M. Sc. Engineering Thesis

Energy Efficient Broadcasting in Wireless Ad hoc Networks

by

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The thesis titled "Energy Efficient Broadcasting in Wireless Ad hoc Network", submitted by Anindya Iqbal, Student No. 100505026P, Session October 2005, to the Department of Computer Science and Engineering, Bangladesh University of Engineering and Technology, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Computer Science and Engineering and approved as to its style and contents.

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This is to certify that the work entitled "Energy Efficient Broadcasting in Wireless Ad hoc Network" is the outcome of the investigation carried out by me under the supervision of Dr. Md. Mostofa Akbar in the Department of Computer Science and Engineering, Bangladesh University of Engineering and Technology, Dhaka – 1000, Bangladesh. It is also declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Abstract

Energy efficiency is a key issue in research area of wireless ad hoc and sensor network. Many wireless applications are inherently broadcasting based and here the energy consumption issue becomes even more pronounced. To address the problem numerous approaches are proposed throughout the last decade. Among these proposed schemes, construction of Connected Dominating Set (CDS) is well established. Research in this area has been fostered by incorporation of selectable directional antennas for the last few years. Reducing number of open antennas significantly conserves energy of wireless node as unnecessary transmissions or receptions may be avoided. In this thesis, we have devised a localized deterministic distributed heuristic to incorporate directional antennas to a CDS which ensures connectivity of wireless nodes and minimizes energy consumption for broadcasting. Considering the best case scenario, we calculated the gain of using our antenna with mathematical analysis. Here we found expected number of open antennas after applying our proposed approach decreases significantly. This decrease in number is inversely proportional to density of the network. This is supported by the simulation analysis. We simulated our proposed algorithm using Network Simulator–2 (NS-2) and found that it increases energy efficiency to a considerable extent. The performance is tested for several topologies with random number of nodes in terms of over all energy consumption of the network and also for the individual nodes which die first. We found in the simulation result that in both these criterion our proposed scheme performs better. However, performance improvement decreases with the increase in node density. Still for all the topologies consisting of different number of nodes (i.e. 25, 50, 100) that we used in our simulation, our approach performs considerably better compared to traditional approaches. We have also analyzed the possible case of local minima in case of routing over this backbone for specific types of network topologies.

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1. Introduction

1.1 Wireless Ad Hoc Networks

A wireless ad hoc network is a network without physical backbone. Every node may participate in packet forwarding in the absence of infrastructure. A communication session is established through single-hop radio transmission if sender and receiver are within transmission range of each other, otherwise intermediate nodes relay packets. Provision of flexible and quick deployment makes it a feasible choice for deployment in search and rescue, disaster relief and battlefield operation, monitoring of environmental properties in hazardous areas for constant, reliable monitoring. So apart from flexibility, robustness and reliability are also emphasized in researches of ad hoc networks. If technological issues are resolved, ad hoc networks could possibly revolutionize the communication world like the Internet did a decade ago [1].The research area includes topology management, routing, broadcasting, QoS, Medium Access Control (MAC) protocols, mobility, security, location privacy, etc. Mobile Ad Hoc networks (MANET) and Vehicular Ad Hoc Networks (VANET) are variations of ad hoc network which are receiving immense attention from researchers in recent times.

1.2 Energy Conservation in Wireless Ad Hoc Networks

Energy conservation is a key issue in all the work related to wireless ad hoc or sensor network. Each node participates in networking tasks by relaying messages, in order to provide a full coverage of the network. This implies a high energy consumption of the radio interface and thus limits the lifespan of the battery unit. The problem of energy consumption is very significant in this type of network as wireless nodes have limited energy. Many solutions have been proposed to decrease the energy consumption. Especially in case of broadcasting where message passing is frequent and abundant, energy of the participating nodes become matter of great concern. Moreover, because of inherent nature of the applications, broadcasting is an indispensably and frequently used operation in wireless ad hoc and sensor networks. So researchers have tried with various approaches to optimize energy conservation for broadcasting or flooding in such type of networks. Numerous works focused on construction of Connected Dominating Set (CDS) [2, 3, 4, 5]. CDS acts as a virtual backbone to compensate the absence of physical backbone infrastructure. CDS is defined and described in Section 2.1. In simple terms, we may say that CDS members are selected from all nodes in such a way that each non-CDS node is at most one hop away from at least one CDS member. Any node, having something to transmit, sends it to the nearest CDS member which then forwards to its CDS neighbors which continue the same operation. Thus the message traverses the CDS. Non-CDS nodes may sleep for some time and after waking up will receive anything destined to it from nearest CDS member which buffered it for the sleeping period. Thus message is transmitted throughout the network without constant involvement of all members. The non-CDS members save significant amount of energy by sleeping for a considerable time. CDSs are constructed in periodic manners based on relative position of nodes and available energy of individual node.

