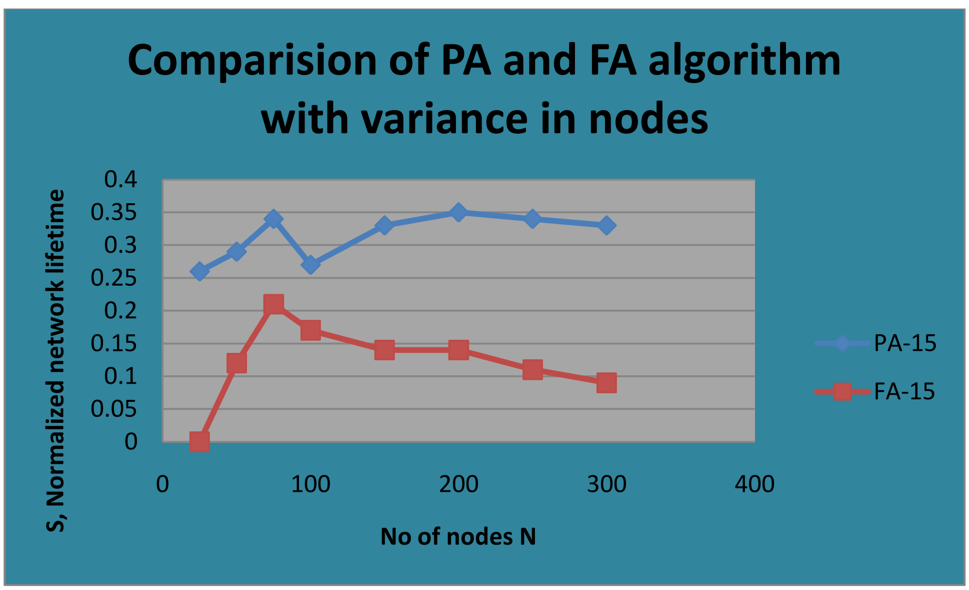


Figure 4.3 Comparison of proposed algorithm and FA algorithm after changing the initial battery level from 25 units to 15 units.

4.4 RESULTS OBTAINED FOR VARYING COMMODITIES WITH FIXED NODES AND FIXED BATTERY LEVEL:

Example 4.4.1: Let us consider a scenario of fixed node of N = 75, fixed battery level B = 20 units and variable commodities of constant load.

Table 4.4.1 Performance comparison of proposed and FA algorithm with variable commodities of constant load.

Number of commodities	S_{PA}	S_{FA}	P_{gain}(%)
2	1	1	0.00
5	0.9	0.86	4.61
10	0.72	0.68	5.00
15	0.42	0.37	13.33
20	0.42	0.38	10.00
25	0.40	0.37	8.00
35	0.41	0.39	5.71
45	0.38	0.29	30.55
55	0.34	0.21	61.21
65	0.3	0.21	38.46

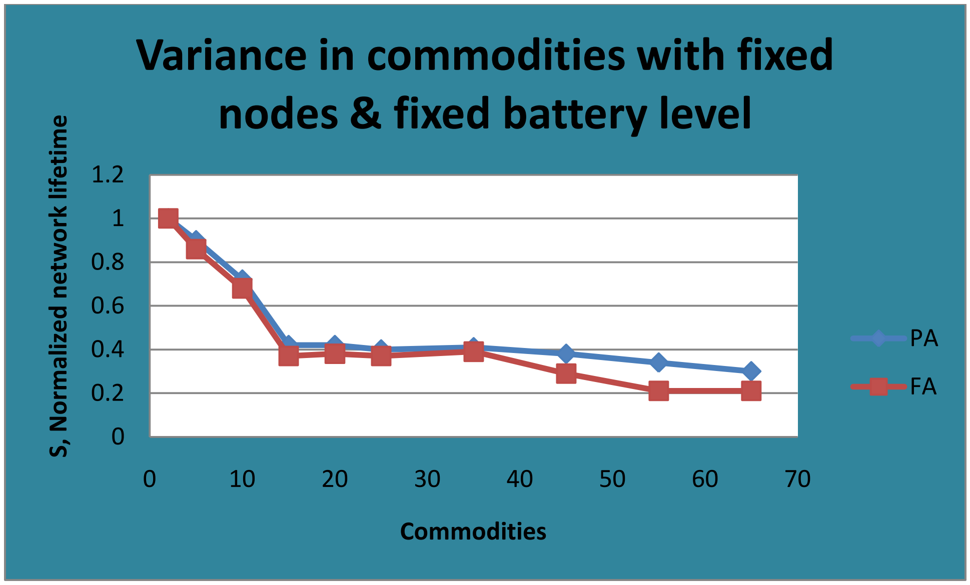


Figure 4.4.1 Comparison of proposed algorithm and FA algorithm with variable commodities of constant load.

