STATIC RANGE ASSIGNMENT IN WIRELESS SENSOR NETWORKS

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ABSTRACT

STATIC RANGE ASSIGNMENT IN WIRELESS SENSOR NETWORKS

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Energy is a limited source in wireless sensor networks and in most applications, it is non-renewable; so designing energy-efficient communication patterns is very important. In this thesis, we define the static range assignment (SRA) problem for wireless sensor networks, which focuses on providing the required connectivity in the network with minimum energy consumption. We propose minimum spanning tree based (MST), pruned minimum spanning tree based (MSTP) and shortest path incremental (SPI) algorithms as efficient heuristics for the SRA problem. As a data dissemination service, multicasting is frequently used for communication in the wireless sensor networks. In a WSN, several multicast requests occur simultaneously. In order to support multiple multicast requests, sensor nodes should have enough power levels for packet transmission between the nodes. In our study we present minimum energy multiple source multicast (MEMSM) problem. MEMSM problem is a special case of the SRA problem and we propose the M-MIPF algorithm as a solution to the MEMSM problem, which is a modified version of the well-known MIPF algorithm in order to support multiple multicast problem. Solutions to MEMSM problem try to make a range assignment that enables all the multicasts in the system and has a minimum energy cost. We compare the algorithms MST, MSTP, SPI and M-MIPF according to their energy consumptions. Our experimental results show that MSTP and SPI algorithms are stable and energy-efficient so-

lutions to the MEMSM problem.

Keywords: Wireless Sensor Networks, Multicasting, Range Assignment, Shortest Path, Spanning Tree

ÖZ

KABLOSUZ ALGILAYICI AĞLARDA SABİT MENZİL AYARLAMA

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Kablosuz algılayıcı ağlarda enerji kısıtlı miktarda bulunmaktadır ve birçok uygulamada enerji kaynakları yenilenebilir değildir. Bu sebepten ötürü enerjiyi az kullanan haberleşme modelleri geliştirmek çok önemlidir. Bu tezde, sabit menzil ayarlama (SRA) problemi tanımlanmaktadır. SRA problemi en az enerji kullanarak gerekli haberleşmeyi sağlama üzerine odaklanmaktadır. SRA probleminin çözümü için en küçük kapsayan ağaç temelli (MST), küçültülmüş kapsayan ağaç temelli (MSTP) ve en kısa yol artış temelli (SPI) algoritmalarını sunmaktayız. Bilgi paketlerinin dağıtımı amacıyla çoklu yayım yöntemi ağda haberleşmeyi sağlamak için sıklıkla kullanılmaktadır. Bundan dolayı bir kablosuz ağda birçok çoklu yayım gerçekleşmektedir. Birden fazla çoklu yayım isteğini desteklemek ve kablosuz algılayıcılar arasında paket transferlerini sağlamak için algılayıcıların yeterli miktarda güç seviyelerinin olması gerekmektedir. Çalışmamızda en az enerji tüketen birçok çoklu yayım (MEMSM) problemini tanımlıyoruz. MEMSM problemi SRA problemini özel bir halini teşkil etmektedir. MEMSM probleminin çözümü için bilinen MIPF algoritmasının değiştirilmiş versiyonu olan M-MIPF algoritmasını sunuyoruz. MEMSM problemi için geliştirilen çözümler ağdaki bütün çoklu yayımları destekleyecek ve bunun yanında en az enerji harcayacak şekilde bir menzil ataması yapmayı amaçlar. Geliştirdiğimiz MST, MSTP, SPI ve M-MIPF algoritmalarını enerji tüketimlerine göre karşılaştırıyoruz. Deney sonuçlarımız göstermektedir ki; MEMSM problemi için MSTP ve SPI algoritmaları kararlı ve enerji verimli çözümlerdir.

Anahtar Kelimeler: Kablosuz Algılayıcı Ağlar, Çoklu Yayım, Menzil Ayarlama, En Kısa Yol, Kapsayan Ağaç

To my family...

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ALGORITHMS

ALGORITHMS

LIST OF ABBREVATIONS

WSN	Wireless Sensor Network
MEMS	Micro-Electro-Mechanical Systems
MEB	Minimum Energy Broadcasting
MEM	Minimum Energy Multicasting
SRA	Static Range Assignment
MST	Minimum Spanning Tree
MSTP	Pruned Minimum Spanning Tree
SPI	Shortest Path Incremental
MEMSM	Minimum Energy Multiple Source Multicasting
GUI	Graphical User Interface

CHAPTER 1

INTRODUCTION

Wireless sensor networks (WSN) consist of small, low-cost, low power and multifunctional sensor nodes [1]. These small sensor nodes have different components with various functions. Main components of a sensor node are sensing, data processing and communicating units. With the recent advances in micro-electro-mechanical systems (MEMS) and wireless communications, wireless sensor networks received high attention and many applications are developed using WSNs. A WSN consists of very large number of nodes and these nodes work collaboratively. Number of nodes in a wireless sensor network could be hundreds or thousands depending on the type of application. Design of a WSN is not easy due to this large number; a considerable effort is required.

In many civil and military applications where wireless network connectivity is needed, sensor nodes are deployed and used for data sensing and communication [13]. There are two main purposes for using WSNs in the applications, these are monitoring and tracking [30]. There are many different fields where using wireless sensor networks provide considerable advantage. One of these areas is military applications. WSNs can be used for tracking and monitoring enemy or allied forces in battlefield. Moreover, in different attack detection techniques, sensor nodes are used to prevent threats. They are easy and fast to deploy and do not require management after deployment. Another main area, which WSNs are widely used is environmental applications. They are deployed to detect some catastrophes such as floods and forest fires. Furthermore, sensor nodes make tracking the animals in the environment easier. Different kinds of devices in a home can communicate with each other using the wireless communication. So deploying sensor nodes for home automation is also useful [1]. Some health areas can also benefit from WSN applications such as monitoring patients and biomedical research [25]. Considering the wide range of applications, it can be stated that WSNs are becoming an integral part of our lives.

In wireless networks, a wired backbone infrastructure does not exist [13]. This provides a flexible structure to the network. Nodes in the network both acts as a router and a host with a forwarding capability to communicate with each other. Two nodes in the network can communicate with each other through a single hop if they are close enough; otherwise they use some intermediate nodes for communication. In a WSN, a very large number of nodes are deployed close to each other and their positions are not predetermined [1]. Generally, they are randomly deployed to increase flexibility of arrangement and decrease the cost of installation.

Sensor nodes have several limitations. They can only operate in a small area, they are limited in memory and computational capacity and they have low power batteries with a limited life. Furthermore, in most of the applications batteries can neither be replaced nor recharged after deployment [20] [31]. Using the batteries efficiently is very important because network lifetime is limited with the battery energy in wireless nodes. Thus, providing efficient use of energy in the wireless sensor networks is very crucial and energy efficieny is the most important design issue for many communication protocols.

Collaboration of sensor nodes is very important for wireless sensor networks, because to achieve a given task in the network, sensor nodes have to communicate with each other. There are three types of data dissemination in wireless sensor network. These are unicasting, broadcasting and multicasting. Multicasting is a generalization of unicasting and broadcasting. In a multicast request, a source node sends the same packet to a group of host nodes in the network. In order to achieve this task, sensor nodes should have enough power levels for transmissions. For this purpose minimum energy multicast (MEM) and minimum energy broadcast (MEB) problems are defined and some solutions are proposed. The main aim of these solutions is to arrange power levels of nodes such that the energy consumption of the network becomes minimum and the multicast source can send packets to host nodes.

In this thesis, we define the static range assignment (SRA) problem. As general characteristics of wireless sensor networks, there is always a communication between sensor nodes. This communication can be defined as a set of node pairs. This set contains all the source and target nodes as pairs. A pair (s,t) in the pair set shows that there is a packet transmission from source node s to target node t. This can be a direct transmission or can be a multi-hop communication which uses some intermediate nodes for communication. Static range assignment on a network determines the ranges of all nodes in the network. The range values are non-negative numbers, which are smaller than or equal to the maximum ranges of nodes. Range of a node denotes the power level of the node and nodes can make direct transmissions to the other nodes in their ranges. If a node has a zero range than this node has no power and could not make any packet transmission.

Static range assignment problem can be defined as finding the best range assignment that satisfies the set of required node pairs. In order to satisfy a communication pair set, the assigned power levels of nodes should be enough to provide connectivity between any source target pair (s,t) in the set. The best range assignment is the one with the least cost of all assignments satisfying the connectivity. Cost of the network is dependent to the assigned power levels of nodes. So smaller node ranges give a better range assignment for the network. Static range assignment problem considers the whole set together and finds a solution that provides connectivity for all pairs in the set. It does not make a range assignment for some of the pairs in the set and does not change the assigned ranges for some other pair set. In our thesis, we prove that the static range assignment problem is NP-hard using the NP-hardness of the MEB problem.

Since the static range assignment problem is NP-hard, we resort to heuristics. We propose three different heuristic algorithms for this purpose. These are minimum spanning tree based (MST), pruned minimum spanning tree based (MSTP) and shortest path incremental (SPI) range assignment algorithms. MST algorithm constructs a minimum spanning tree and makes range assignments using this spanning tree. MST algorithm is taken as a baseline in our evaluations. The second algorithm is the MSTP algorithm. It performs an efficient pruning technique over the MST algorithm. It reduces the ranges assigned with the MST algorithm with pruning. But at the same time MSTP algorithm ensures that the reduced ranges continue to satisfy the pair set. The last algorithm that we propose is SPI algorithm. The SPI algorithm assigns ranges incrementally and uses a shortest path based approach. SPI algorithm uses the properties of the wireless medium in order to increase the performance and to make a better range assignment.

As we stated previously, multicasting is commonly used in wireless sensor networks for data dissemination. So, in a WSN, several multicast requests occur for communication. In our study, we deal with this situation and present some approaches to solve multiple source multicasting problem efficiently. Finding an energy efficient solution to this problem is named as minimum energy multiple source multicasting problem (MEMSM). MEMSM problem is a generalization of MEM problem. The difference from the MEM problem is that there can be more than one source node in MEMSM problem and for each source node there is a multicast group, which source nodes make transmissions. On the other hand, we show that the MEMSM problem is a special case of static range assignment (SRA) problem and we prove that the MEMSM problem is NP-hard.

We use the proposed algorithms MST, MSTP and SPI to solve the MEMSM problem. In addition to these algorithms we also present the M-MIPF algorithm for the MEMSM problem. M-MIPF algorithm is a modified version of the well-known MIPF [27] algorithm. MIPF algorithm is specified for single source multicast problem and solves the MEM problem efficiently. M-MIPF algorithm behaves all the multicast requests independently and find solutions to them separately. All these different solutions are used to produce a final solution for M-MIPF algorithm. M-MIPF algorithm is a strong baseline for the MEMSM algorithm. Totally four algorithms are presented in this thesis for MEMSM problem, which are MST, MSTP, SPI and M-MIPF algorithms.

The rest of the thesis is organized as follows. In the next chapter we give information about studies related to minimum energy broadcast and minimum energy multicast problems and analyze different approaches for efficient solutions. In chapter 3, we describe the SRA problem and propose three heuristic algorithms MST, MSTP and SPI to solve SRA problem. In this chapter, we describe these three algorithms in detail and give their pseudocodes. In chapter 4, we introduce the minimum energy multiple source multicast (MEMSM) problem and present the M-MIPF algorithm. In the fifth chapter, we evaluate our proposed algorithms and show experimental results. In the following chapter we present our graphical user interface developed for deploying network, creating multicast groups and running algorithms. Finally, we conclude the thesis and discuss some possible future works.

CHAPTER 2

BACKGROUND AND RELATED WORK

In the design of a wireless sensor network application, there are several factors to be considered. But the primary focus is on the energy consumption [1]. Because sensor nodes are tiny microelectronic devices that contain only limited battery power. This battery power must be utilized in a very effective way. In most of the applications in wireless sensor networks, recharging or replacing the battery is almost impossible [3]. This means that lifetime of the sensor node is equal to the lifetime of the battery. In a wireless network, sensor nodes serve as transceivers. They both receive messages from neighbor nodes and make transmissions to their neighbor nodes. In a multi-hop communication, sensor nodes on the path of communication become the relay nodes. Hence every node in the network is very important for the communication between nodes and for the continuity of the wireless sensor network. If some of the sensor nodes in the system run out of battery, this will have a negative effect on the system. In such a situation, sensor network topology changes and required paths for communication are recalculated. These side effects of exhausted nodes decrease the efficiency of the wireless sensor network. So battery usage is a very crucial and many of the algorithms developed for wireless sensor networks take the energy efficiency into consideration and generally make it the primary design issue.

On the other hand, in other wireless networks the situation is different. Energy efficiency is not the primary design concern in conventional wireless networks. Because the battery can be replaced or recharged so the node lifetime is not equal to the battery lifetime. The main aim of these kind of wireless networks is the quality of service [1], which is defined as the accepted measure of the service quality that network users can benefit [6]. So in wireless networks the basic design principle can change if the network is a sensor network.

In a wireless sensor network, sensor nodes sense data, process information, transmit packets to neighbor nodes and receive incoming packets. A node performs different types of operations in the network. A sensor node uses its energy basically for three reasons. These power consumption areas are *sensing*, *communication* and *processing*. In a wireless sensor network, most of the energy is used for communication purposes [1]. Energy spent for sensing data and processing data is much less compared to the energy spent for communication. Hence, the energy efficiency of the wireless sensor network is mostly depends on the design of communication protocols.

In order to decrease energy usage in a wireless network generally two control mechanisms are used [13]:

- Power mode control: Power mode control protocols put the nodes into sleep state in order to decrease power consumption when they are in listening mode.
- Transmission power control: Transmission power control protocols adjust transmission ranges to manage energy consumption.

Transmission power control is mainly used in broadcasting and multicasting. These are data dissemination services in wireless networks. Broadcasting is a one-to-all service where one node sends its data to all the other nodes in the network. This node is called as the source node. If the range of source node is enough to send a packet to another node in the network, it makes just one transmission and sends the packet directly to the target node. Otherwise it uses some other nodes as relays and sends the message to target node using these intermediate nodes. These nodes are on the path of packet transmission. This kind of communication is called as multi-hop communication. Another data dissemination service is multicasting, which is generalization of broadcasting. It involves sending the same data to a group of sensor nodes named as multicast group. In the case of broadcast, multicast group is all the nodes except the source. Multicasting is very important in the applications, in which nodes need frequent communication with each other. Multicasting provides nodes to exchange messages in the network. This is a very important operation for networks with limited bandwidth and having nodes with limited battery power [21].

Broadcast and multicast data dissemination protocols play very important role as communication services for many routing protocols. Routing protocols need multicasting to control the network topology and update their states. Using the data transfers between nodes, routing protocols decide the routing paths and maintain the routings between nodes. In addition to these, data dissemination is very important to inform other nodes about environmental changes. Because these changes would have several considerable effects on the system. Therefore data dissemination services are very important for wireless sensor networks and designing an energy efficient algorithm for these services is very crucial in the development of wireless sensor networks [13].

The optimization problem of finding an energy efficient solution to multicasting and broadcasting is defined as minimum energy multicast (MEM) and minimum energy broadcast (MEB) problems. MEM and MEB problems take lots of attention and many algorithms are developed to solve these problems efficiently. The main aim of these algorithms is to provide an efficient communication for the system. Selecting the transmission nodes in the multicast or broadcast session and arranging their power levels are the main considerations of the multicast or broadcast algorithms [13]. MEM and MEB problems are easy to define but finding optimal solution to these problems are not so easy. It is proven that MEB problem is an NP-hard problem [19]. MEM problem is a generalization of MEB and it is also an NP-hard problem. Therefore, generally heuristics are defined to solve these problems.

One of the most important issues in the solution of MEB and MEM problems is *wireless multicast advantage* property. It is very critical for communication services. Algorithms designed for MEB and MEM problems would consider this property in order to be a more energy efficient algorithm. In a wireless medium, if a node wants to communicate with another node and send some packets, its range must cover the other node. In other words, power of the node must be enough to send a packet. If the distance between two nodes s and k is r and if s is the sender and k is the receiver node, than the power needed for node s to communicate with node k is r^{α}, which α is the propagation loss constant that takes a value between 2 and 4. Its value depends on the properties of the communication medium.

In a wireless network, when a node makes a transmission of a packet, this packet is received by the neighbor nodes in the area specified with the radius of the node. This is the nature of wireless medium if omni-directional antennas are used. However in a wired network this packet has to be sent all the neighbor nodes separately. In a wireless medium, if the source node s needs to send a broadcast message to the nodes in its range, the cost of this transmission will depend on the value of the range. It is not affected by the number of nodes in the range or their distances. Let define the p_i as the power needed to reach node k_i from the source node s and $k_1, k_2 \dots k_n$ be the neighbors of s. Then the total power p needed to transmit a broadcast packet from source s to all neighbors is defined as:

$$p = \max_{i=1 \dots k} p_i \tag{2.1}$$

However for the wired network case the situation is totally different. The total power p becomes the sum of all the transmission costs from node s to all neighbors. So it is defined as:

$$p = \sum_{i=1}^{k} p_i \tag{2.2}$$

Figure 2.1 shows this situation with a source node and three neighbor nodes within the range of source. Here if the source node s wants to make a packet transmission to all the neighbors, it needs just the power required to reach the farthest of all nodes, which is k_1. By this way the closer nodes k_2, k_3 and k_4 will also be in the coverage area of the source node and any packet transmitted to the medium will be received by these three nodes. By contrast, in the case of wired medium, the total power is the sum of three power costs needed to make transmissions between source s and nodes k_1, k_2, k_3 and k_4. This is the nature of wireless sensor networks and the energy reduction obtained by this way is the *wireless multicast advantage* property. This property gives a big advantage to wireless networks when designing algorithms. However WMA property makes the broadcasting and multicasting problems more complicated. For instance, the MEB and MEM problems are NP-hard [19] on the other hand, in a wired network the same optimization problem has an easier solution.

There are several solutions to minimum energy broadcast (MEB) and minimum energy multicast (MEM) problems. These solutions have different approaches and they are classified into groups according to these approaches. In the following sections different kinds of algorithms are mentioned as a solution to MEB and MEM problem.