1.3 Motivation

In recent years, research in this area is very much influenced by use of directional antennas (also known as smart antenna) [6, 7, 8, 9, 10]. However, most of these works are globalized, i.e., either a centralized entity has to gather knowledge of the full topology and diffuse information to organize the network, or each node has to know the entire topology of the network to locally compute the broadcast spanning tree. This approach is not efficient in ad hoc networks, because of a high communication overhead. We are interested in localized protocols, which require only information about the neighborhood.

In one-to-all communication model (omnidirectional antenna), each node in the network can only change its transmission power. In one-to-one and one-to- many models, we assume that all the nodes have directional antennas. They can hear messages from every neighbor and send messages to every neighbor in unicast communications, by aiming the beam to the addressee. Compared with the omni-directional antennas, a smart antenna can form directional beams for both transmission and reception, which achieves better signal-to-noise ratio (SNR) and reduces interference. Apart from conservation of bandwidth and energy, benefits of directional antennas include capacity and range increases, supporting new services such as location estimation, better security, and reduced multipath propagation [8]. Reducing number of open antennas significantly conserves energy of the node concerned and that is the main motivation of using this type of antenna model here.

1.4 The Problem and Objective

Our problem is to find out an energy-efficient broadcast scheme for wireless ad hoc network. Broadcasting is used for transmitting information to all nodes in a network. Any node starts broadcasting with a special destination address. Every node forwards any received message to all direction throughout this event. Therefore, it causes transmission of huge number of messages, resulting in consumption of good amount of energy. Nodes in an ad hoc network equipped with directional antennas may keep some antennas closed to conserve energy during broadcasting. However, keeping antennas closed may hamper full delivery of message. That is, some nodes may become disconnected and will not receive broadcast message causing the main purpose unachieved.

Our goal is to find a set of directional antennas of the nodes that must be open in the ad hoc network so that (1) reachability is maintained for full delivery of message from any node in the network and (2) the total number of open antennas in the network is minimized. This will conserve energy of the nodes in a wireless ad hoc network.