Table 4.4.1 and Figure 4.4.1 illustrate the case, where the initial battery level of each sensor node is of 20 units, fixed nodes of N = 75 and the variation in the network lifetime is measured with an increase in the number of commodities. From the graph, we can observe that the performance of proposed algorithm started to increase slightly as the number of commodities increased.

Example 4.4.2: Let us consider a scenario of fixed node of N = 100, fixed battery level B = 100 units and variable commodities of constant load.

Table 4.4.2 Performance comparison of proposed and FA algorithm with variable commodities with constant load.

No of commodities C	P_{gain}**(%)**
25	4.00
50	2.00
75	13.52
100	28.60

Example 4.4.3: Let us consider a scenario of fixed node of N = 200, fixed battery level B = 200 units and variable commodities of constant load.

Table 4.4.3 Performance comparison of proposed and FA algorithm with variable commodities with constant load.

No of commodities C	P_{gain}**(%)**
50	6.40
75	11.71
100	3.20
150	2.28
175	13.28
200	19.19

Table 4.4.2 and Table 4.4.3 show the percentage gain $\boldsymbol{P_{gain}}$ of proposed algorithm over flow augmentation algorithm with varying commodities of constant load. Here in this table, the normalized network lifetime S_{PA} or S_{FA} is not shown, as the optimal solution could not be obtained for commodities due to the increasing number of unknown variables.

From the table, one can say that as the number of commodities starts increasing with fixed number of nodes and battery level, the performance of our algorithm outperforms FA algorithm.

4.5 RESULTS OBTAINED FOR VARYING LOADS WITH FIXED NODES, FIXED BATTERY LEVEL AND FIXED COMMODITY:

Now let us consider a scenario of fixed nodes, fixed battery level and fixed commodity. But vary the load of data that needs to be transmitted out of commodity c.

Example 4.5.1: Let us consider a fixed node of N = 75, fixed battery level B = 100 units and fixed commodity C = 35.

Table 4.5.1 Performance comparison of proposed and FA algorithm with variance in load L.

Number of Load L	S_{PA-35}	S_{FA-35}	P_{gain}(%)
5	1.0	1.0	0.00
10	0.94	0.60	57.07
15	0.63	0.4	57.07

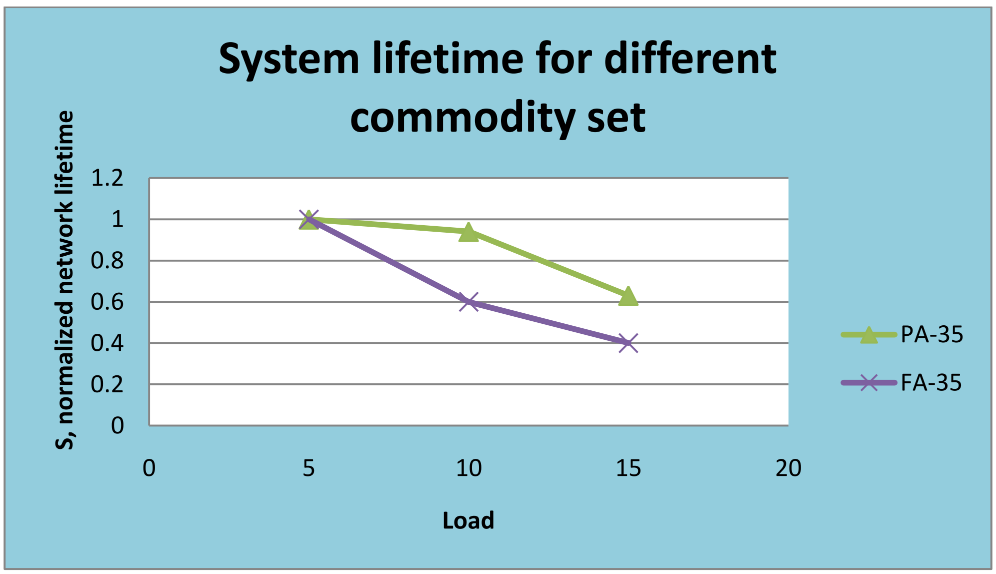


Figure 4.5.1 Comparison of proposed algorithm and FA algorithm with variance in load L.