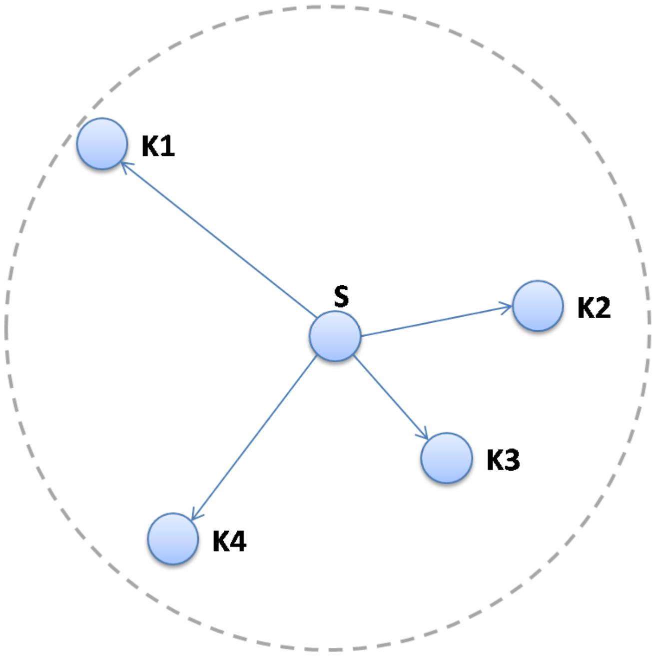

Figure 2.1: Wireless multicast advantage property.

2.1 Minumum Energy Broadcast Problem

Minimum energy broadcast problem is a difficult optimization problem. Some exact optimal algorithms are developed to solve this problem [8]. These algorithms are developed using MILP models. However, these solutions are not useful in practice [13]. To find a good solution to this problem, generally heuristic algorithms are used. There exists many efficient heuristic algorithms for minimum energy broadcast energy problem. These algorithms do not guarantee the exact optimal solution but generally executes in polynomial time. Heuristic algorithms are classified into three different classes according to their design perspectives [13]. These three groups of algorithms are:

- Spanning tree algorithms
- Topology control algorithms
- Local search algorithms

In the following sub-sections, these algorithms are discussed.

2.1.1 Spanning Tree Algorithms

In spanning tree algorithms, main purpose is to construct a spanning tree or a very similar structure to a spanning tree with a greedy approach. By using this tree structure all the nodes in the network can communicate with tree links. By this way, a source node in the network can reach all the other nodes with a multihop path over many nodes. Spanning tree algorithms builds the tree with an iterative way by adding some new nodes at each step of the algorithm. Building a minimum spanning tree like structure is a basic but an efficient way to solve minimum energy broadcast problem. There are many proposed algorithms based on this approach. Here we overview MST [29], BIP [29], SPT [29] and BAIP [26] algorithms.

MST algorithm is a straightforward algorithm that constructs a spanning tree based on Prim's MST algorithm [23]. In this algorithm the link costs between nodes are calculated as the required power for node communication. Complexity of MST algorithm is $O(n^3)$ in general, where n is the number of nodes in the network. If the Fibonacci heap is used in implementation then the complexity becomes $O(n^2)$. MST algorithm is a simple algorithm and it is easy to implement but it is not an efficient algorithm in terms of energy consumption. After the MST algorithm is executed, the ranges assigned to the nodes are not very effective. Greater ranges are assigned to most of the nodes than they require. So the broadcast tree needs some pruning operation after the MST algorithm is applied. In MST algorithm *link based* approach is used to construct minimum energy broadcast tree. This is an old model, and many of the previously developed models for broadcast and multicast use *link based* model [10]. In a *link based* model, a node has to transmit its data separately to each of its neighbors. This causes several independent transmissions. *Link based* models are appropriate for wired applications and they do not carry the properties of wireless network environments. The other model used in communication protocols is *node based* model. This model uses the nature of wireless medium. In this model, when a node makes a transmission, all the nodes in its transmission range receive the message if omnidirectional antennas are used. Many of the currently developed algorithms for multicast and broadcast consider the properties of wireless medium and use *node based* model in the design.

SPT uses a *linked based* approach like MST algorithm but it has a different heuristic than MST algorithm. It constructs a shortest path tree instead of minimum spanning tree. Root of the shortest path tree is the source node in the broadcast. In SPT algorithm, shortest paths are calculated from the source node to all the other nodes in the network. Dijkstra's algorithm [9] is used to find the shortest paths between the nodes. Shortest paths calculated from the source node constitute the shortest path tree. SPT is a broadcast tree because it enables the source node to send a message to any other nodes in the network. Source node can use the calculated shortest path to reach a specified node. It uses the Dijktra's algorithm, so the complexity of the SPT algorithm is $O(n^2)$, where n is the number of nodes in the network. On the other hand, SPT algorithm is not energy efficient, it needs some improvements like pruning or Sweep [29].

BIP algorithm is proposed by Wieselthier *et al.* and it uses a similar heuristic with Prim's MST algorithm. The aim of the algorithm is to build a minimum energy tree that reaches all the nodes in the tree from the source node. By this way, all transmission nodes and their power levels are determined. The energy cost of the tree is the total energy consumed by the nodes. If the range of a node is zero, then it does not have any effect on the energy cost of the tree. Main difference from the MST algorithm is the strategy used in adding new nodes to the tree structure. A *node based* approach is used in the design of algorithm and this increases the energy efficiency. A new node is added to the tree according to the minimum incremental cost instead of minimum cost as in MST. Wieselthier *et al.* defined minimum incremental cost as the power required to increase the range of a node to reach another node in the network. Complexity of the BIP algorithm is $O(n^3)$, where n is the number of nodes. BIP algorithm makes a good range assignment to the nodes and it is more energy efficient than MST and SPT algorithms.

In BIP algorithm *wireless multicast advantage* property is used in order to build the spanning tree. BIP uses a greedy approach and when adding a new node to the energy tree, it selects the node with the least incremental cost. It considers the WMA property of the wireless medium and makes the selection according to this. In Figure 2.2, adding a new node to the energy tree with BIP algorithm is shown. The aim is to construct an energy efficient broadcast tree rooted at s. Currently the broadcast tree contains the nodes s, k_1, k_3, k_4. Algorithm decides which new node can be added to the tree with minimum incremental power. There are two options. Either node s increases its range to reach node k_2, or node k_1 can transmit to its neighbor node k_2, which is not in the tree. If the distance between node s and nodes k_1 and k_2 are r_{s,k_1} and r_{s,k_2}, and the propagation loss constant is α, then the cost of transmission between nodes s and k_1 and k_2 becomes r^{α}_{s,k_1} and r^{α}_{s,k_2} respectively. Therefore the cost of increasing the range of node s is r^{α}_{s,k_1} - r^{α}_{s,k_2}. Increasing the range of node k_1 from *zero* to r_{k_1,k_2} is another option to add the node k_2 to the energy tree. In this example, the first option has a lower energy cost so node s increases its range to reach k_2. BIP algorithm uses the *wireless multicast advantage* property, because node s can reach both of the nodes k_1 and k_2 when it transmits with sufficient power.

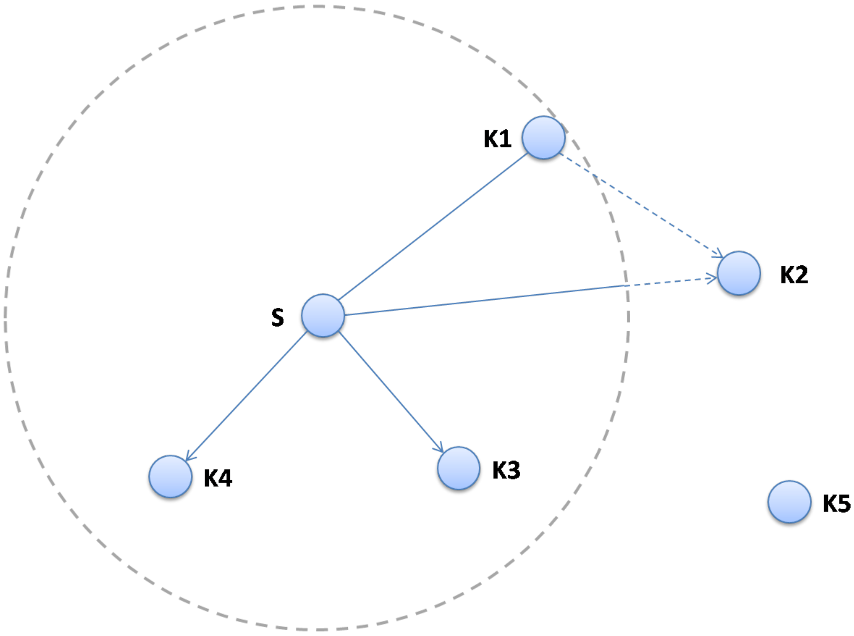

Figure 2.2: BIP uses wireless multicast advantage.

BAIP algorithm is a variation of BIP algorithm. It is proposed by Wan *et al.*. It is very similar to BIP algorithm except that at each step more than one node can be added to the tree. New nodes are added to the tree according to the average incremental cost metric [26]. Average incremental cost is a more general form of incremental cost approach. At each step of the algorithm, the energy required for adding n nodes to the broadcast tree is divided by n and average incremental cost is calculated. For each n this calculation is made and n nodes, which give the minimum value is added to the broadcast tree.

2.1.2 Topology Control Algorithms

Topology control algorithms have a different design perspective than spanning tree algorithms. In topology control algorithms, each node in the network makes its own decisions, such as assigning range and determining transmission nodes from neighbors of a node [13]. Localized algorithms are in this group of algorithms. In localized algorithms, a node uses its neighbor information to make decisions. Node can use one hop, two hop or multi hop neighbor information. Some of the localized algorithms are RNG [5], LMST [17] and LBIP [14].

Minimum spanning tree (MST) is a sub graph of relative neighborhood graph (RNG). Relative neighborhood graph can be used for broadcasting in wireless sensor networks. RNG can be constructed using local information. It is an advantage for broadcasting problem, but it is shown that RNG algorithms are not energy efficient [18]. Another approach to satisfy connectivity is using minimum spanning trees. By using local network information, local minimum spanning tree is constructed [11]. Every node uses 1-hop neighbor information and constructs 1-hop MST. After then in the construction of LMST, these local minimum spanning trees are used. By this way a connected structure is built with one hop neighbor information. One of the other localized algorithms is LBIP [14], which is a localized version of BIP. In LBIP algorithm, every node applies BIP algorithm and broadcasts its calculations. At the end, a connected structure used for broadcasting is constructed. In LBIP algorithm two hop neighbor information is needed.

In localized topology control algorithms, in order to construct required structures some control messages have to be transferred between nodes in the network. If the number of messages that flow through the network is higher, then collisions of these messages will be more. This will cause loss of information and wrong topology construction. In addition to this, energy consumption is also increased by the number of transferred messages. So the number of control messages sent by nodes is a very critical issue in the design of localized topology control algorithms.

2.1.3 Local Search Algorithms

Local search algorithms are used to improve the performance of existing MEB algorithms. First, one of the MEB algorithms is applied to the network then a local search algorithm is used to build a better topology. These algorithms do not change the broadcast connectivity property of the network. Local search algorithms can be applied several times to the network until no other further improvements can be done. Local search algorithms are classified into two categories. These are tree based and power assignment based local search algorithms [13]. Tree based algorithms improves the tree structure with updates in the tree structure in each step. In power assignment based algorithms a new power assignment is made to the nodes to decrease the energy spent by nodes in the network. Here we overview Sweep [29], EWMA [4], BIDP [11], r-shrink [7] and LESS [15] algorithms.

Sweep algorithm is proposed by Wieselthier *et al.* in order to improve energy efficiency of the BIP algorithm. After the BIP algorithm is applied and tree structure is constructed, Sweep procedure is used on the tree. It is a tree based algorithm. It finds unnecessarily long transmission ranges and shortens them or it finds some redundant transmissions between nodes and removes the links between these nodes. Sweep procedure is developed to increase performance of BIP algorithm, but it can be used on any spanning tree structure. Sweep keeps the connectivity property of the tree while making it more energy efficient. Figure 2.3 shows broadcast tree constructed with BIP algorithm. s is the source of the energy tree. r_1 and r_2 are relay nodes and other nodes are the leaf nodes of the tree. Nodes r_1 and r_2 are in the range of node s. s transmits broadcast packets to nodes r_1 and r_2. r_1 behaves as a relay and sends the packet to nodes l_1 and l_2. Similarly r_2 makes transmissions to nodes l_3, l_4 and l_5. So s can make transmission to any node in the network. However this broadcast tree can be improved with Sweep procedure. In this example the range of node s is the distance to node r_2. It makes direct transmission to node r_2, but it is not required because node r_1 can reach to the node r_2 with its current range so node s can reduce its power to reach only node r_1.

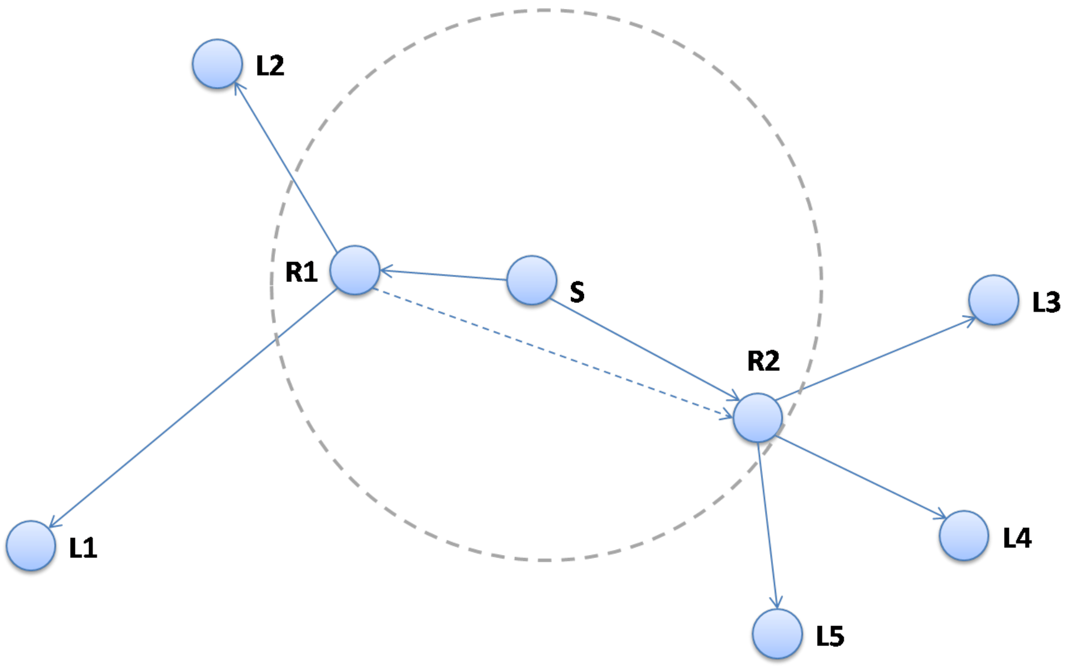

Figure 2.3: Sweep procedure.

BIDP makes more improvement after sweep procedure is applied on spanning tree. BIDP is tree based search procedure like sweep. BIDP does not only remove redundant transmission ranges, but it also reconstructs the broadcast tree by changing tree links at each iterative step of the algorithm. It links some nodes, which are not connected and removes links between some nodes using network topology information. At the end, broadcast tree topology changes to a more efficient topology [13].

The r-shrink [7] is another local search procedure used to improve existing solutions for minimum energy broadcast problem. It is a power assignment based algorithm. r-shrink is applied to a node and deals with the transmissions from this node to other nodes. It shrinks the range of the node and by this way it decreases the energy expenditure of the node when sending messages. However when the range decreased, some of the previously reachable nodes can become unreachable from this node. So after this shrinking operation, another parent node must reach these nodes in order to preserve the broadcast tree topology. Shrinkage can be applied several times until no further improvements are obtained with this procedure.

Other two local search algorithms are EWMA [4] and LESS [15]. In EWMA main purpose is to modify the spanning tree by changing the previously assigned links. It starts from the source node and checks if it is more advantageous to increase the power level to reach more nodes. Range of source node increases but it can be more energy efficient if range of a child node decreases to zero. This procedure is applied until reaching the leaf nodes of the tree. LESS algorithm is a generalized form of EWMA. In LESS, when a node increases its range, some of its children nodes' ranges may decrease or reduce to zero. It can continue to transmit with a lower range. LESS gives a better performance than EWMA, because it finds all possible gains in the network [13].

2.2 Minumum Energy Multicast Problem

Minimum energy multicast problem is a generalization of MEB problem. In MEM problem one node sends a packet to a previously determined group of nodes. This group is named as multicast group. In broadcast case, this group is all of the other nodes except the sender. So broadcast is a special case. There are many approaches to solve the minimum energy multicast problem. To find the optimal solution to this MEM problem some MILP models are developed. These models are extended versions of MILP models used in MEB problem [12]. Another way of solving this problem is defining good heuristics. These heuristic approaches can be classified into three groups [13]. These three groups are:

- Pruning algorithms
- Minimum Steiner tree algorithms
- Local search algorithms

General approach in pruning algorithms is to prune the broadcast tree obtained by solving the MEB problem. First one of the MEB heuristics is applied, then the required pruning operation is executed on the connected broadcast structure. Many of the solutions to MEM problem use pruning approach. In pruning, the nodes that do not have any children in multicast tree are specified and their ranges are decreased to zero because there is no need for them to transmit any messages. There are pruned versions of well-known MEB algorithms. Such as P-MST and P-BIP where P stands for ”pruned”. P-BIP is also known as MIP [29]. In MIP algorithm BIP algorithm is executed first, then pruning operation is started for some nodes according to the multicast group.

Using a minimum Steiner tree is another approach to solve the MEM problem. Minimum Steiner tree problem is to find a minimum energy multicast tree [24]. Minimum Steiner tree construction is an NP-hard problem and there exist no optimal solution but there are some good heuristics to solve this problem. These heuristic solutions can be used to solve the MEM problem. The two heuristic solutions we present here are SPF and MIPF [27]. SPF algorithm builds a tree and makes the source node as the root of the tree. Starting from the source node, algorithm adds a group of nodes, which are on the least cost path at each iterative step. Least cost path is selected from all the paths that are between the nodes in the tree and the nodes not in the tree but in the multicast group. Algorithm repeats this step until all the nodes in the multicast group are reachable. On the other hand, MIPF algorithm uses a similar approach with the BIP algorithm. It uses wireless multicast advantage property as a difference from the SPF algorithm. In MIPF, similar to SPF, a tree where the root is the source node is built. At each iterative step of the algorithm, considering the minimum incremental power property, some nodes are added to the tree structure. The nodes, which are added to tree, are on the path with the least incremental power. The incremental energy costs of the paths are calculated for the paths between the nodes in the tree and the nodes in the multicast group but not in the tree yet. The path with the minimum energy cost becomes the least incremental power path. Then all the nodes on this path are added to the tree structure. This procedure continues until all the nodes in the multicast group are added to the tree.