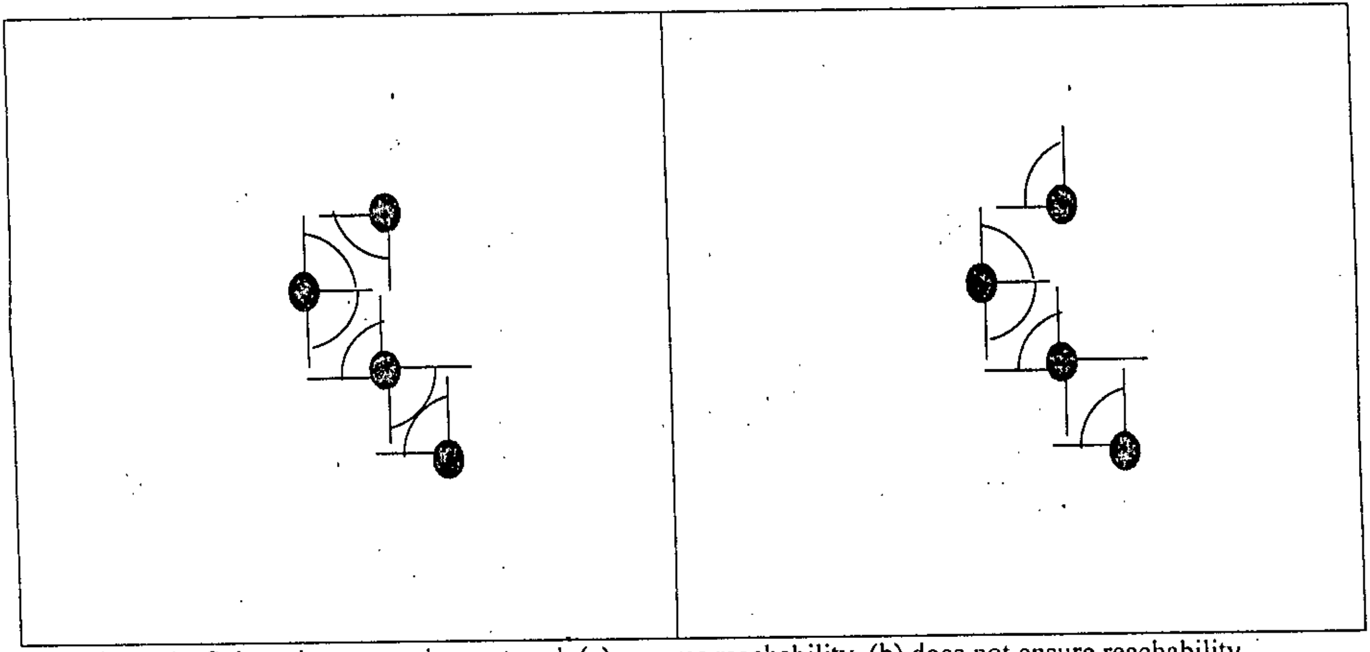

Figure 1: Selected antennas in a network (a) ensures reachability, (b) does not ensure reachability.

In Figure 1, we show such two networks with selected open antennas where (a) shows an example maintaining reachability whereas (b) does not maintain reachability of the top two nodes.

1.5 Main Focus

In this research, we have incorporated directional antennas to a well established CDS construction algorithm [1] to further reduce energy consumption. We developed a heuristic to select set of directional antenna ensuring CDS members' connectivity and coverage of non-CDS members. The selection is based on the information of two hop neighbors received during CDS construction phase. We have also analyzed the possible case of local minima in case of routing over this backbone for specific types of network topologies and discussed a potential solution. We simulated our proposed algorithm using Network Simulator–2 (NS-2) and found that it increases energy efficiency to a considerable extent. The performance is tested in terms of over all energy consumption of the network and also for the individual nodes which die first.

1.6 Organization of the Thesis

The rest of the thesis is organized as follows. Section 2 deals with preliminary ideas on CDS and directional antenna model. Section 3 introduces related work of other researchers. The description and analysis of our distributed algorithm is given in section 4. Section 5 discusses simulation result. Section 6 concludes with direction to future work.

2. Preliminaries

Connected Dominating Set (CDS) is a widely used approach for energy conservation in wireless ad hoc and sensor network. Research in this area has been fostered by incorporation of selectable directional antennas for the last few years. We have used these two concepts in proposed scheme. Here we discuss the basics of CDS and different directional antenna models with their respective characteristics.

2.1 Connected Dominating Set (CDS)

It may be assumed that all nodes in a wireless ad hoc network are distributed in a two dimensional plane having equal maximum transmission range. In other words, in the unit graph model, two nodes can communicate if and only if their distance is R, where R is the transmission radius, equal for all nodes. Two hosts within range of each other can communicate, and are said to be neighbors. Then the topology can be modeled as a Unit Disk Graph (UDG), a geometric graph in which there is an edge between two nodes if and only if their distance is at most one (see Figure 2)[2].

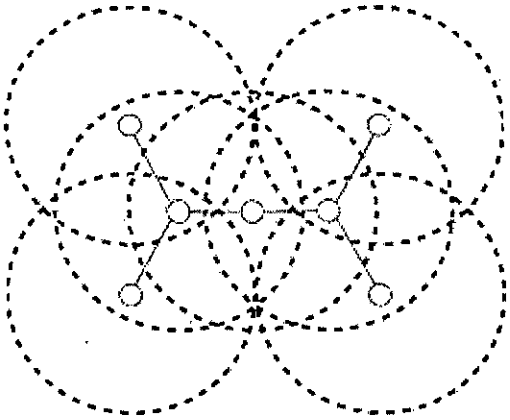

Figure 2: Unit Disk Graph represents wireless ad hoc network.