Example 4.5.2: Let us consider a fixed node of N = 75, fixed battery level B = 100 units and fixed commodity C = 65

Table 4.5.2 Performance comparison of proposed and FA algorithm with variance in load L.

Number of Load L	S_{PA-65}	S_{FA-65}	$P_{gain}(\%)$
5	1.00	0.82	25.00
10	0.59	0.40	46.15
15	0.40	0.27	46.15

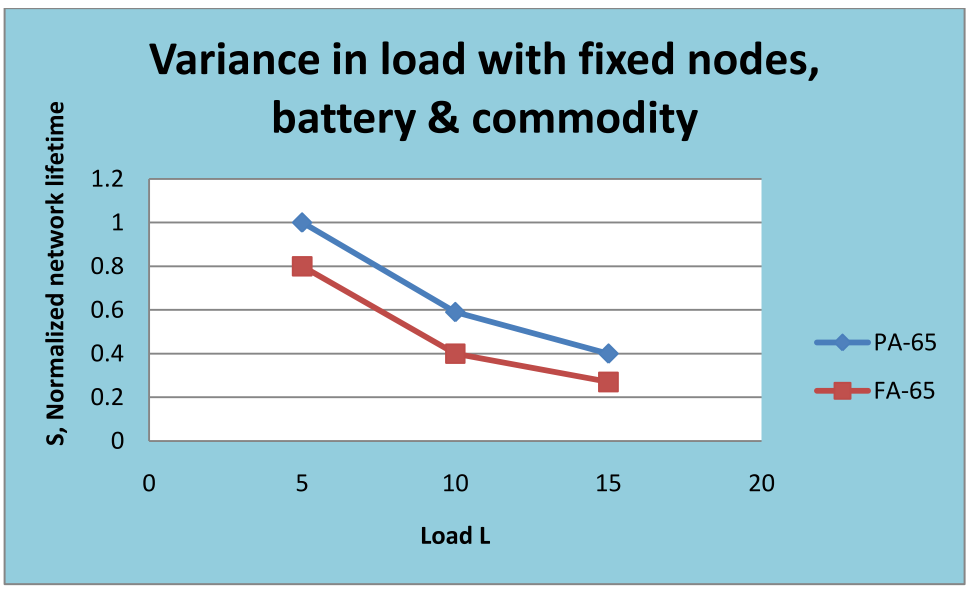


Figure 4.5.2 Comparison of proposed algorithm and FA algorithm with variance in load L.

Example 4.5.3: Let us consider a fixed node of N = 200, fixed battery level B = 200 units and fixed commodity C = 200.

Table 4.5.3 Performance comparison of proposed and FA algorithm with variance in different load.

No of Load L	P_{gain}**(%)**
9	0.00
11	10.00
13	25.15

Example 4.5.1 through 4.5.3 demonstrates variance in system lifetime as the number of load increased of a fixed commodity and fixed battery level. Again the proposed algorithm clearly outperforms FA algorithm.

4.6 Conclusion:

In sensor networks, the most notable problem is limited battery energy. If any one of the node dies due to battery outage, the whole system dies. Therefore, efficiently utilizing the available resource is one of the primary concerns in sensor networks.

By this notion, we proposed a new algorithm in comparison to existing flow augmentation algorithm for fixed information generation rates. The idea behind this protocol is very simple – updating of residual energy immediately after each commodity transmits its data and carefully routing the packets through nodes that have excess of energy resource, excelling in maximizing the system lifetime.

More importantly there is no conflict between commodities as in FA algorithm, sharing a common resource for different data packets leading to data collapse. The simulation results showed that the proposed heuristic performance is always better than the flow augmentation algorithm. This is a significant theoretical improvement over the previously proposed FA heuristics. Also analyzed the significance of smaller information generation window against larger information generation window and showed the importance of smaller window.

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Maximizing the System Lifetime in Wireless Sensor Networks using Improved Routing Algorithm

Major Professor: Dimitrios Kagaris