Local search procedures are used for the same purpose they are used in MEB problem. They can improve the solutions to MEM algorithms. Some of these algorithms are S-REMIT [28], MIDP [11] and DMEM [22] algorithms. S-REMIT and MIDP algorithms are tree based local search algorithms, on the other hand DMEM is power assignment based local search algorithm. DMEM and S-REMIT are distributed and MIDP is a centralized algorithm.

S-REMIT algorithm improves the existing multicast tree that is constructed after any MEM algorithm is executed. It changes some links in the tree to make the tree more energy efficient. Centralized MIDP algorithm is similar to S-REMIT algorithm. It is also tree based, but it does not use a multicast tree as an initial tree. It uses a broadcast tree and improves this tree at each step of the algorithm. At the end, the broadcast tree turns out to a multicast tree and this tree is the output of the algorithm. The distributed algorithm DMEM is power assignment based and each node in the network makes its own decisions about its power level. These nodes can be tree or non-tree nodes. Nodes give this decision by considering their distances to all neighbors. At each step, using these calculations, total power levels assigned to nodes are decreased. In addition to energy efficiency increase in the system, the multicast property of the topology is conserved [13].

CHAPTER 3

STATIC RANGE ASSIGNMENT PROBLEM

In this chapter, we present the static range assignment (SRA) problem for wireless sensor networks and propose three algorithms as solution to the SRA problem.

3.1 General Framework

The wireless sensor nodes are generally deployed into a field in order to sense and extract information that need to be forwarded to some other nodes. In this thesis, we study the scenario in which some nodes multicast their information periodically. Most of the previous work on this topic solves multicasting problem using radius assignment. For each multicast request in the system, the power levels of the nodes are adjusted according to this new request. However changing power levels for each multicast request is not very applicable in real systems [16]. We focus on the case that a node is not able to change its transmission range dynamically. Thus, nodes make transmission with their predetermined range that is statically assigned before they are started to operate. However, it is possible that nodes have different transmission ranges.

The aim is to determine such ranges for wireless sensor nodes as to ensure transmission of messages between some source-destination pairs and minimizing the total energy consumed or the number of transmissions. In Figure 3.1 a sample 5 node network is displayed. There are two transmissions in this network, one is from node 2 to node 4 and the other one is from node 1 to node 5. Node 3 is a relay node and it has to transmit packets received from nodes 1 and 2. After the static range assignment for this network, power level of node 3 should be enough to send the farther of the two nodes, which is node 5.

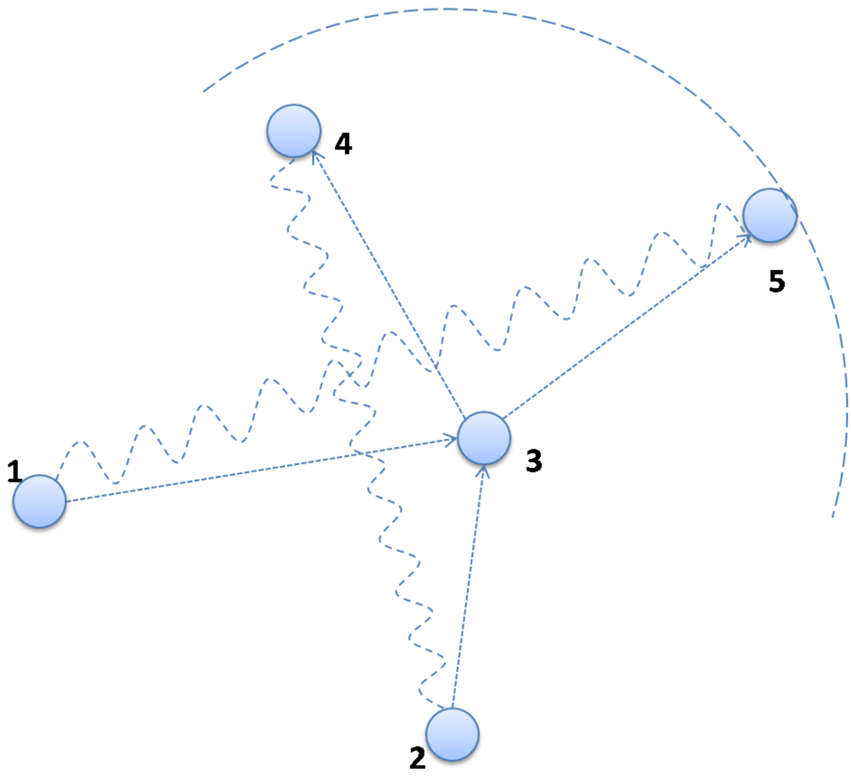

Figure 3.1: A sample deployment of sensor nodes illustrating a static range of a node.

3.2 Formal Problem Definition

We are given a set $\mathcal{S} = \{s_1, s_2, \ldots, s_n\}$ of n nodes where each node s_i is associated with a point $p(s_i)$ in r-dimensional[1] space R^r. The distance $d(s_i, s_j)$ between two nodes s_i and s_j is defined as the euclidean distance between the respective locations $p(s_i)$ and $p(s_j)$, i.e.,

$$d(s_i, s_j) = \|p(s_i) - p(s_j)\|_r \tag{3.1}$$

Given this notation, the static range assignment (or simply, range assignment) of a set $\mathcal{S}$ of nodes is defined as follows.

Definition 3.2.1 (Static Range Assignment) *A static range assignment* $\Phi : \mathcal{S} \rightarrow \mathrm{R}^+ \cup \{0\}$ *is a function from the set* $\mathcal{S}$ *to a set of non-negative real values, where* $\Phi(s_i)$ *refers to the assigned range of node* s_i.

In Figure 3.2, an 8 node wireless sensor network is displayed with their specified locations. In this figure the range of node 1 is shown as a circle with radius r. This figure also illustrates the

[1] $r = 2$ is often the case.

distance between two nodes. The distance between nodes 4 and 7 is drawn as a line between nodes.

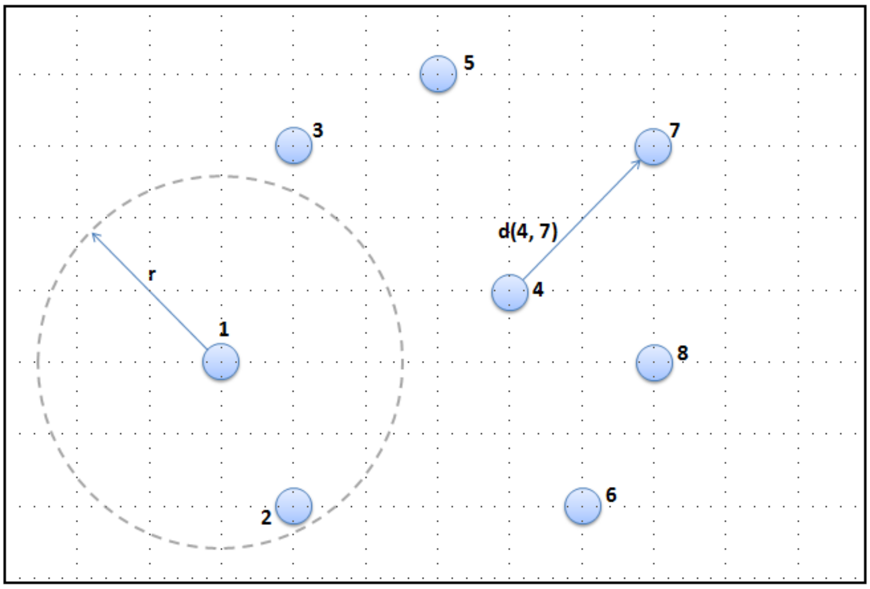

Figure 3.2: A sample figure illustrating locations of the nodes, distances between nodes and range of a node.

Definition 3.2.2 (Range Graph) *For a range assignment Φ, the range graph $G(\Phi) = (\mathcal{V}, \mathcal{E})$ is a directed graph with n vertices, where a node $v_i \in \mathcal{V}$ corresponds to the node $s_i \in \mathcal{S}$ and a directed edge $(v_i, v_j) \in \mathcal{E}$ refers to that node s_i can reach to node s_j within the range $\Phi(s_i)$.*

$$\mathcal{E} = \{(v_i, v_j) : d(s_i, s_j) \leq \Phi(s_i)\} \tag{3.2}$$

Figure 3.3, contains two small figures. Top figure shows the ranges of nodes after a sample range assignment. At the bottom figure corresponding range graph is displayed for the same sensor network. Range graph is a directed graph. If two of the nodes are in the range of each other, then the arrow is two-sided. If only one of the nodes(source) covers the other node(target), then there is an arrow from source to target node. In the figure there is no outgoing arrow from nodes 6 and 7, which states that these nodes have zero range. They do not make any transmissions in the network.

We are also given a non-decreasing binary function f which maps each range $r \in R^+$ to a real valued positive cost and such that $f(0) = 0$. The function f often refers to the energy spent by node s_i during one message transmission. As a result, the cost $c(\Phi)$ of an assignment is

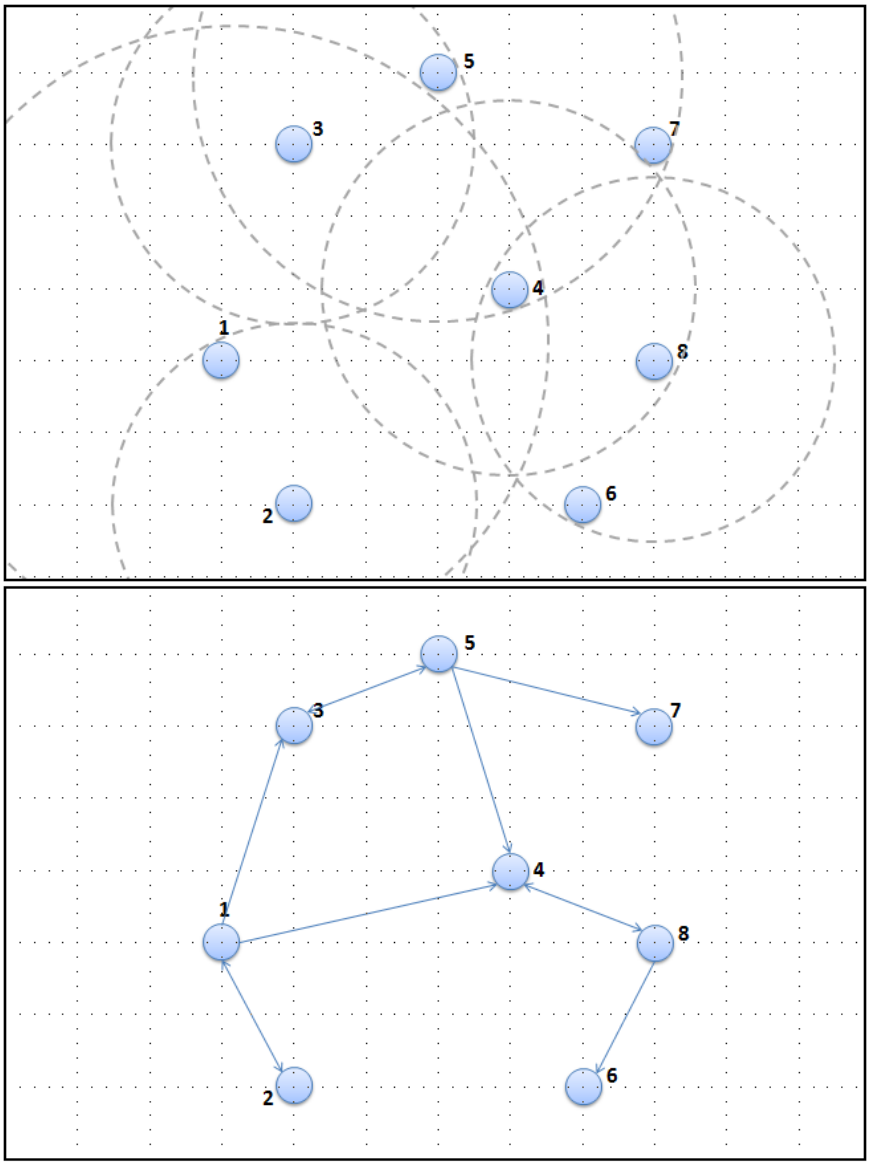

Figure 3.3: A sample (a) static range assignment and (b) corresponding range graph.

defined as follows:

$$c(\Phi) = \sum_{s_i \in \mathcal{S}} f(\Phi(s_i)) \tag{3.3}$$

Finally, we are given a set $\mathcal{P} = \{(s_{i_1}, s_{j_1}), (s_{i_2}, s_{j_2}), \ldots, (s_{i_p}, s_{j_p})\}$ of p pairs of nodes of $\mathcal{S}$, where each pair (s_i, s_j) indicates the necessity of any path from v_i to v_j. We say a graph $\mathcal{G}$ *satisfies* $\mathcal{P}$ if for each pair $(s_i, s_j) \in P$, there exists a path from v_i to v_j in $\mathcal{G}$. Given all these notations, the static range assignment problem is defined in Problem 1.

Figure 3.4 shows the same network topology and range graph with Figure 3.3. This figure illustrates how a range graph satisfies a given pair set $\mathcal{P}$. For instance the pair set $\mathcal{P} = \{(3, 8), (1, 7)\}$ is satisfied with this graph. There exists a path from 3 to 8, which is $3 \rightarrow 5 \rightarrow 4 \rightarrow 8$. Also the path $1 \rightarrow 3 \rightarrow 5 \rightarrow 7$ used for the communication from 1 to 7. These paths are drawn as bold in the figure. On the other hand, this range graph does not satisfy the pair set $\mathcal{P} = \{(5, 8), (4, 3)\}$ because no path exists from 4 to 3.

Problem 1 (Static Range Assignment Problem (SRA)) *Given a set $\mathcal{S}$ of nodes with associated points at R^r and a set $\mathcal{P}$ of pair of nodes in $\mathcal{S}$, find a range assignment Φ such that the range graph $G(\Phi)$ satisfies the set $\mathcal{P}$ and the cost $c(\Phi)$ is minimized.*

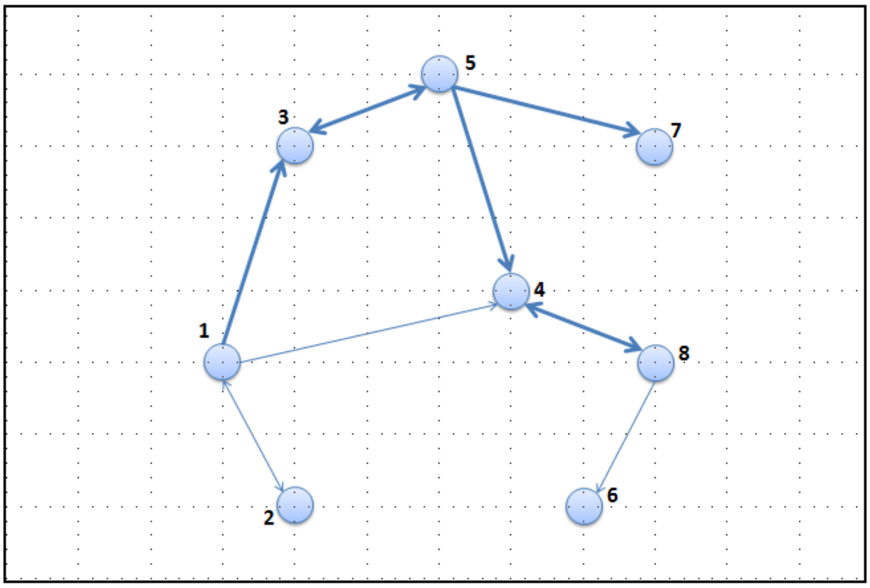

Figure 3.4: A sample range graph that satisfies pair set $\mathcal{P} = \{(3, 8), (1, 7)\}$ and does not satisfy pair set $\mathcal{P} = \{(5, 8), (4, 3)\}$

Theorem 3.2.3 *Static range assignment problem is NP-hard.*

Proof. Consider the decision version of SRA problem where we aim at determining whether there exists such a static range assignment that the resultant cost does not exceed a given bound T or not. We choose to show the NP-hardness of the problem by reducing from the decision version of minimum energy broadcast (MEB) problem to the decision version of SRA problem. In MEB problem, we are given a set of nodes with associated locations as well as a broadcast source $s \in \mathcal{S}$. In decision case of MEB problem, for a given energy bound T, the goal is to determine whether there exists a range assignment which ensures the broadcast where total energy spent by nodes does not exceed T or not. We reduce this problem to the decision version of SRA as follows. The node set $\mathcal{S}$ is constituted as same as that of MEB problem instance as well as the locations of nodes. The pair set $\mathcal{P}$ is constructed as

$$\mathcal{P} = \{(s, s_i) : s_i \in \mathcal{S}, s_i \neq s\} \tag{3.4}$$

where s is the broadcast source in the MEB instance. Finally the function f is set to be the energy function used in MEB problem, i.e., $f(r)$ denotes the consumed energy for the transmission of with range r. Since in a broadcast each node carries out exactly one transmission in its own predetermined range, finding a static range assignment with cost not greater than T is equivalent to finding a broadcast range assignment with total consumed energy is not greater than T.Since the decision version of MEB problem is NP-complete [19], the decision version of SRA problem is also NP-complete due to reduction, and thus SRA problem is NP-hard. ■

The static range assignment (SRA) problem is different from the range assignment problem in static ad-hoc networks. In ad-hoc networks, the assigned ranges of stations ensure the strong connectivity of the network [2]. However, in our definition of static range assignment, the required connectivity in the wireless sensor network should be satisfied with the assigned power levels of the sensor nodes. Furthermore, our definition of SRA problem uses a general cost function. In order to make the objective as minimizing the total consumed energy in the network, then cost function is defined as the energy consumption with one transmission. For a different objective, a different cost function can be used.

3.3 Algorithms

Since the static range assignment problem is NP-complete, we resort to heuristics. For this purpose, we present three algorithms, one of which, namely minimum spanning tree based (MST) algorithm is taken as a naive baseline. Thus, we propose two algorithms to solve SRA problem, namely pruned minimum spanning tree based range assignment (MSTP) algorithm and shortest path based incremental range assignment (SPI) algorithm. The former algorithm employs an effective pruning technique over MST algorithm, whereas the latter one incrementally assigns ranges conducting shortest path based approach at each step. For the sake of simplicity in complexity calculations, we denote n and p as the number of nodes of $\mathcal{S}$ and the number of paths in pair set $\mathcal{P}$, respectively.