The backbone formation can be considered to be a problem of determining a CDS from corresponding UDG. A dominating set (DS) of a graph G = (V, E) is a subset of V such that each node not in the subset is adjacent to a node in the subset. A connected dominating set is a DS which induces a connected sub graph [2]. The task of finding a minimum CDS in an ad hoc network is NP-hard [1, 2, 3]. However, in an ad hoc network with high chances of link failures and topology changes due to mobility, constructing a minimum CDS is not necessary. Some redundancy in the backbone in fact increases reliability of the network and makes the backbone maintenance easier [1].

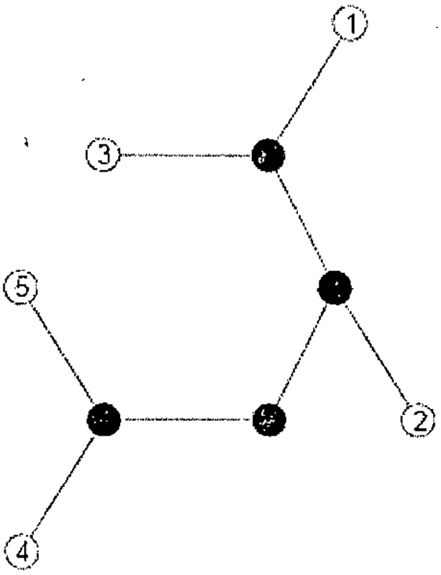

Figure 3: Example of a CDS.

A CDS is shown in Figure 3 where the nodes numbered from 1 to 5 are at most one hop away from any CDS member. CDS members have to participate constantly in data forwarding process while non-CDS members periodically spend some time in power-saving mode. A good CDS construction algorithm concentrates on allowing as many nodes as possible to turn their radios off.

2.2 Directional Antenna Model

Two techniques are used in smart antenna systems that form directional transmission/reception beams: switched beam and steerable beam [11, 12]. Switched beam systems use fixed antenna patterns to transmit to or receive from specific directions. A simplified and yet popular antenna model for those systems is ideally sectorized [12, 13, 14], as shown in Figure 4a. The effective transmission range of each node v is equally divided into k non-overlapping sectors. Each node can switch on one or several sectors for transmission or reception. For example, to transmit to nodes u and w, node v can switch on both sectors 1 and 2. Aligned sectors are assumed in most existing protocols; that is, sector i (i = ¼, 1, 2, . . ., k) on all nodes point to the same direction. Steerable beam systems can adjust the bearing and width of a beam to transmit to or receive from certain neighbors. The corresponding antenna mode is an adjustable cone [9], [13], as shown in Figure 4b. Most protocols also use omnidirectional transmission and reception modes. However, due to the different antenna gains in directional and omnidirectional modes, the effective transmission range in omnidirectional mode (represented by the dashed circle in Figure 4a) is usually smaller than the area jointly covered by all directional transmission ranges. Both antenna models assume regular beam shapes for ease of computation, especially for estimating directions of neighbors based on location information. In practical systems, however, antenna beams have irregular shapes due to the existence of side lobes (as shown in Figure 4c), which causes inaccurate estimations. This work uses an antenna model based on very few assumptions, such that the proposed directional broadcast protocol does not rely on a specific antenna type. Figure 4d illustrates this model. Each node can transmit and receive in k directions with id's 1, 2, . . ., k.

In switched beam systems, each direction corresponds to a fixed antenna pattern. In steerable beam systems, a small set of beam settings, with different bearings and uniform or non-uniform widths, can be selected to cover a given neighborhood area. The shape of each direction does not have to be regular or aligned. For example, in Figure 4d direction 1 of node v is a cone, while direction 1 of node w is a ring. The only constraint is that each direction must have a fixed size and shape. Directions can also be overlapping, as shown by the shadowed area between directions 1 and 2 of node v. Unlike in the ideally sectorized model, each node can only transmit in one direction at any moment. Multidirection transmission is emulated via sweeping [12], i.e., multiple directional transmissions in consequent time slots. Although this method incurs extra delay, it can be easily implemented on most directional antenna systems. In addition, single direction transmission has much longer transmission distance than omnidirectional or multidirection transmission. This enhanced per-hop transmission distance is essential for finding a shortest path with the minimum hop count in an on-demand route discovery process. There are two reception modes: the omnidirectional mode, where a node can receive from all neighbors, and the directional mode, where a node receives from neighbors in a single direction.

In our approach we have used the generalized simple model 360/k which is a preferred choice of hardware designers because of simplicity of design and implementation. However, simulation is done with different values of k.

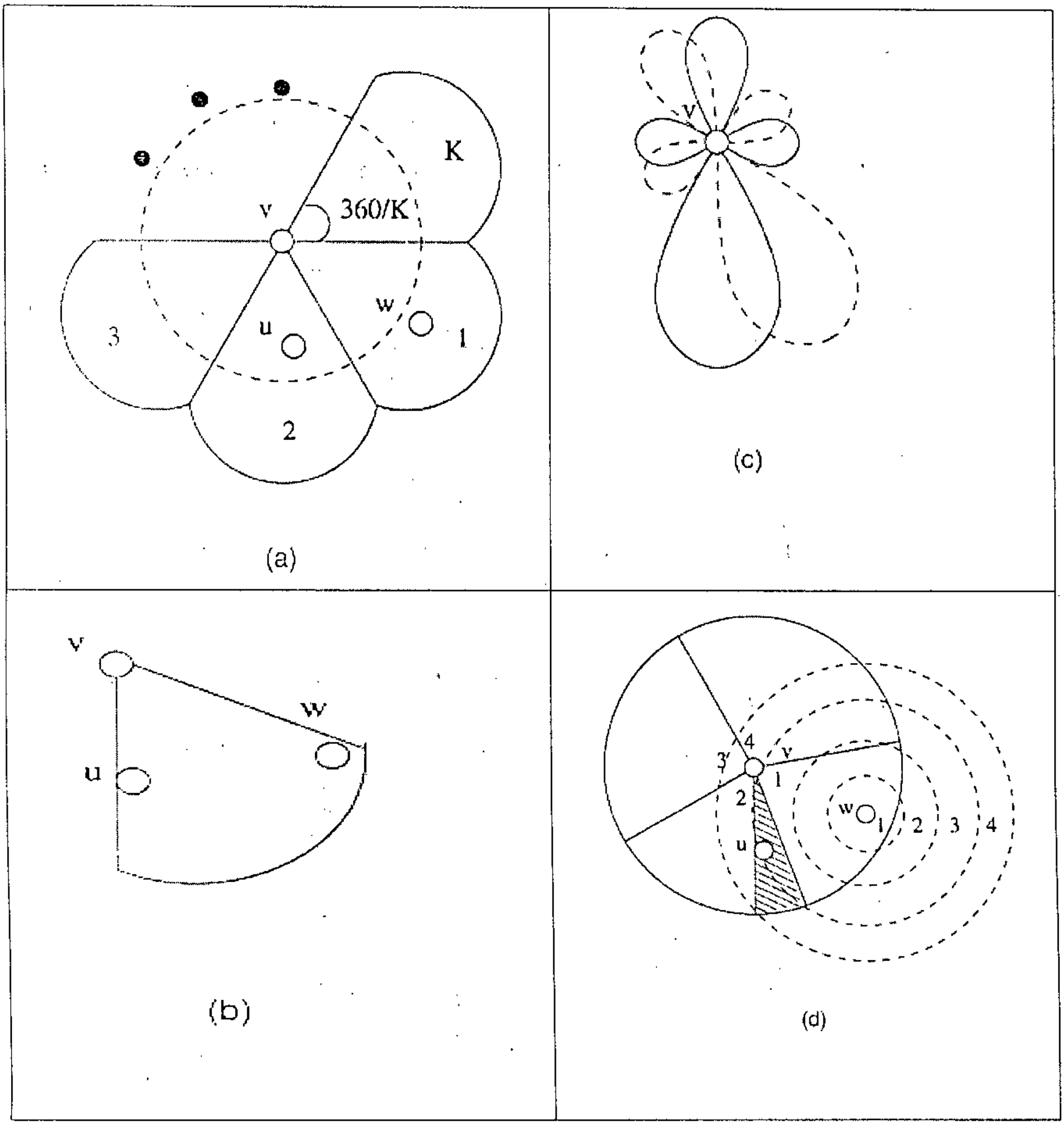

Figure 4: Directional antenna models. (a) Ideally sectorized, (b) adjustable cone, (c) irregular beam pattern, and (d) a general model