3.3.1 Baseline: Minimum Spanning Tree Based Range Assignment (MST)

Algorithm 3.1 shows the undirected graph constructing procedure, which is commonly used by several algorithms presented in this section, from a given set of nodes (with associated points) and cost function. Mainly, we define an edge between each (unordered) pair of nodes with associated weight of the incurred cost of sending message within the range of the distance in terms of given cost function. This procedure runs in $O(n^2)$ time.

Algorithm 3.2 begins with conducting an undirected graph construction over the set $\mathcal{S}$ of nodes with respect to locations and cost function f. Subsequently, a minimum spanning tree algorithm is performed to construct a rooted tree $\mathcal{T}$. Upon this, the ranges of nodes assigned such as to ensure that each node can reach both its parent (except root) and its children. Complexity of MST algorithm is $O(n^2)$.

Require: $\mathcal{S}$: set of nodes, f: cost function
$\Phi \leftarrow \vec{0}$
$\mathcal{V} \leftarrow \mathcal{S}$
$\mathcal{E} \leftarrow \binom{\mathcal{V}}{2}$
for each $\{v_i, v_j\} \in \mathcal{E}$ **do**
    $w(v_i, v_j) \leftarrow f(d(s_i, s_j))$
return $\mathcal{G} = (\mathcal{V}, \mathcal{E}, w)$

Algorithm 3.1: CONSTRUCT_GRAPH Procedure

Figure 3.5 shows a sample network of 8 nodes. The numbers on the edges show the distance

Require: $\mathcal{S}$: set of nodes, $\mathcal{P}$: set of pairs, f: cost function

$\Phi \leftarrow \vec{0}$
$\mathcal{G} \leftarrow$ CONSTRUCT_GRAPH($\mathcal{S}, f$)
$\mathcal{T} \leftarrow$ MINIMUM_SPANNING_TREE($\mathcal{G}$)
for each $v_i \in \mathcal{T}$ **do**
  $v_j \leftarrow \mathcal{T}$.parent[$v_i$]
  if $\Phi(s_i) < d(s_i, s_j)$ **then**
    $\Phi(s_i) \leftarrow d(s_i, s_j)$
  if $\Phi(s_j) < d(s_i, s_j)$ **then**
    $\Phi(s_j) \leftarrow d(s_i, s_j)$
return Φ

Algorithm 3.2: MST-based Algorithm

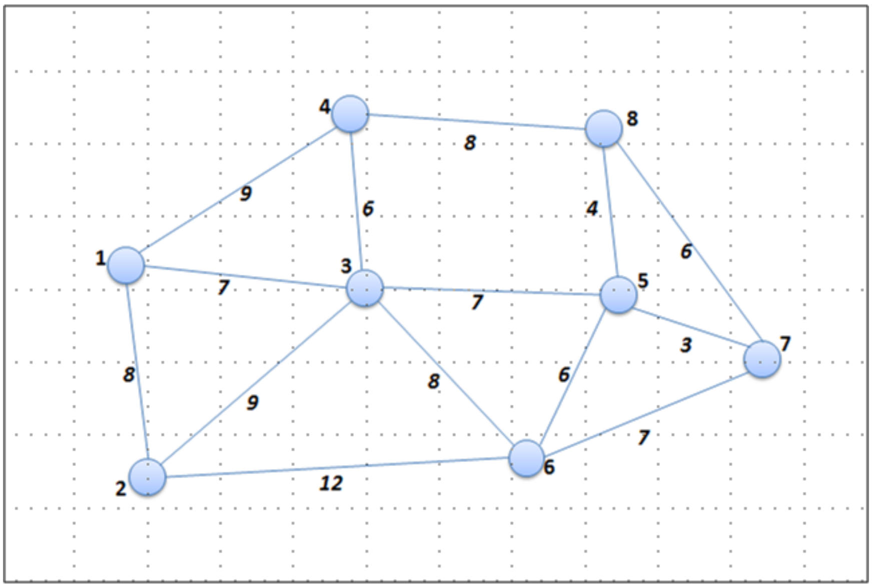

Figure 3.5: A sample wireless sensor network with 8 nodes.

between nodes. In this network there should be connection between nodes (1,5), (1,6) and (4,7). This means the pair set $\mathcal{P} = \{(1,5), (1,6), (4,7)\}$ will be satisfied with the range graph of the assignment. When the MST algorithm is used as a solution, it first constructs the network graph, than finds the minimum spanning tree of the network and makes the range assignment ensuring that the range of nodes are enough to reach children and parent nodes. Figure 3.6 shows the constructed minimum spanning tree and Figure 3.7 shows the range graph after assignment. MST algorithm assigns ranges greater than zero to all the nodes in the network even some of the nodes are not used in the transmissions as a source or relay node. For example node 2 and node 6 have ranges of 8 and 6 respectively, however they are leaf nodes and these ranges are redundant.

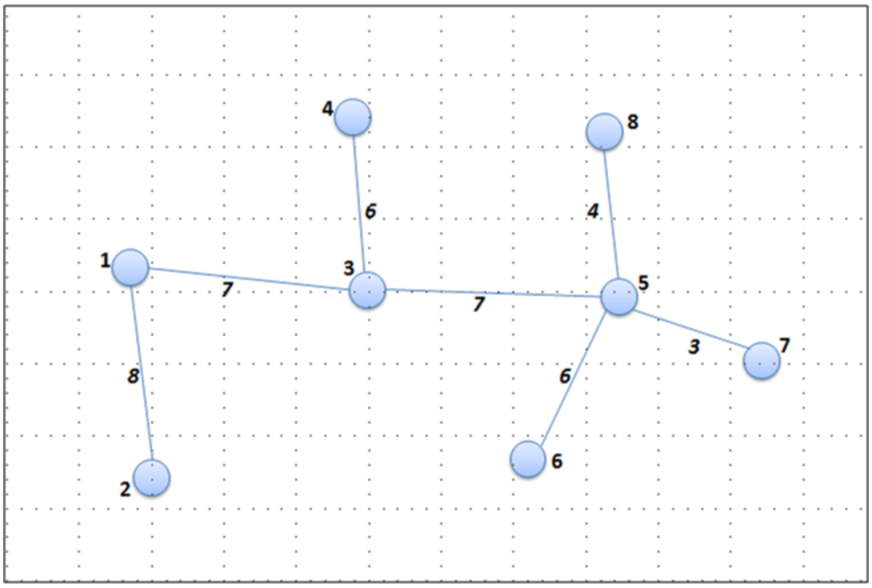

Figure 3.6: Minimum spanning tree of sample network.

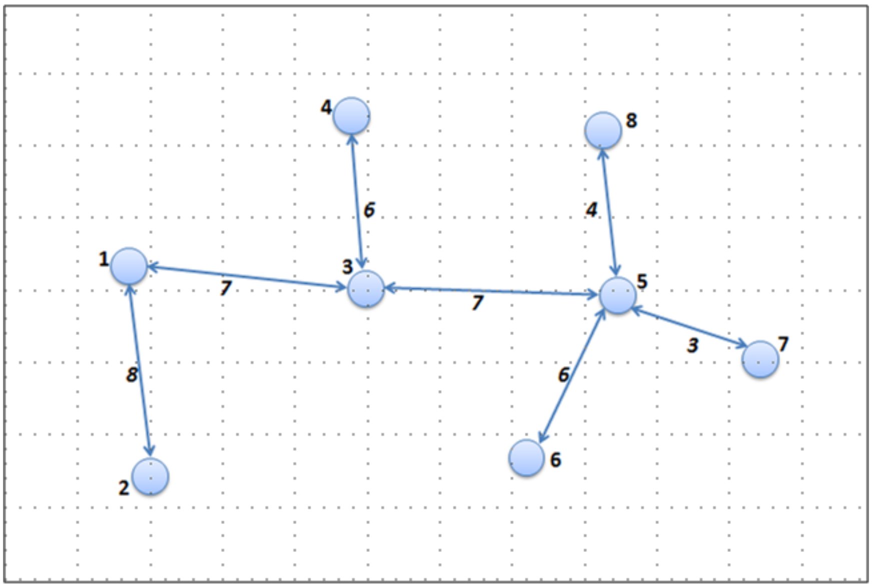

Figure 3.7: Range graph after the MST algorithm is executed for range assignment.

3.3.2 Pruned Minimum Spanning Tree Based Range Assignment (MSTP)

As Algorithm 3.2 performs, Algorithm 3.3 also constructs an undirected graph using the procedure defined in Algorithm 3.1 at the beginning. Discrepantly, Algorithm 3.3 assigns ranges more effectively. Since the aim is to ensure a good transmission performance between some particular pairs, the ranges of nodes are assigned such as message transmission can be performed between those source-destination pairs using the constructed tree $\mathcal{T}$ as an overlay network. That is, consider a source-destination pair which has exactly one path over $\mathcal{T}$, which we refer here as source-destination path. The range assignment is performed such that nodes can reach successive nodes on any such source-destination paths. MSTP algorithm runs in $O(n^2 + np)$ time.

Require: $\mathcal{S}$: set of nodes, $\mathcal{P}$: set of pairs, f: cost function
$\Phi \leftarrow \vec{0}$
$\mathcal{G} \leftarrow$ CONSTRUCT_GRAPH($\mathcal{S}, f$)
$\mathcal{T} \leftarrow$ MINIMUM_SPANNING_TREE($\mathcal{G}$)
for each $p_k = (a_k, b_k) \in \mathcal{P}$ **do**
    $P_k \leftarrow$ EXTRACT_PATH($\mathcal{T}, a_k, b_k$)
    for each $(v_i, v_j) \in P_i$ **do**
        if $\Phi(s_i) < d(v_i, v_j)$ **then**
            $\Phi(s_i) \leftarrow d(v_i, v_j)$
return Φ

Algorithm 3.3: MSTP Algorithm

When the MSTP algorithm is used as a solution to the sample network given in the Figure 3.5, as similar to MST algorithm it first constructs the network graph, than finds the minimum spanning tree of the network. However MSTP algorithm uses an efficient pruning tecnique over the MST algorithm. It extracts the paths for each pair in the pair set and uses these paths for range assignment. Figure 3.8 shows the extracted paths in the network. After all the paths are determined in the network, ranges of nodes are assigned using the paths passing over the nodes. There do not exist any paths passing over the nodes 2 and 6 so their assigned ranges are 0. However with the MST algorithm their ranges are 8 and 6 respectively. In addition to these improvements, some node ranges can also be decreased when compared to MST algorithm. For instance there is just one path passing over node 1 and it should provide connectivity of this path. MST algorithm assigns a range of 8, however 7 is enough for communication. Figure 3.9 also shows the range graph after assignment. This range graph shows that there is a good energy improvement over the MST algorithm, when compared to the range graph of MST algorithm.

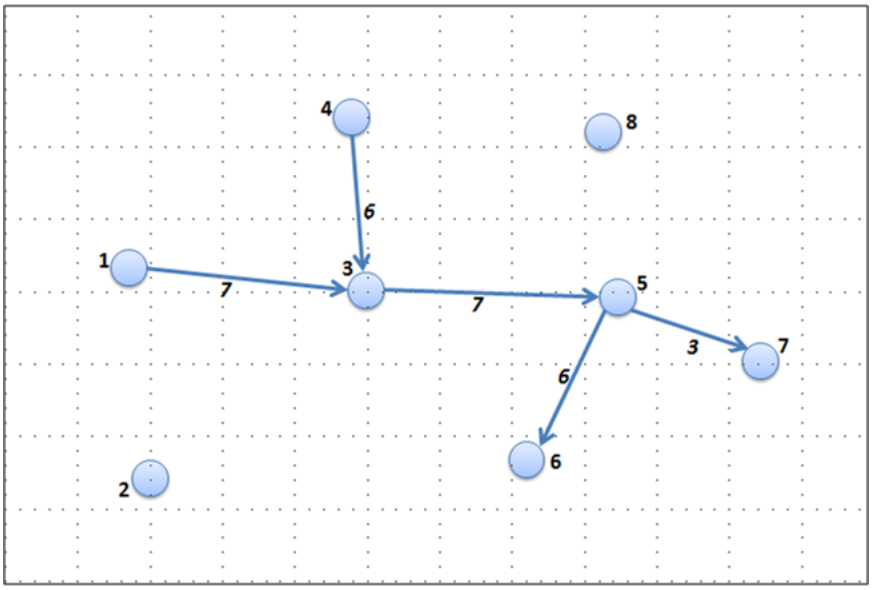

Figure 3.8: Extracted paths for pairs in the pair set.

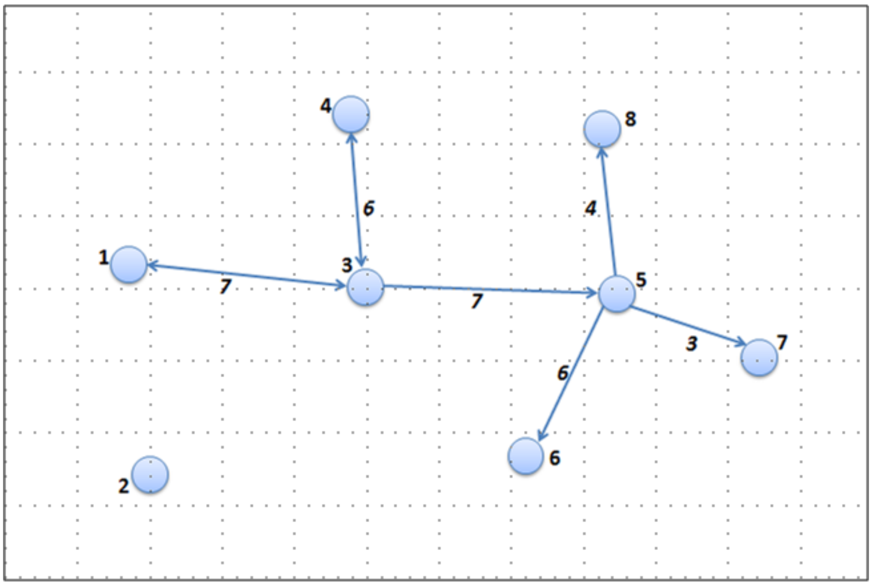

Figure 3.9: Range graph after the MSTP algorithm is executed for range assignment.

3.3.3 Shortest Path Based Incremental Range Assignment (SPI)

The following definition and theorem is given to support the SPI algorithm presented in this subsection.

Definition 3.3.1 (Cost Graph) *For a range assignment* Φ *and a cost function* f*, the cost graph* $C(\Phi, f) = (\mathcal{V}, \mathcal{E}, w)$ *is a directed graph with* n *vertices, where a node* $v_i \in \mathcal{V}$ *corre-*

sponds to the node $s_i \in \mathcal{S}$ and the weight of a directed edge $w(v_i, v_j)$ refers to that how much additional cost necessary to be incurred to make s_i reach to s_j, i.e.,

$$w(v_i, v_j) = \begin{cases} f(d(s_i, s_j)) - f(\Phi(s_i)) & \Phi(s_i) < d(s_i, s_j) \\ 0 & o.w. \end{cases} \tag{3.5}$$

Theorem 3.3.2 *For a given set $\mathcal{S}$ of nodes, cost function f, a range assignment Φ and a pair (a, b) of nodes, the minimum total incremental cost that should be incurred such that range graph $\mathcal{G}(\Phi)$ satisfies (a, b) is equal to the length of the shortest path from a to b in cost graph $C(\Phi, f)$.*

Proof. A minimum total increment cost should be lead by a minimal increment of ranges, i.e., no less increment of all ranges will lead to satisfy (a, b). Consider a minimal increment of ranges of nodes such as (a, b) is satisfied by $\mathcal{G}(\Phi')$ where Φ' denotes the range assignment that become after the increments. Because of the minimality each node, whose range is to be incremented, has to reach a node that was not previously reached. This implies an edge in the cost graph. Thus, each minimal increment of ranges induces a path in cost graph with length same as the total increment cost. Counterside, each path in cost graph induces a minimal increment of ranges with cost same as the length of the path. Therefore, the minimum total incremental cost that should be incurred such that range graph $\mathcal{G}(\Phi)$ satisfies (a, b) is equal to the length of the shortest path from a to b in cost graph $C(\Phi, f)$. ■

Corollary 3.3.3 *For a given set $\mathcal{S}$ of nodes, cost function f and a range assignment Φ, $\mathcal{G}(\Phi)$ satisfies a pair (a, b) of nodes if and only if shortest path from a to b in $C(\Phi, f)$ is equal to 0.*

Algorithm 3.4 shows the cost graph constructing procedure that is similar to Algorithm 3.1, where the main difference is that the edges are directed. We define an edge between each distinct pair of nodes with associated weight of the incurred cost of sending message within the range of the distance in terms of given cost function.

SPI, which is presented in Algorithm 3.5, is the most sophisticated heuristic among the ones presented in this section. At the beginning, (line 2) a set of yet-unsatisfied pairs is constructed. Since, all initial assigned ranges are zero, all pairs of $\mathcal{P}$ are unsatisfied. Immediately after, (line 3) the cost graph C is constructed using the procedure shown in Algorithm 3.4. At any step of the algorithm, it is an invariant that C holds the cost graph (as in Definition 3.3.1) with respect to up-to-date range assignment Φ. Hence, $w(v_i, v_j)$ is equal to zero if s_i already reaches s_j within the range $\Phi(s_i)$. Otherwise, $w(v_i, v_j)$ is set to be $f(d(s_i, s_j)) - f(\Phi(s_i))$. Until all pairs in $\mathcal{P}$ are satisfied, the ranges are incrementally modified as follows. At each iteration, (line 5–16), the pair that would be satisfied with minimum incremental cost is selected among the not yet satisfied pairs. This pair is found by the shortest path on current C (lines 5–8), because the length of shortest path on C is equal to the minimum incremental cost to achieve transmission from source node to destination node of the pair, referring to Theorem 3.3.2. Upon determining such pair, (lines 9–16) we incrementally modify the ranges (line 11) as to provide transmission from source node to destination node on the shortest path of the pair. Concurrently, (lines 12–16) we also update the weights of the edges of graph C to conserve its cost graph property with respect to modified range assignment Φ. Time complexity of SPI algorithm is $O(n^2p^2)$.

Note that SPI reduces to MIPF and BIP algorithms that are state-of-the-art algorithms for minimum energy single source multicasting (MEM) and minimum energy broadcasting (MEB) problems, respectively.

Require: $\mathcal{S}$: set of nodes, f: cost function
$\Phi \leftarrow \vec{0}$
$\mathcal{V} \leftarrow \mathcal{S}$
$\mathcal{E} \leftarrow \{(v_i, v_j) : v_i, v_j \in \mathcal{V}, v_i \neq v_j\}$
for each $(v_i, v_j) \in \mathcal{E}$ **do**
    $w(v_i, v_j) \leftarrow f(d(s_i, s_j))$
return $C = (\mathcal{V}, \mathcal{E}, w)$

Algorithm 3.4: CONSTRUCT_COSTGRAPH Procedure

When the SPI algorithm is used to make range assignment over the sample network given in the Figure 3.5, it behaves totally different from the MST and MSTP algorithms. First of all, all the pairs in the pair set $\mathcal{P} = \{(1,5), (1,6), (4,7)\}$ are put in the unsatisfied pair set, then the cost graph of the network is constructed. For each of the unsatisfied pairs in the set, shortest paths are calculated. At each iterative step, pair with the least cost is chosen and used to rearrange the ranges previously assigned. At first, the least cost pair (1,5) is chosen and in order to satisfy connection between nodes 1 and 5 range of nodes 1 and 3 are assigned as 7. At the second step, using the cost graph, the shortest paths are recalculated considering the previously assigned ranges. Incremental cost of pair (1,6) is smaller than the cost of pair (4,7).

Require: $\mathcal{S}$: set of nodes, $\mathcal{P}$: set of pairs, f: cost function

```
Φ ← 0⃗
𝒰 ← 𝒫
C ← CONSTRUCT_COSTGRAPH(𝒮, f)
while 𝒰 ≠ ∅ do
    for each p_i = (a_i, b_i) ∈ 𝒰 do
        S(p_i) ← SHORTEST_PATH(C, a_i, b_i)
        if w(S(p_i)) < w(S(p_min)) then
            p_min = p_i
    for each (v_i, v_j) ∈ S(p_min) do
        if Φ(s_i) < d(v_i, v_j) then
            Φ(s_i) ← d(v_i, v_j)
            for each v_k ∈ 𝒱 s.t. v_k ≠ v_i do
                if d(v_i, v_k) < Φ(s_i) then
                    w(v_i, v_k) ← 0
                else
                    w(v_i, v_k) ← f(d(s_i, s_k)) − f(Φ(s_i))
return Φ
```

Algorithm 3.5: SPI Algorithm

So the pair (1,6) is chosen. In order to satisfy connection between nodes 1 and 6, increasing the range of node 3 from 7 to 8 is enough. Here we see the benefit of using wireless multicast advantage property. After this assignment, both the pairs (1,5) and (1,6) becomes satisfied. Only the pair (4,7) remains in the unsatisfied pair set. At the last step, this pair is chosen and the ranges 6 and 3 are assigned to the nodes 4 and 5. SPI algorithm assigns range 3 to the node 5, on the other hand the MSTP algorithm assigns 6. Figure Figure 3.10 shows the range graph after the assignment. SPI algorithm performs better than the MSTP algorithm for this sample range assignment example, because it does not use the underlying minimum spanning tree structure and uses the advantages of wireless medium.

3.4 Discussions

Here, a quite general definition is given for static range assignment from both cost function f and pair set $\mathcal{P}$ perspective. That is, this problem definition and proposed solutions can be applied to scenarios where arbitrary cost functions are conducted and/or pair set is restricted to have some criteria. By performing proper reductions, we can solve more specific problems. However, one should be careful on the objective. The objective of SRA problem is determined by the sum of individual costs of assigned ranges. Thus, the objective correctly captures of the objective of a problem, only if nodes perform equal number of transmissions.

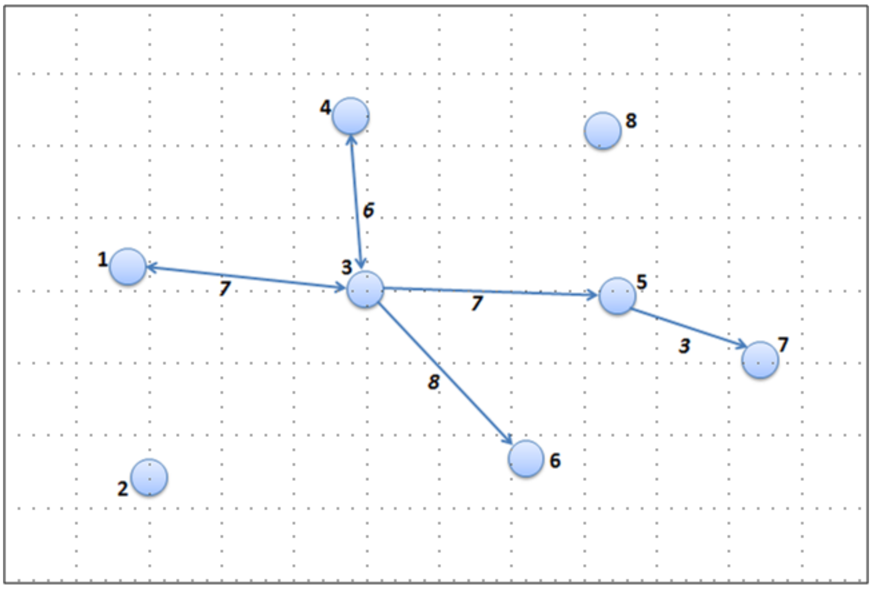

Figure 3.10: Range graph after the SPI algorithm is executed for range assignment.

Another issue is about cost function f. If function f is given as to capture the consumed energy of a transmission, then the objective relates to minimizing total consumed energy. Whereas, in case of that f is a binary function referring to existence of a transmission, i.e., $r > 0$, the objective reduces to minimizing number of transmitter nodes.

CHAPTER 4

MULTIPLE SOURCE MULTICASTING

In this chapter, we define the multiple source multicasting problem (MEMSM) and propose an algorithm as a solution to MEMSM problem.

4.1 Multiple Source Multicasting Framework

Single source multicast is a typical scenario for wireless sensor networks. Here, we study the case where the number of multicast tasks can be more than one. The multiple multicasting tasks can be considered independent. However, the nodes make transmissions with their predetermined static ranges, that is, it is not possible to modify the range for different multicasting tasks. Thus, the multicasting tasks are related in sense of static range assignment.

We assume that after deploying to field, each wireless sensor node operates as follows. Upon receiving a message from other nodes, it relays the message with its predetermined range only if both the range is greater than zero and the message is not relayed previously by the sensor node. In order to check whether the same message is sent before, each sensor node maintains its own list containing the identifications of previously relayed messages. For the sake of being identical, each message is identified by its owner node's id concatenated with the number of messages previously originated by the owner node.

Figure 4.1 shows a multiple source multicast scenario. In this network there are two multicast groups. First multicast group contains nodes 1,4 and 5. Source node of this group is 1. The other multicast group has nodes 5,4,2 and 3. This group has the source node 5. Source nodes 1 and 5 make transmissions to nodes in the multicast groups. In figure this situation is illustrated.

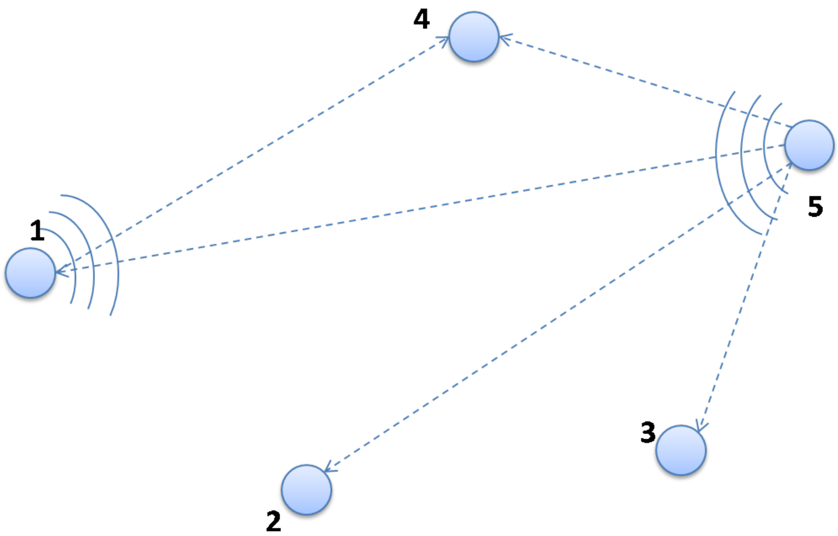

Figure 4.1: A sample deployment of nodes illustrating two source multicasting with corresponding multicasting group.

4.2 Formal Definition

Minimum energy multiple source multicasting (MEMSM) problem is a more general version of minimum energy multicasting (MEM) problem, where there does not have to be unique source, that is more than one multicast source nodes with different groups to multicast their data are allowed. Whereas, MEMSM problem is a special case of static range assignment (SRA) problem (see Chapter 3) in a sense that the range cost function f is given such that $f(r)$ corresponds to the consumed energy per transmission within the range r. Given such f function, the cost $c(\Phi)$ of SRA problem captures the total consumed energy for one transmission per node. However, nodes can make more than one transmissions. This objective exactly corresponds to minimizing energy in multiple source multicasting scenario, under the assumption that each node performs a transmission within its predetermined range for each multicasting task, i.e, for each multicast source. Otherwise, the SRA objective approximates the objective of MEMSM problem.

In MEMSM problem, we are given a set $\mathcal{S}$ of nodes and their associated points. A multicasting task m_i is shown by a pair $m_k = (s_k, \{s_k^1, s_k^2, \dots, s_k^{n_k}\})$ meaning that node v_i multicasts to a set $\gamma_k = \{s_k^1, s_k^2, \dots, s_k^{n_k}\} \subset \mathcal{S}$ of nodes. For a range assignment Φ, the total consumed energy $E(\Phi)$ is taken as the cumulative energy consumptions of each transmission. The energy consumed by a transmission within a range r is defined with following formula:

$$e(r) = \begin{cases} r^{\alpha} + c_e & r > 0 \\ 0 & r = 0 \end{cases} \tag{4.1}$$

Problem 2 (Minimum Energy Multiple Source Multicasting (MEMSM)) *Given a set $\mathcal{S}$ of nodes with associated points at R^r and a set $\mathcal{M} = \{m_1, m_2, \ldots\}$ of multicasting tasks of nodes in $\mathcal{S}$, find a range assignment Φ such that the total consumed energy $E(\Phi)$ is minimized.*

Theorem 4.2.1 *MEMSM problem is NP-hard.*

Proof. We prove the NP-hardness of MEMSM problem by reduction from minimum energy broadcast (MEB) problem which is known to be NP-hard [19]. Broadcasting is a special case of multicasting where the group size is equal to all nodes but the source node and there exists single source node. That is, if s is the broadcast source, then the set $\mathcal{M}$ of multicasting tasks is constructed as

$$\mathcal{M} = \{m_1 = \{s, \mathcal{S} - \{s\}\}\} \tag{4.2}$$

Upon this transformation, minimizing objective of MEMSM problem in constructed MEMSM instance corresponds to minimizing objective of MEB problem for given MEB instance. Since MEB is NP-hard, we conclude that MEMSM is also NP-hard. ■

4.3 Combinatorial Reduction to Static Range Assignment Problem

As to solve MEMSM problem, we use combinatorial reduction to static range assignment (SRA) problem as follows.

Require: $\mathcal{S}$: set of nodes, $\mathcal{M}$: set of multicast tasks
$\mathcal{P} \leftarrow \emptyset$
for each $m_k = (s_k, \gamma_k) \in \mathcal{M}$ **do**
    for each $s_j \in \gamma_k$ **do**
        $\mathcal{P} \leftarrow \mathcal{P} \cup \{(v_k, v_j)\}$
$\Phi \leftarrow \mathrm{SRA}(\mathcal{S}, \mathcal{P}, f)$
return Φ

Algorithm 4.1: MEMSM-to-SRA Reduction

As seen in Algorithm 4.1, for each multicasting task $m_k = (s_k, \gamma_k)$, we introduce paths in $\mathcal{P}$ from source node s_k to each node in respective multicast group γ_k. This reduction is exact in sense that minimization objective of SRA problem for constructed instance correctly corresponds to minimizing the total consumed energy of given MEMSM energy under the assumption that for each multicasting task, every node performs transmission uniquely. Once, such reduction is constructed, it is possible to employ proposed algorithms for SRA problem. Thus, we use MST algorithm as a baseline, whereas MSTP and SPI algorithms are considered as novel ones in order to solve MEMSM problem.

4.4 Baseline: Merging-based Range Assignment (M-MIPF)

Here, the modified version of known MIPF [27] algorithm is presented which is referred as M-MIPF. The MIPF algorithm is modified as to capture multiple source scenario as follows. As also seen in Algorithm 4.2, we first treat the multicasting tasks independently and for each multicasting task, we perform individual range assignment using MIPF which is an algorithm specified for single source multicasting. Afterwards, the individual ranges are merged as to ensure performance of all multicasting tasks by setting a sensor node's range as the maximum of the individual ranges assigned for each multicasting task. M-MIPF is happened to be the strong baseline of MEMSM problem among the proposed algorithms. M-MIPF algorithm has a time complexity of $O(n^2 p)$, where p is equal to $|\gamma_1| + |\gamma_2| + \ldots |\gamma_k|$.

Require: $\mathcal{S}$: set of nodes, $\mathcal{M}$: set of multicast tasks
$\Phi \leftarrow \vec{0}$
for each $m_k = (s_k, \gamma_k) \in \mathcal{M}$ **do**
  $\Phi_k \leftarrow \text{MIPF}(\mathcal{S}, s_k, \gamma_k)$
  for each $s_i \in \mathcal{S}$ **do**
    if $\Phi(s_i) < \Phi_k(s_i)$ **then**
      $\Phi(s_i) \leftarrow \Phi_k(s_i)$
return Φ

Algorithm 4.2: M-MIPF Algorithm

The M-MIPF algorithm is also used for range assignment over the wireless sensor network given in Figure 3.5. The pair set $\mathcal{P} = \{(1,5), (1,6), (4,7)\}$ contains two different multicast requests. The source nodes are 1 and 4. One multicast request is from 1 to 5 and 6, the other is from 4 to 7. The M-MIPF algorithm treats these two different multicasting tasks independent from each other and makes individual range assignments using MIPF algorithm.

After the range assignment for the first multicast request, which has the source 1, the range 7 is assigned to the node 1 and range 8 is assinged to node 3. Range assignment for the second multicast request assigns ranges 8 to node 4, 4 to node 8 and 3 to node 5. Because this is the least cost assignment for this single multicast request with MIPF algorithm. However previous assignment assigned range 8 to the node 3 and this can be used in the solution of this request. This is the drawback of M-MIPF algorithm. Figure 4.2 shows the range graph after assignment.

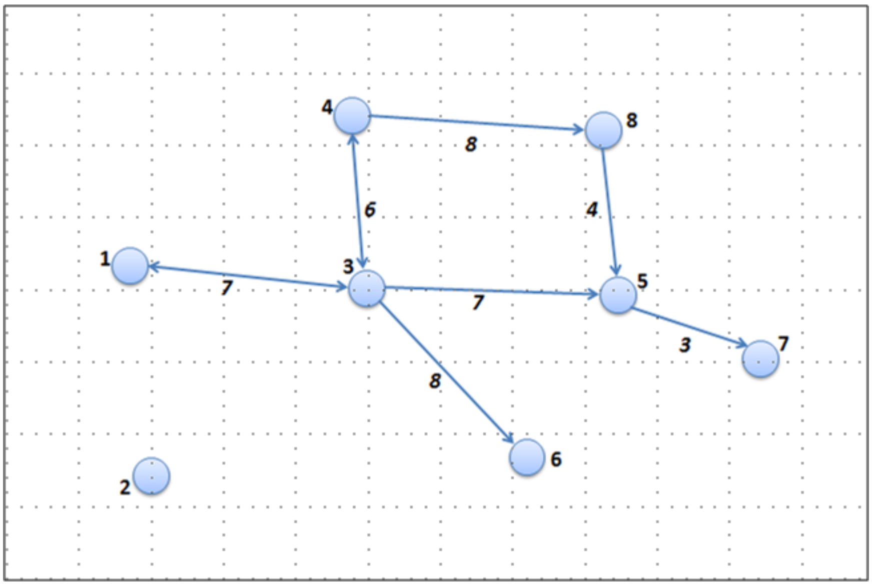

Figure 4.2: Range graph after the M-MIPF algorithm is executed for range assignment.

CHAPTER 5

EXPERIMENTAL RESULTS

In this chapter, we discuss the experimental results of the algorithms that are presented in the previous chapters. We evaluate these algorithms and compare them with each other. In the experimental process, we use many network instances as inputs to algorithms. We create random network topology instances with different node numbers in a square region. In addition to network instances, multicast groups are determined for each of the network instances. The transmission powers of nodes are not limited to a fixed number. Any node can make transmission to another node in the network. So the max ranges of the nodes are not less than the distance between the farthest nodes in the network. This chapter has two sections. In the first section the setup procedure is given in detail. This procedure includes preparing the data required for algorithms. Creation of network topology instances and multicast groups are discussed in this part. In addition, the performance measures of algorithms and the way of execution is given. In the second section, results of algorithms are given for multiple source multicasting. Different inputs are used in the execution of algorithms. Results are displayed with graphics for a better illustration. Comparison of algorithms and their evaluations are also done in this part.

5.1 Setup and Data

Two main data generation processes are required for the execution of algorithms. First one is deploying network topology instances where the algorithms are executed. The other one is creating the multicast groups and determining their sizes and source nodes. Several network instances are used for evaluation of algorithms. Node numbers of created network instances are varied from 10 to 100. The value set of network node number is $10, 20 \ldots 100$ and 10 network topologies are generated for each different network size. Total 100 network topologies are produced and used in the experiments. Each of these network instances is used in the evaluation process. Using many different network instances, gives us more accurate experimental results. For each of the network topology, node positions are determined randomly in a 500×500 square region. In Figure 5.1, we can see a 40 node network, which is randomly deployed.