3. Related Work

Since energy conservation is a key issue in wireless ad hoc network, researchers have followed different approaches to find an optimum solution for energy efficient broadcasting. Construction of Connected Dominating Set (CDS) is one of these approaches which attracted the attention of researchers for more than a decade. Another direction was cluster-based approaches where cluster heads have the responsibility of receiving and forwarding messages on behalf of member nodes by having extra power. However, our work does not follow this approach. Use of omni-directional and directional antennas with ad hoc and sensor devices has added new dimension to this research area. Countless efforts are being made to optimize energy consumption by using optimum number of antennas. Some of these approaches are probabilistic, some are deterministic, some use global information, some are localized. Here we describe some notable efforts in this regard.

3.1 CDS Based Approaches

Numerous works have been done to develop heuristics for construction of Minimal Connected Dominating Set (MCDS). [2] and [3] by Alzoubi and Wan are widely cited where the approach was to construct a dominating set and then make the component connected. Another most representative algorithm proposed by Wu and Li [4] initially constructs a CDS and then tries to reduce size. It was popular for its simplicity but had the disadvantage of having approximation factor equals $n/2$, instead of a constant. SPAN [5] is a distributed, randomized algorithm where nodes make local decisions on whether to sleep or join a forwarding backbone as a coordinator. Each node makes its decision on an estimate of how many of its neighbors will benefit from its being awake and the amount of energy available to it. Ikiz, Ogale and Garg [1] proposed an energy conserving backbone based routing technique for ad hoc networks. Our scheme extends the power saving scheme in SPAN with variable history based sleeping times. We also take into consideration mobility issues and ensure that, if possible, coordinators in the backbone will periodically change to maximize overall life of the network.

3.2 Different Types of Antenna-based Approaches

Application of directional antenna to reduce broadcast redundancy is relatively new approach. Most of the work followed probabilistic approach in the beginning [12, 14]. However, localized deterministic approaches are considered to be better [8]. Choudhury and Vaidya [4] proposed to reduce the broadcast redundancy in relaying routing request by switching off transmissions in directions toward the last forward node. Hu et al. [14] presented three schemes to improve the broadcast efficiency: on/off directional broadcast, relay-node-based directional broadcast, and location-based directional broadcast. In the first scheme, each node switches off its transmission beams toward known forward nodes. In the second and third schemes, each forward node designates only one neighbor as a forward node in each direction. In the third scheme, the selection of forward nodes is aided by location information. The relay-node-based directional broadcast applies directional antennas to neighbor-designed, one-hop neighbor based broadcast. The location-based directional broadcast attempts to approximate the (directional) additional coverage area while the location-based scheme at [15] provides a linear estimate of the additional coverage area. A few localized deterministic schemes were proposed by Stojmenovic et al. [13] and Shen et. al. [15]. The approach presented in [13] considers that each node forms a single beam with an adjustable width to reach all neighbors that are not covered by transmissions of known forward nodes. Location information is used to calculate the angle and orientation of the transmission beam. Dai and Wu [8] proposed a deterministic localized broadcast protocol using directional antennas, where directional self- pruning (DSP) is developed to reduce transmission directions.

3.2.1 Spanning Tree Based Protocols

The protocol BIP [16] is an omni-directional protocol which constructs a spanning tree based on energy consumption. For each step, the algorithm decides if the best solution is to create a new transmission beam or to increase the range of an existing transmission. The directional version [17] of BIP proposes two protocols. The first protocol is called RB-BIP (Reduced Beam BIP) and uses one-to-one communication model (with minimal angle) to join neighbors in the BIP tree. The second protocol is D-BIP (Directional BIP). In this protocol, each node can send only one message by broadcast, the protocol has to decide, at each step, if it is better to extend the beam and/or the range of a node, or to add a new communication beam. This decision is made with respect to the energy consumption. Hence the natural tendencies of D-BIP are to favor transmissions with large radii and beam angles, to avoid retransmissions by every node.

3.2.2 Neighboring Graph Based Broadcast Protocols

Cartigny et. al. have proposed RBOP (RNG Broadcast Oriented Protocol) [18], a localized broadcast protocol for reducing energy consumption with omnidirectional antennas. Each node constructs an RNG (Relative Neighborhood Graph) [12] subgraph from its neighboring graph. RNG has several advantages: each node needs to know only its neighbors and the distance between them. Furthermore, the required information can be gathered in a localized manner. The protocol RBOP consists of a Neighbor Elimination Scheme (NES) [19, 20] limited to RNG neighbors where a transmitting node adjusts its communication range to reach all non-covered RNG neighbors. In an NES protocol, each node eliminates from the list of neighboring nodes for retransmission of those nodes that are supposed to receive the same packet received by given node one or more times in previous retransmissions. A directional version of this protocol, called DRBOP (Directional RNG Broadcast Oriented Protocol), has been proposed in [21]. This algorithm proposes that each node sends a separate unicast message to each of its non-covered RNG neighbors. The protocol is efficient and gives results reasonably close to the centralized MST protocol because DBIP protocol has an average neighbor degree of 1.99 (which is average degree of a minimal spanning tree), and DRBOP has average degree about 2.6, as found by experiments. Li et al. [22] have proposed LMST (Local Minimum Spanning Tree) which offers a better graph reduction than RNG, with a degree of approximately 2.04. The LMST method is simple: each node applies MST algorithm on its local topology (the list of neighbors and links between them), and keeps only links that are present in LMST of both endpoints. The LMST algorithm is localized and offers a lower subgraph degree than RNG (in fact, LMST is a subgraph of RNG). Both LMST and RNG require 2-hops information to be computed. Experimentally, the LMST degree is approximately 2.04, which is closer to the BIP degree (1.99) than RNG (2.6).

3.2.3 Probabilistic Approaches

Probability-based schemes allow a node to forward a packet with certain probability *p* when it receives the packet for the first time. Ni et al. [11] introduce the broadcast storm problem and propose various probability-based and area-based solutions. Krishnamachari et al. [24] and

Sasson et al. [25] studied probability-based schemes with a focus on its bimodal (phase transition) behavior. In particular, for finite networks that are large enough, a phase transition phenomenon is observed in [24].

Cartigny and Simplot [26] propose several density aware schemes that combine probability and distance based (to be defined next) schemes, where probability is calculated from density and/or neighbor information and distance is approximated from neighbor information. Haas et al. [27] present GOSSIP, a family of protocols, which extend the probabilistic scheme in the following ways: first, GOSSIP introduces the parameter k such that nodes located within k hops from the source of the broadcast always forward the packet. It then introduces the parameter m to represent the number of packets received from neighbors, which is equivalent to the counter-based scheme. GOSSIP further uses two forwarding probabilities p_1 and p_2, instead of a single probability p as in the former two schemes, where $p_2 > p_1$. A packet is forwarded with p_2 if m is below some threshold; otherwise, it is forwarded with p_1. Results from percolation theory are applied to the broadcast schemes to explain their bimodal behavior.

Shen et al. [15] devised directional versions of probabilistic protocols like GOSSIP. Here each node switches off transmission in a direction, if all neighbors in this direction are also neighbors of a known forward node. They introduced the use of directional antennas to the broadcast problem and presented counter, distance, and neighbor-based schemes for use with directional antennas, in addition to the probability based schemes studied by GOSSIP. They have also differentiated bond percolation from site percolation, and map probability-based omnidirectional and directional broadcast into site and bond percolation, respectively.

3.2.4 Random Assessment Delay (RAD)-based Schemes

Random Assessment Delay (RAD)-based schemes, including counter-based, distance-based, and position- based schemes, is also proposed by Ni et al. [11]. The basic idea is to collect duplicate packets received from neighbors for a random period of time after the first packet is received, and discover knowledge from these packets to make a forwarding decision. For the counter-based scheme, the knowledge is the total number of received duplicates, and the packet is forwarded if it is below a counter threshold. For the distance-based scheme, the knowledge is the minimum distance from the node to the sender of these packets, which is an estimation of the node's additional (broadcast) coverage area, and the packet is forwarded if it is over a distance threshold. The location-based scheme leverages the precise location information to provide a more accurate estimation of the additional coverage area.