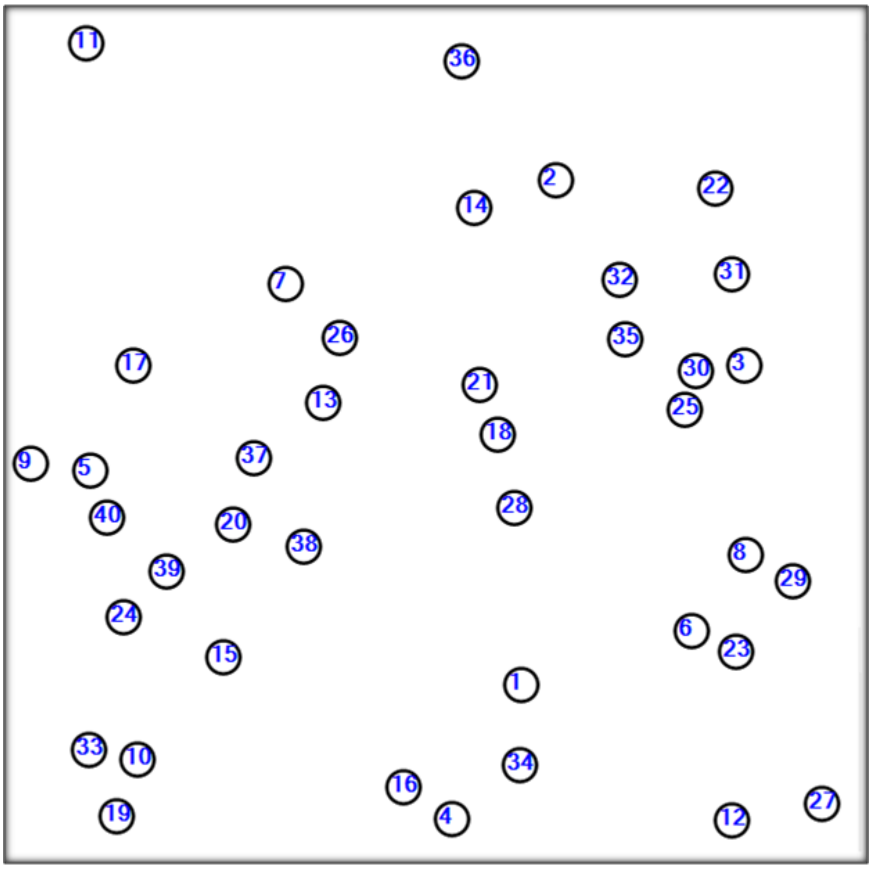

Figure 5.1: Randomly deployed 40 node sensor network.

Specifying the multicast groups and source nodes is another important issue for input generation process. Multicast group sizes and number of multicast groups are changed according to the number of nodes in the network. A constant percentage of sensor nodes constitute the multicast groups. We generate multicast groups of sizes 10%, 20% and 100% of the node number in the network. Similarly we specify the number of multicast groups according to the node number in the network. The number of multicast groups in the network would be 10%, 20% and 100% of the node number in the network. For instance, for a wireless sensor network with 40 nodes, if the number of multicast groups is 10% and multicast group size is 20% of the sensor node number in the network, then there is 4 multicast groups with 8 nodes. There are 10 different network sizes and 3 different multicast group sizes and 3 different multicast group numbers. A total of $3 \times 3 = 9$ different multicast schemes are generated for each network size. These schemes are applied on every network instances and used in the execution of the algorithms. In Table 5.1, generated schemes for node number 50 are listed.

Table 5.1: Multicast schemes generated for 50 node network topologies.

Multicast Scheme	**Number of Multicast Groups**	**Multicast Group Size**
Scheme 1	5	5
Scheme 2	5	10
Scheme 3	5	50
Scheme 4	10	5
Scheme 5	10	10
Scheme 6	10	50
Scheme 7	50	5
Scheme 8	50	10
Scheme 9	50	50

Performance measure of the algorithms is defined as the total power of multicast or broadcast trees constructed as a solution to MEMSM problem. This total power is the sum of all the power levels of the transmitting nodes in the network. Nodes with zero transmission power do not have any effect on the total power. They do not make any packet transmissions or do not behave as relay nodes in any other transmissions. Range of a node specifies the required power level of the node. So assigning smaller ranges to nodes will produce a more energy efficient multicast/broadcast tree. So algorithms with a better range assignment will have a better performance over others.

Algorithms are executed for each of the network instances generated. We compare the performance of the algorithms for each 9 multicast schemes. We define $M(x, y)$ as the multicast scheme where the number of multicast groups is $x\%$ and multicast group size is $y\%$ of all the nodes in the network. Furthermore for each network topology, we define $C_i(n, M(x, y))$ as the cost of multicast tree with number of nodes n and multicast scheme $M(x, y)$, generated with algorithm i.

There are 10 network topologies with the same node number n. For an algorithm i and multicast scheme $M(x, y)$ these 10 different network instances are executed separately. After these executions, geometric averages of results are calculated. This average value gives the actual cost of an algorithm with a specified node number and multicast scheme.

In our evaluation of algorithms we use normalized costs of algorithms to provide a better understanding about the results. We take the MST algorithm as a baseline and normalize any of the other algorithms with the performance of MST. We define normalized cost as:

$$C'_i(n, M(x, y)) = \frac{C_i(n, M(x, y))}{C_{MST}(n, M(x, y))} \quad (5.1)$$

Normalized costs give us the performance of an algorithm compared to MST algorithm. Therefore comparing the power consumptions of any of four algorithms at the same time becomes easier.

The size of the square region (500×500) where the network is deployed does not affect the performance results of the algorithms. If the size increases by a factor of n, then the distances between nodes also increase by the same factor. So for the propagation loss constant α, the total power consumption of an algorithm increases by a factor n^α. Therefore the actual costs of algorithms change but all of the algorithms are affected with the same amount; the normalized values of algorithms do not change.

We generate performance graphics after the execution of algorithms. In our graphics, the x axis shows the node number and y axis shows the normalized energy cost of the algorithm with the multicast scheme. The aim of these graphics is to compare the performance of 4 algorithms with specified multicast scheme. Using these graphics, the performances can also be compared with different node numbers. For each node number there are 10 different network topologies. In the performance graphics, the geometric average costs of network instances are displayed. In the following section the performances of algorithms are explained in detail.

5.2 Multiple Source Multicasting

MST, MSTP, SPI and M-MIPF algorithms are executed for the multicast schemes $M(10, 10)$, $M(10, 20)$ and $M(10, 100)$. In these multicast schemes, number of multicast groups are 10% of the node number. On the other hand, multicast group sizes change for each multicast scheme. For the first scheme, size of multicast group is 10% of the node number. For the second and third schemes this ratio becomes 20% and 100% respectively. Propagation constant is taken as $\alpha = 2$. The execution results of the algorithms are displayed in Figure 5.2.

In Figure 5.2 we can see performance of the algorithms for three different multicast schemes. Top graphic shows the performance of the algorithms for multicast scheme $M(10, 10)$. For small sensor node numbers, SPI and M-MIPF algorithms almost have the same performance. However, if node number exceeds 30, SPI algorithm provides a better performance than MST, MSTP and M-MIPF algorithms. This advantage does not change as the node number increases in the network. For small sensor node numbers, M-MIPF algorithm performs better than the MSTP algorithm and it has a similar performance with SPI algorithm. However when node number increases it loses this advantage and becomes the worse of these three algorithms. For networks containing more than 80 nodes the cost of M-MIPF algorithm becomes larger than MST algorithm. On the other hand, MSTP algorithm has a worse performance than the SPI algorithm for almost all network sizes but its performance does not decrease dramatically like M-MIPF algorithm as the node number increases.

In the middle graphic, performances of the algorithms for the multicast scheme $M(10, 20)$ are displayed. Algorithms have a similar performance for the $M(10, 20)$ multicast scheme, which they show for the multicast scheme $M(10, 10)$. Again the best algorithm is the SPI algorithm. It gives the minimum cost for all node numbers. For this multicast scheme, The M-MIPF algorithm again has a performance decrease when the node number exceeds 30. If node number is bigger than 70, the performance of M-MIPF algorithm is even worse than the MST algorithm. The MSTP algorithm has a lower cost performance than the SPI algorithm but it is more efficient than the M-MIPF algorithm for this multicast scheme.

The bottom graphic shows the case when multicast group size is equal to the number of nodes in the network. This means all the multicasts are broadcasts. Again the number of multicast groups is 10% of the node number in the network. In this graphic it is seen that the normalized costs of algorithms are higher when compared to the previous cases for small node number. In the above two graphics the normalized costs are below 0.5 for small node numbers, however for this multicast scheme normalized costs of all three algorithms are higher than 0.6. The reason for this is the size of multicast groups. In the case of large multicast groups, more sensor nodes become transmitters, so the energy consumption in networks increases. This

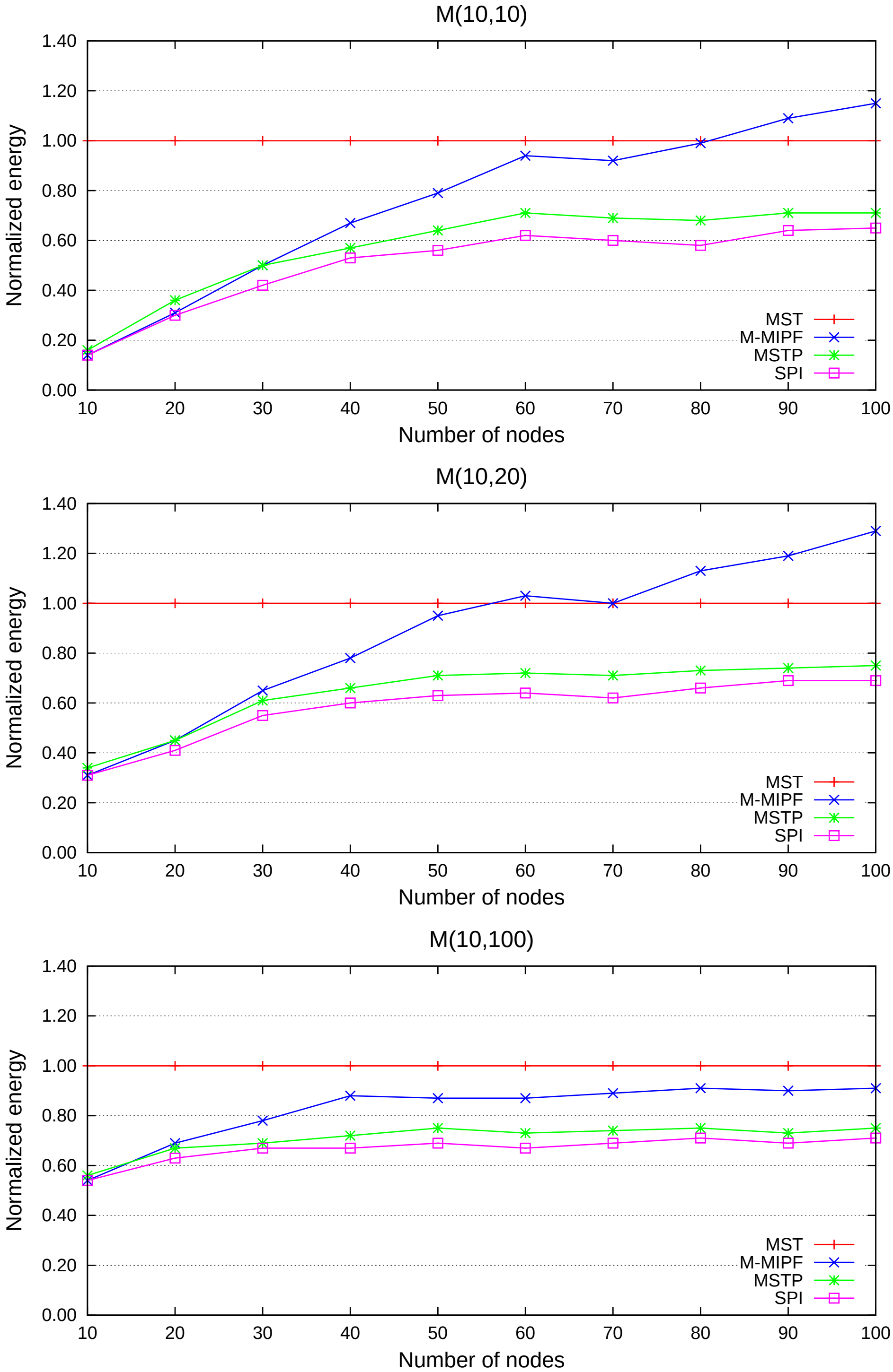

Figure 5.2: Normalized costs of algorithms for Multicast schemes $M(10, 10)$, $M(10, 20)$ and $M(10, 100)$ (Top to bottom). $\alpha = 2$.

situation decreases the performance gains obtained with more energy efficient algorithms and performance of these tree algorithms come closer to the performance of MST algorithm. With this multicast scheme again SPI algorithm performs best. MSTP algorithm has a similar cost performance with SPI algorithm. As a difference to other two multicast schemes discussed, for each sensor node number, M-MIPF algorithm has a better performance than MST algorithm. It is energy cost is never higher than the energy cost of MST algorithm, so normalized cost of M-MIPF algorithm does not exceeds 1 for any node number.

In Table 5.2, the average normalized costs of algorithms are listed for multicast schemes $M(10,10)$, $M(10,20)$ and $M(10,100)$. For each of these three multicast schemes, average values are calculated by taking the average of normalized costs for each different network topologies which are shown in Figure 5.2. Average normalized cost of MST algorithm is 1 for all multicast schemes. For multicast scheme $M(10,10)$, average cost of SPI algorithm is 0.5, which means it is two times more efficient than the MST algorithm. MSTP algorithm has an average cost of 0.57, which is 14% higher than the cost of SPI algorithm. Cost of M-MIPF algorithm is 0.75 for this multicast scheme, which is 50% more than the cost of SPI algorithm. For multicast scheme $M(10,20)$, SPI algorithm has the lowest normalized energy cost, which is 0.57. MSTP has 12% and M-MIPF has 52% more energy cost than the SPI algorithm for the same multicast scheme. The last multicast scheme in the table is $M(10,100)$. Again the least average cost algorithm is SPI. Its average normalized cost is 0.66. MSTP and M-MIPF algorithms have higher normalized costs that are 0.7 and 0.82. By the increase in the multicast group size, the performance difference between algorithms decreases. For this multicast scheme, MSTP algorithm has 6% and M-MIPF algorithm has 24% more energy cost than SPI algorithm. These values are lower when compared to other multicast schemes with same multicast group count. Last column of the table shows the average normalized costs of algorithms for three multicast schemes. SPI algorithm is the best of these four algorithms which has a normalized cost of 0.58. So it outperforms MSTP and M-MIPF algorithms in the range assignment process with these three multicast schemes having multicast group count of 10% of all node number.

For the evaluation of algorithms with a different set of multicast schemes, MST, MSTP, SPI and M-MIPF algorithms are executed for the multicast schemes $M(20,10)$, $M(20,20)$ and $M(20,100)$. In these multicast schemes, number of multicast groups are 20% of the node

Table 5.2: Average normalized costs of algorithms for multicast schemes $M(10,10)$, $M(10,20)$ and $M(10,100)$

Algorithm	**Average Normalized Cost**			
	$M(10,10)$	$M(10,20)$	$M(10,100)$	Total Average
MSTP	0.57	0.64	0.70	0.64
SPI	0.50	0.57	0.66	0.58
M-MIPF	0.75	0.87	0.82	0.81

number. On the other hand, multicast group sizes change for each multicast scheme. For the first scheme, size of multicast group is 10% of the node number. For the second and third schemes this ratio becomes 20% and 100%. Propagation constant is taken as $\alpha = 2$. The execution results of the algorithms are displayed in Figure 5.3.

In Figure 5.3, three graphics are displayed one for each multicast scheme. The top graphic is for the multicast scheme $M(20,10)$. This multicast scheme states that multicast group count is 20% of the node number and every multicast group has a size of 10% of the node number. SPI algorithm has a lower energy cost than the other algorithms for all node numbers with this multicast scheme. When the node size is smaller than 30, SPI, MSTP and M-MIPF algorithms have a similar performance. However, when node number exceeds 30, M-MIPF algorithm shows a dramatic increase in the energy consumption and its normalized cost becomes 1.4. Normalized costs of SPI and MSTP algorithms never take a value bigger than 0.8.

In the middle graphic we see the results for multicast scheme $M(20,20)$. The performance of the algorithms for multicast scheme $M(20,20)$ is similar to $M(20,10)$. In this scheme the number of multicast groups does not change, but size of the multicast groups increase and becomes 20% of all the nodes. SPI and MSTP algorithms are two most successful algorithms with this multicast scheme. SPI algorithm performs better than all the algorithms for each node number. Energy cost of M-MIPF algorithm is higher than the energy cost of MST algorithm for the network topologies that have more than 40 nodes. Its normalized value exceeds 1 in these topologies. Because the M-MIPF algorithm makes calculations for each of the multicast schemes separately and uses these results for the overall assignment.

The bottom graphic shows the energy cost of algorithms for multicast scheme $M(20,100)$. This multicast scheme denotes that all the multicast groups have 100 nodes, which means all

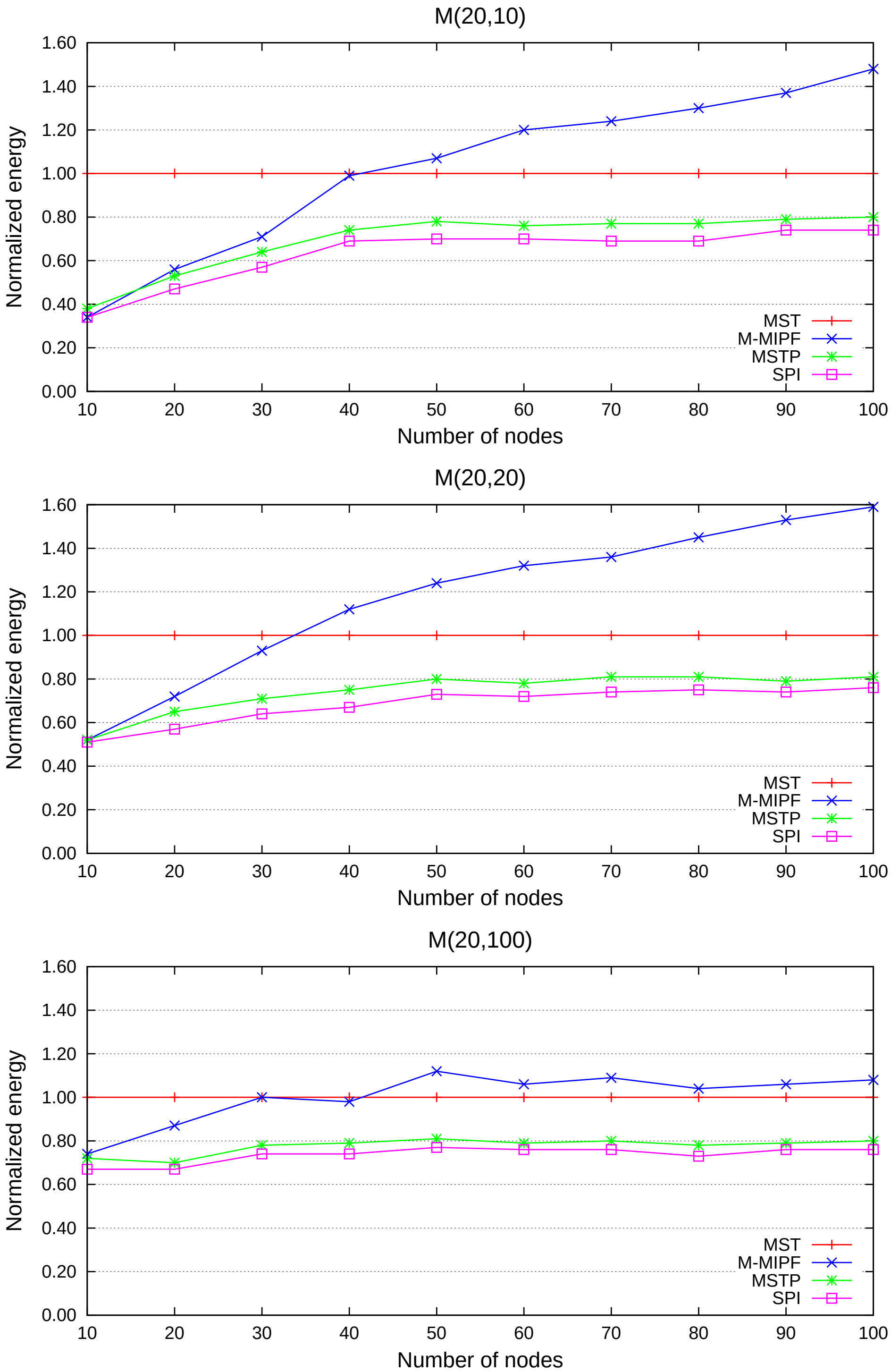

Figure 5.3: Normalized costs of algorithms for Multicast schemes $M(20, 10)$, $M(20, 20)$ and $M(20, 100)$ (Top to bottom). $\alpha = 2$.

of them are broadcasts. The count of multicast groups does not change. It is same with the other multicast schemes, which is 20% of the node number. With this multicast scheme, M-MIPF, SPI and MSTP algorithms have higher normalized values when compared to previous multicast schemes. SPI and MSTP algorithms have normalized values of 0.8 for almost all node numbers. M-MIPF algorithm has a normalized value less than 1 for small node numbers. When node number exceeds 30, its energy cost becomes larger than energy cost of MST algorithm. Again the SPI algorithm makes the most energy efficient range assignment to the sensor nodes for this multicast scheme.

In Table 5.3, the average normalized costs of algorithms are listed for multicast schemes $M(20,10)$, $M(20,20)$ and $M(20,100)$. For each of these three multicast schemes, average values are calculated by taking the average of normalized costs for each different network topologies which are shown in Figure 5.3. Average normalized cost of MST algorithm is 1 for all multicast schemes. For multicast scheme $M(20,10)$, average cost of SPI algorithm is 0.63, which is the smallest of all average costs for this multicast scheme. MSTP algorithm has a average cost 0.69, which is 9% higher than the SPI algorithm. M-MIPF algorithm has the highest normalized energy cost that is 1.02 for this multicast scheme. It is 2% more than the energy cost of MST algorithm. Second column of the table shows the average costs of algorithms for multicast scheme $M(20,20)$. SPI algorithm has the lowest normalized energy cost, which is 0.67. MSTP has 8% and M-MIPF has 76% more energy cost than the SPI algorithm for the same multicast scheme. M-MIPF algorithm has the worst performance. Its energy cost is 18% higher than the MST algorithm. The last multicast scheme in the table is $M(20,100)$. Again the least average cost algorithm is SPI. Its average normalized cost is 0.73. MSTP and M-MIPF algorithms have higher normalized costs, which are 0.77 and 1. The M-MIPF algorithm has the same performance with the MST algorithm in this multicast scheme. Last column of the table shows the average normalized costs of algorithms for three multicast schemes. SPI algorithm is the best of these four algorithms which has an average of 0.68. In the average, MSTP algorithm has 7% and M-MIPF algorithm has 54% higher energy cost than SPI algorithm. M-MIPF algorithm has 7% more normalized energy cost than MST algorithm in the average. This means range assignment with M-MIPF algorithm is more expensive than MST algorithm in the case of energy consumption. The most energy efficient range assignment is done with SPI algorithm for these three multicast schemes having multicast group count of 20% of all node number.

Table 5.3: Average normalized costs of algorithms for multicast schemes $M(20, 10)$, $M(20, 20)$ and $M(20, 100)$

Algorithm	Average Normalized Cost			
	$M(20, 10)$	$M(20, 20)$	$M(20, 100)$	Total Average
MSTP	0.69	0.73	0.77	0.73
SPI	0.63	0.67	0.73	0.68
M-MIPF	1.02	1.18	1.00	1.07

As a third different group of multicast schemes, MST, MSTP, SPI and M-MIPF algorithms are executed for the multicast schemes $M(100, 10)$, $M(100, 20)$ and $M(100, 100)$. In these multicast schemes, number of multicast groups are 100% of the node number. On the other hand, multicast group sizes change for each multicast scheme. For the first scheme, size of multicast group is 10% of the node number. For the second and third schemes this ratio becomes 20% and 100%. Propagation constant is taken as $\alpha = 2$. The execution results of the algorithms are displayed in Figure 5.4.

Top graphic in the Figure 5.4, shows the execution results of algorithms for the multicast scheme $M(100, 10)$. In this multicast scheme multicast group count is equal to the number of nodes in the network. All the multicast groups have a size of 10% of all nodes. This means all the nodes in the network are source nodes and makes multicast to 10 other nodes in the network. MST, SPI and MSTP algorithms have almost same performance. Normalized costs of SPI and MSTP algorithms are very close to 1. MST algorithm performs well with this multicast scheme because all the nodes make multicast and there are many packet transmissions between nodes so most of the radii assigned with MST algorithm are required in communication. M-MIPF algorithm has the worst performance. As the node number increases its normalized cost also increases. Its normalized cost is more than 2 if the node number is greater than 60.

Middle graphic is the normalized energy cost graphic for the multicast scheme $M(100, 20)$. In this multicast scheme, all the nodes are transmitters, but this time the size of the multicast groups are 20% of the node number. This graphic is similar to the previous one. For all node numbers from 10 to 100, normalized cost of SPI and MSTP algorithms are very close to 1. M-MIPF algorithm has the highest energy cost among these four algorithms. It is normalized cost is never less than 1 and it performs worse than MST algorithm. Because M-MIPF algorithm

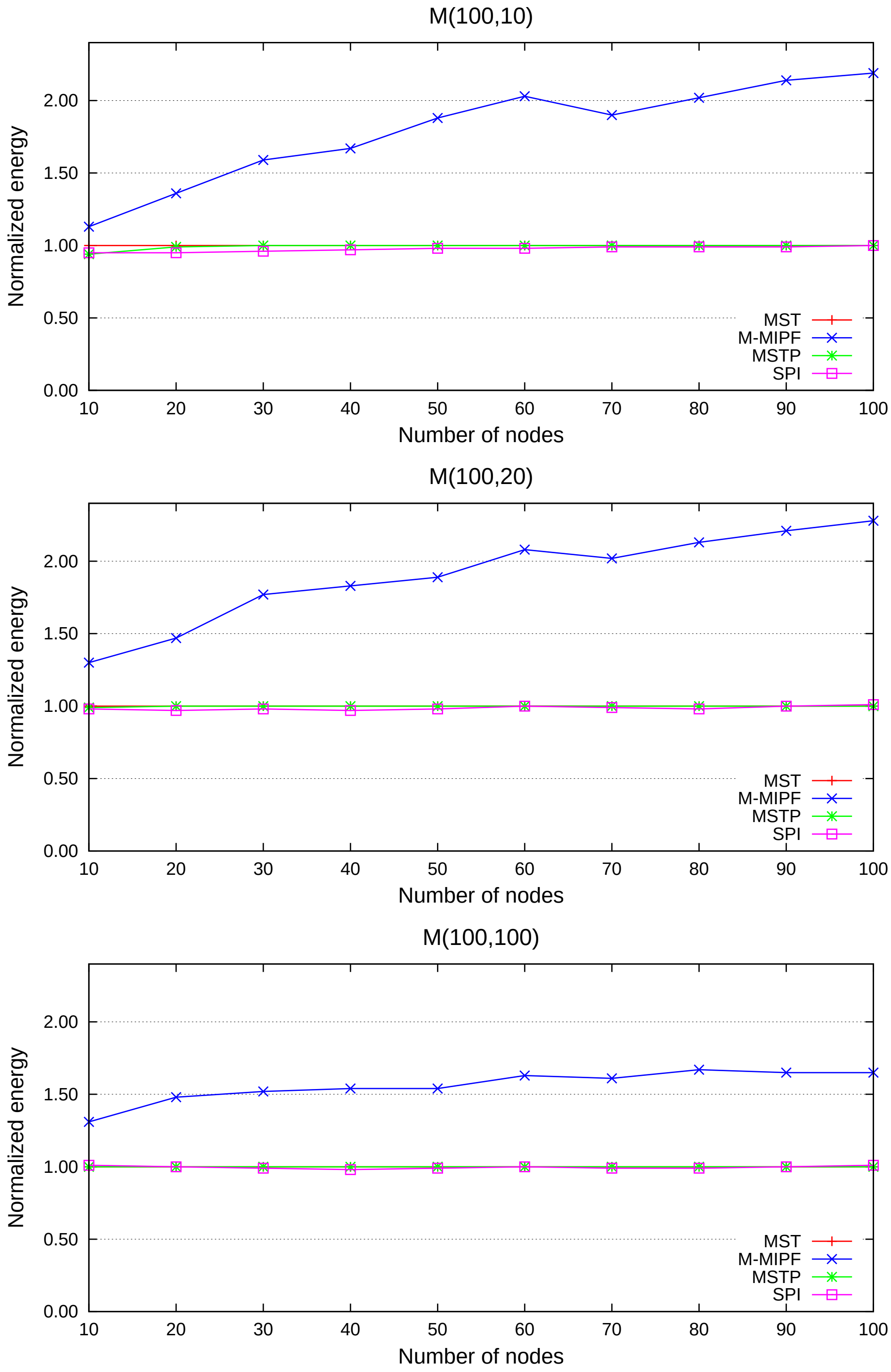

Figure 5.4: Normalized costs of algorithms for Multicast schemes $M(100, 10)$, $M(100, 20)$ and $M(100, 100)$ (Top to bottom). $\alpha = 2$.

makes radius assignment for each of the multicast groups separately and does not consider the advantage of solving multiple multicasting at the same time.

In the bottom graphic, we see the performance results of algorithms for multicast scheme $M(100, 100)$. This is a all-to-all communication. In this multicast scheme, all the nodes are the source nodes and each multicast group has a size of 100. There are 100 different broadcasts each from a different node. So there must be a transmission path between any two nodes in the network. Energy expenditure of M-MIPF algorithm is the highest among all the algorithms. However with multicast scheme $M(100, 100)$, its normalized cost is lower than other multicast schemes with 100 multicast groups. In this all-to-all multicast scheme, energy costs of SPI, MST and MSTP algorithms are very close to each other.

In Table 5.4, the average normalized costs of algorithms are listed for multicast schemes $M(100, 10)$, $M(100, 20)$ and $M(100, 100)$. For each of these three multicast schemes, average values are calculated by taking the average of normalized costs for each different network topologies which are shown in Figure 5.4. Average normalized cost of MST algorithm is 1 for all multicast schemes. For each multicast schemes, normalized average costs of SPI and MSTP algorithms are very close to 1. For multicast scheme $M(100, 10)$, average costs of MSTP and SPI algorithms are 0.99 and 0.97 respectively. They perform better than MST algorithm with 1% and 3% percents. M-MIPF algorithm has a 1.79 normalized average value. This is 79% higher than the cost of MST algorithm. Its performance also not good for the multicast scheme $M(100, 20)$. Average normalized value of M-MIPF algorithm is 1.89 in this multicast scheme. On the other hand, MSTP algorithm is 1% more efficient than the MST algorithm and SPI algorithm is 1% more efficient than the MSTP algorithm. It has a normalized average cost of 0.98. The third column of the table shows the average costs of algorithms for the $M(100, 100)$ multicast scheme. In this scheme all the nodes are broadcasting. The energy cost of the MSTP algorithm is exactly same with MST algorithm. MSTP algorithm performs a pruning over the output of the MST algorithm as discussed in the previous chapters. However in the case of a all-to-all communication, the pruning operation has no function. So MST and MSTP algorithms have the same performances. The SPI algorithm is 1% better than the MST and MSTP algorithms. It has an average normalized cost of 0.99. The M-MIPF algorithm performs better when compared to previous two multicast schemes. It is average value is 1.55. In the last column of the table the average values of multicast schemes are listed. These values are 0.99, 0.98 and 1.74 for algorithms MSTP, SPI and M-MIPF respectively. For these

Table 5.4: Average normalized costs of algorithms for multicast schemes $M(100, 10)$, $M(100, 20)$ and $M(100, 100)$

Algorithm	Average Normalized Cost			
	$M(100, 10)$	$M(100, 20)$	$M(100, 100)$	Total Average
MSTP	0.99	0.99	1	0.99
SPI	0.97	0.98	0.99	0.98
M-MIPF	1.79	1.89	1.55	1.74

multicast schemes, which the number of multicast groups is equal to the node number, again the SPI algorithm outperforms MSTP and M-MIPF algorithms.

We also execute algorithms with propagation loss constant $\alpha = 4$. A greater α means there is more loss in communication due to environmental conditions. So more energy is required to make a transmission between two specified nodes when compared to $\alpha = 2$ case. The execution results of algorithms with multicast schemes $M(10, 10)$, $M(20, 20)$ and $M(100, 100)$ and $\alpha = 4$ are displayed in Figure 5.5. In these multicast schemes, node number in the multicast groups and size of multicast groups are equal. Top graphic shows the performance of the algorithms for multicast scheme $M(10, 10)$. Number of multicast groups are 10% of all the nodes in the network in this multicast scheme. Multicast group size of each multicast group is also equal to 10% of the node number. In this case, SPI algorithm performs best among all of the algorithms. MSTP has a lower energy cost than M-MIPF algorithm. As a difference from the $\alpha = 2$ case, the M-MIPF algorithm performs better and its normalized cost never exceeds 1. This means it is efficient than the MST algorithm for all node numbers. For the multicast scheme $M(20, 20)$, change in the α value does not make a considerable effect on the performances of SPI and MSTP algorithms. Their normalized costs take a value close to 0.8 for networks having more than 50 nodes for each α value. However change in the α value has a big effect in the performance of M-MIPF algorithm. As we see in the Figure 5.3 the performance of M-MIPF algorithm diminishes as the node number increases. It has an average normalized cost of 1.5 for big node numbers. But for $\alpha = 4$ average normalized cost of M-MIPF algorithm never exceeds 1.2. The bottom graphic is for the multicast scheme $M(100, 100)$. In this multicast scheme, SPI, MST and MSTP algorithms have similar performances. Normalized costs of SPI and MSTP algorithms are very close to 1. The M-MIPF algorithm has a normalized cost of 1.2 for almost all node numbers. This means a better performance when compared to $\alpha = 2$ case. Because it is seen in Figure 5.4 that, for $\alpha = 2$, normalized energy cost is greater than 1.4 for small node numbers and exceeds 1.6 when node number is bigger than 60.

When we consider the $\alpha = 4$ and $\alpha = 2$ cases, we can say that the biggest performance difference is in the algorithm M-MIPF. It shows a better performance with $\alpha = 4$. When there is more propagation loss in the environment, nodes do not prefer to transmit their packets to far nodes, they make transmissions to closer nodes. So transmission count increases in the network and the power levels of the nodes decrease. Therefore, the ranges of nodes required to solve minimum energy multicast problem also decrease. M-MIPF algorithm merges these range values for each node. Merging smaller range values produces more efficient results. Thus the M-MIPF algorithm gains more than 10% performance when $\alpha = 4$.

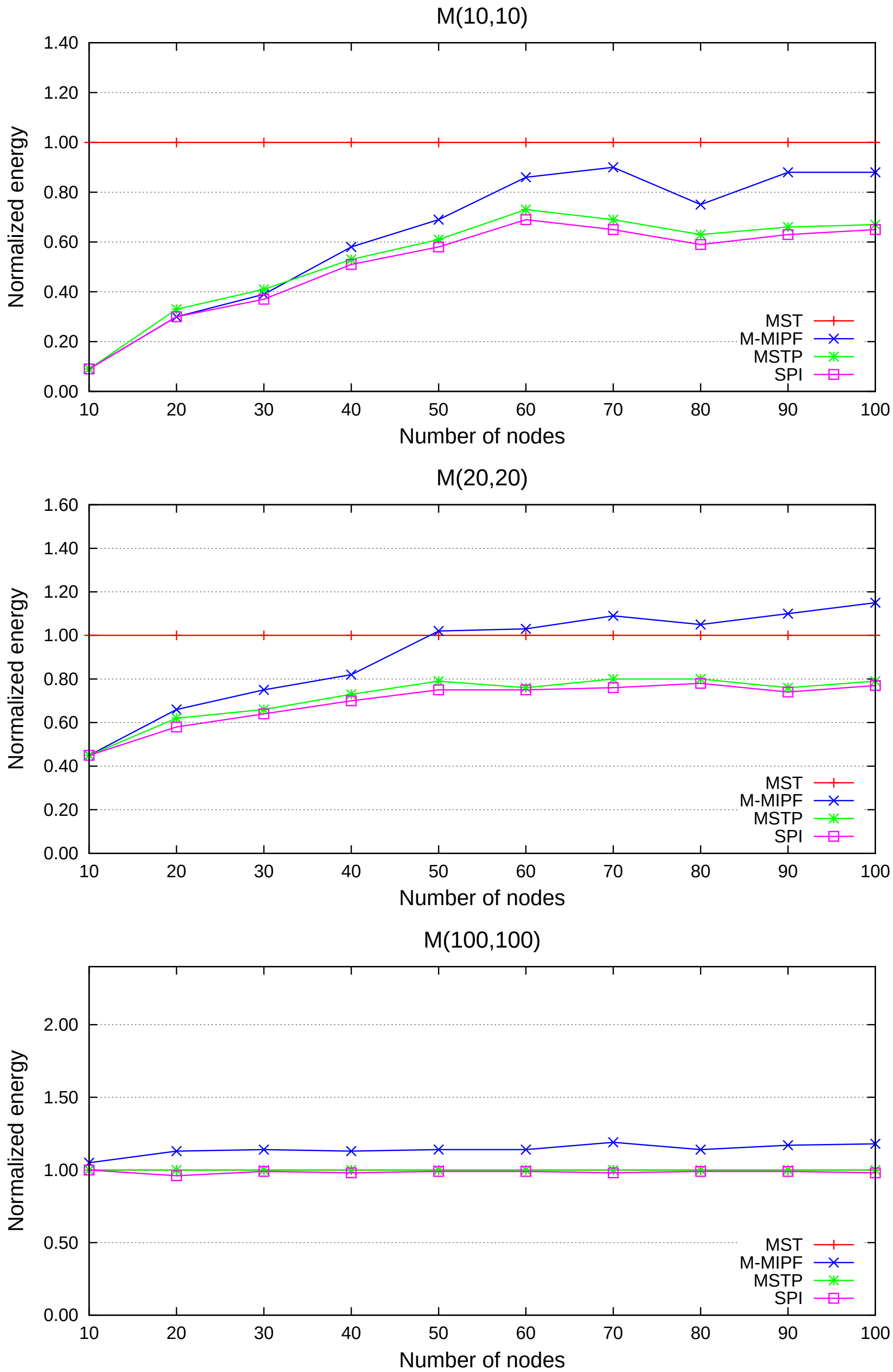

Figure 5.5: Normalized costs of algorithms for Multicast schemes $M(10,10)$, $M(20,20)$ and $M(100,100)$ (Top to bottom). $\alpha = 4$.

CHAPTER 6

GUI FOR ALGORITHM VISUALIZATION

In this chapter, we give detailed information about the graphical user interface, which is developed to run algorithms and visualize their behaviors. Figure 6.1 shows the main window of the application. Main screen has two different parts. Left of the window is the free space that is used to deploy network topologies. Right part contains the controls used to manage network topology, create multicast schemes and specify algorithm type. Algorithm type and multicast schemes are given as inputs to the system. Left panel is also used to visualize the execution results of the algorithms. After the range assignment, range values are displayed on the network topology.

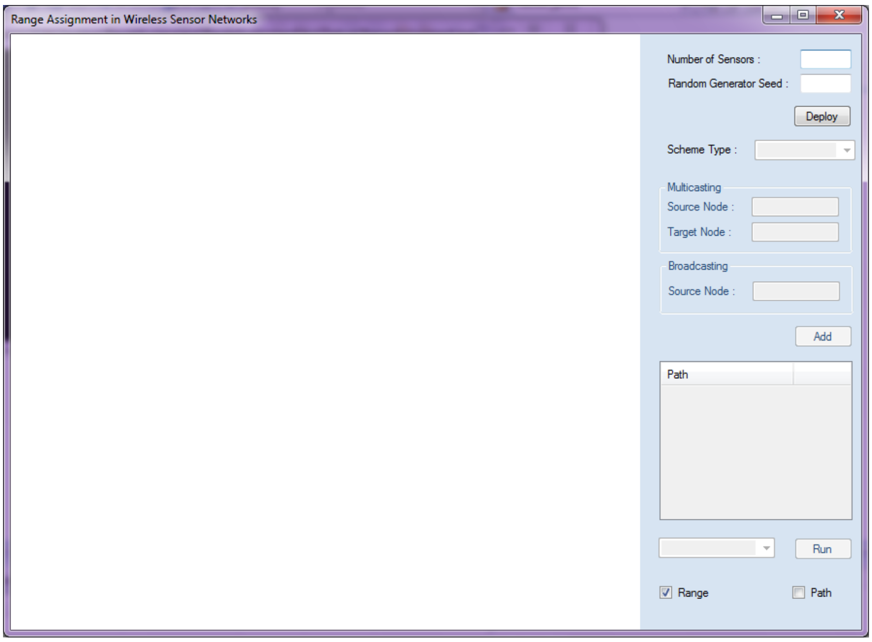

Figure 6.1: Main Screen.

In order to deploy a wireless sensor network topology user enters the node number of the network to the system. Then user specifies the seed value for random generation of nodes. Network instance is generated using node number and seed value. Seed value is required to generate the same network instance any time required. There is no restriction for the node number; any number of sensors can be deployed in the network. Figure 6.2 shows a network topology, which contains 30 nodes and has a seed value of 17.

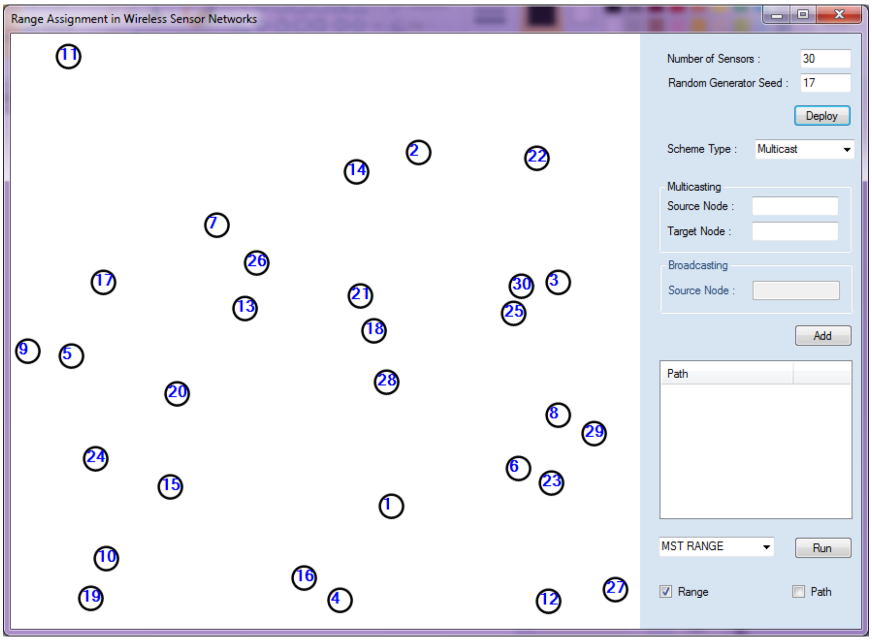

Figure 6.2: A sample network topology with 30 nodes and seed value 17.

After network topology deployment, user should enter the multicast groups to the system. There are two options to enter the multicast groups as input to the application. If a broadcast is the case, then user chooses the broadcast from the combo box to specify the type of the communication. Broadcast textbox is enabled and the source node is entered, which the broadcast starts. No target nodes are entered to the system because in broadcast data dissemination protocol, all the nodes except the source node are the targets. User clicks the "Add" button to append the specified broadcast group to the list. If the source node is s then this multicast scheme is added to the path list as $s \rightarrow *$. "$*$" denotes all the nodes in the network. So this means there is a packet transmission to all the nodes in the network from node s.

If a multicast group is to be added to the system, this time user selects multicast as communication type. Multicast source and target textboxes becomes enabled to enter the source of the multicast and the target nodes in the multicast group. User enters the source sensor node to the source textbox. Target nodes of the multicast group are entered to the target textbox together separated with "-". For instance, let m be a multicast group that contains sensor nodes s, t_1, t_2, t_3, t_4 and t_5. If source node is s and target nodes are t_1, t_2, t_3, t_4, t_5 then $t_1 - t_2 - t_3 - t_4 - t_5$ is entered to the multicast target textbox. Afterwards, user clicks the "Add" button in order to append the multicast group m to previously added multicast or broadcast groups. Multicast group is not directly added to the list, it is divided into paths and these paths are appended. For multicast group m, paths $s \rightarrow t_1$, $s \rightarrow t_2$, $s \rightarrow t_3$, $s \rightarrow t_4$, $s \rightarrow t_5$ are appended to the paths list. This path list shows the required paths for the communication in the wireless sensor network.

After all these broadcast and multicast groups are added to the list, the algorithm type is selected by the user. There are four algorithms, which are MST, MSTP, SPI and M-MIPF. User selects the algorithm that is going to be executed with specified path list and network topology. Then user clicks the "Run" button in order to execute algorithm and see the range assignment done by the algorithm.

There are two different views in order to visualize the range assignment. The first one is the default option "Range". The second one is the "Path" option. First option is used to see the ranges of each sensor node in the network after the range assignment. If the range of a node is r after the assignment process, then a circle is displayed with radius r. Its center is the location of the node. In Figure 6.3, we can see ranges of all the nodes in the network after the SPI algorithm is executed for a network of 30 nodes. There is just one broadcast from 1 to all the other nodes in the network.

The other option "Path" is used to see the range graph after the range assignment. Range graph of a wireless sensor network is discussed in the previous chapters. It is a very good way to understand how the algorithm behaves in the range assignment process. Range graph is a directed graph and an edge belongs to the range graph if and only if there is a connection between the source and the target. This means range of the source node is enough to cover the target node. Figure 6.4 shows the same network instance with the Figure 6.3, after the same range assignment process. Again there is just one multicast scheme which is a broadcast from the node 1. SPI algorithm is executed for range assignment. However this time range graph is displayed instead of just displaying the ranges of the sensor nodes.

One of the best properties of the range graph is providing a checking mechanism for the

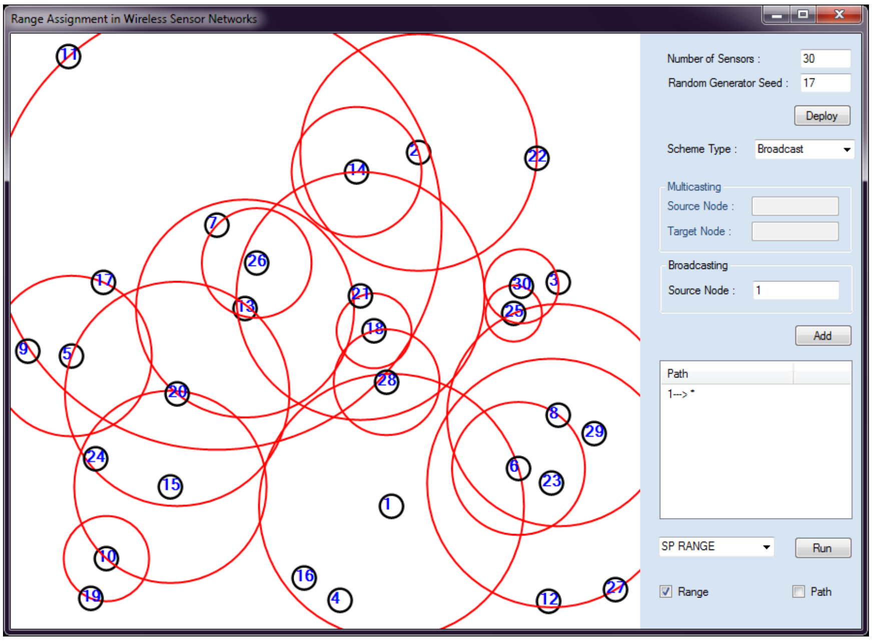

Figure 6.3: Node ranges of a sample range assignment. Algorithm is SPI and network has 30 nodes.

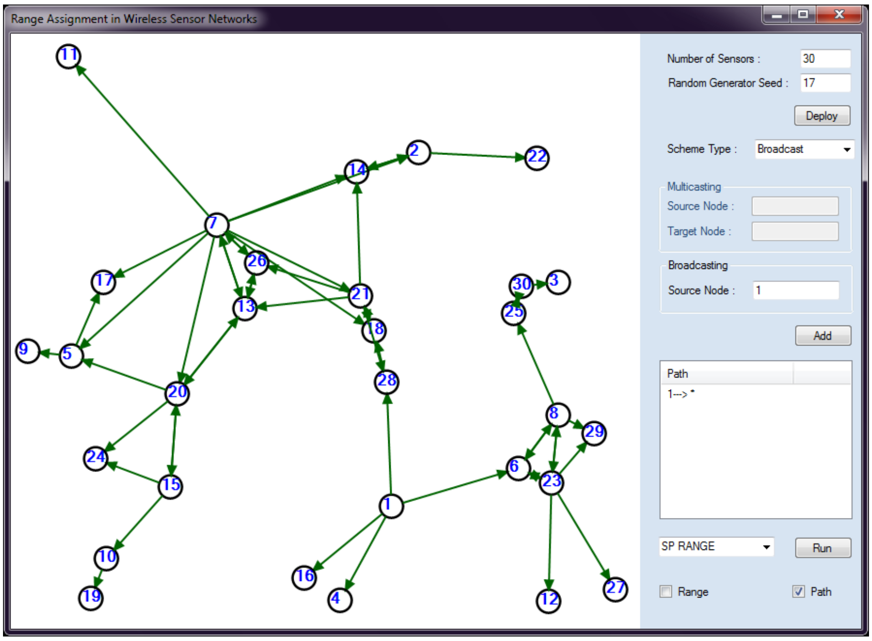

Figure 6.4: Path graph of a sample range assignment. Algorithm is SPI and network has 30 nodes.

assignment process after the algorithm is executed. Using the range graph, user can control if all the paths in the list are satisfied with this assignment. For example, for nodes s and t, if path $s->t$ is in the paths list, which means s is the source node and t is the target node and there is a data transmission from node s to node t, then there must be a path between these two nodes in the range graph. User can traverse and check for a path between nodes on the range graph.

”Range” and ”Path” options can be used at the same time in the application. User checks both of the checkboxes and both the circles denoting the ranges of the nodes and the range graph of the network are displayed. Figure 6.5 shows this alternative.

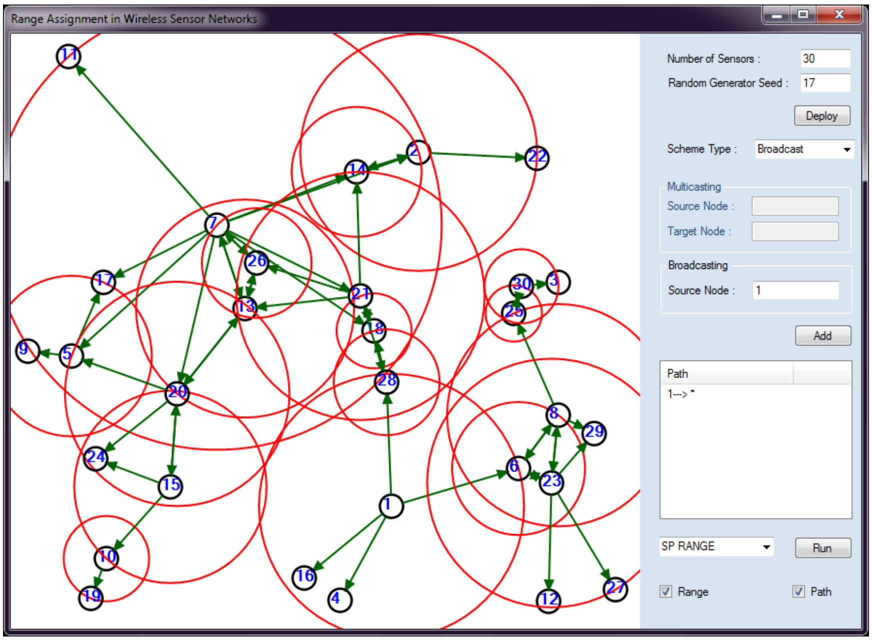

Figure 6.5: Path graph and node ranges of a sample range assignment. Algorithm is SPI and network has 30 nodes.

CHAPTER 7

CONCLUSION

In this thesis, we have defined the static range assignment problem and have proposed MST, MSTP and SPI algorithms as efficient heuristics to solve this problem. MST algorithm is developed as a baseline to other algorithms. It constructs a minimum spanning tree on the network and makes the range assignment using this minimum spanning tree. MST algorithm uses a naive approach and does not make a very effective assignment. A pruning procedure is applied with the MSTP algorithm over the MST algorithm to get better results. SPI algorithm is the third algorithm proposed, it is the most sophisticated one from these three algorithms. It uses a shortest path based approach and advantage of wireless medium in its design.

After describing the SRA problem and propose these algorithms, we have defined the multiple source multicasting in wireless sensor networks and have introduced the MEMSM problem as a special case of SRA problem. MEMSM problem is a generalization of MEM problem. It focuses on finding an energy efficient range assignment on sensor networks with multiple multicast requests. We have presented the M-MIPF algorithm as a baseline to the MEMSM problem. It modifies the well-known algorithm MIPF which is developed for MEM problem.

We have implemented a graphical user interface to run our algorithms and visualize their behaviors. Using this application it is possible to construct network instances with any node number. Furthermore, the multicast scheme and algorithm type can be specified as inputs to the system. The radius assignment and the range graph of the network could be displayed with this interface. We have executed the MST, MSTP, SPI and M-MIPF algorithms with different network sizes and various multicast schemes for evaluation. We have calculated their energy expenditures using a cost function.

In our evaluation we have used the normalized costs of algorithms according to the baseline

MST algorithm. We have generated different graphics for each multicast scheme. Evaluation results show that the SPI algorithm performs better than other three algorithms for almost all different network sizes and multicast schemes. MSTP and M-MIPF algorithms has a similar performance for small node numbers, however for bigger networks the MSTP algorithm outperforms the M-MIPF algorithm. Therefore algorithms developed for MEMSM problem, which are MSTP and SPI outperforms the algorithm M-MIPF, which is a modified version of MIPF algorithm that solves the MEM problem.

A multiple source multicasting is a possible scenario for wireless sensor networks and as a result of these experiments, we conclude that our algorithms MSTP and SPI are stable and energy efficient solutions to MEMSM problem. However our most sophisticated algorithm is SPI and it outperforms even the MSTP algorithm.

In our thesis we assume that all the nodes in the network use omni directional antennas. As a future work, our algorithms can be modified considering that some of the nodes might have directional antennas. Furthermore all of the algorithms are developed for the wireless sensor networks, which have stationary sensor nodes. Their designs can be improved for handling mobile sensor nodes in the network. In our cost calculations we consider only the energy spent for communication between nodes, for more accurate results the processing costs of nodes can also be taken into account.

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