3.2.5 Neighbor Based Schemes

Neighbor-based schemes avoid broadcast storm by forwarding the packet to a smaller subset of nodes while maintaining comparable coverage [28]. The selection of nodes is mostly based on the knowledge about a node's two-hop and, possibly, one-hop neighbors. Based on whether the forwarding decision is made by the sender or the receiver, the schemes can be further classified [28] into neighbor designed [29, 30, 31, 32] and self-pruning [28, 33, 34, 35]. Lim and Kim [30] propose a simple neighbor-based scheme in which a node includes its one-hop neighbor list, available via neighbor discovery, inside its broadcast packet. A node receiving a packet compares its neighbor list to the sender's neighbor list. If the receiving node could not reach any additional node, it would not forward the packet. Nasipuri et al. [36] present two protocols that apply directional antenna to minimizing the query flood by forwarding the (query) packet in the sectors along the direction of the destination.

4. Incorporation of Directional Antennas to CDS

In this research work, we have incorporated directional antennas to a well established CDS construction algorithm [1] to further reduce energy consumption. We developed a heuristic to select set of directional antenna ensuring CDS members' connectivity and coverage of non-CDS members using locally available information. In this chapter we are going to discuss our principle, depict the proposed algorithm, describe the algorithm with some example and also theoretically compute the gain of our algorithm considering best case. We have also proved the rechability of our algorithm and analyzed the possible case of local minima if this approach is applied in routing.

4.1 Principle of Our Approach

The approach proposed in [1] is used to construct CDS for omni directional antennas. We have presented an additional post processing approach to incorporate directional antennas to further reduce energy consumption. During construction of CDS phase for omni directional antennas, every node will exchange message consisting of id, coordination status, neighbor list and remaining energy of its neighbors. As a result, after this construction phase, every node will have two-hop neighbor information. Based on this local information, minimal set of selectable directional antennas will be chosen where relative position of other nodes and remaining energy of eligible nodes will be considered and connectivity of all nodes is ensured.

First the CDS members, termed as *coordinators* in SPAN [5], will select the antennas which must be open to ensure CDS connectivity and which solely cover some non-CDS members. Then CDS members send messages by offering coverage to the non-CDS nodes mentioning their eligibility in terms of other potential coverable nodes in that region and their remaining energy. A non-CDS node responds by accepting the offer from a CDS node based on the list of coverable nodes and remaining energy.

The activities performed by the nodes can be depicted in the following diagram:

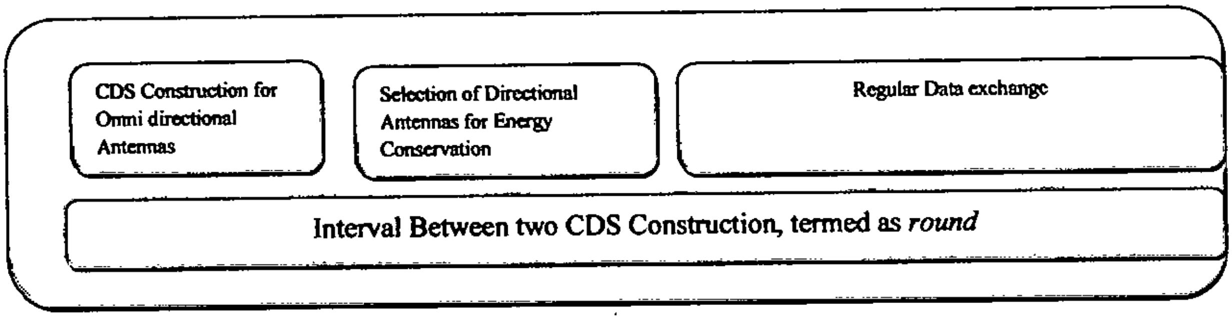

Figure 5: Activities within a round.

new CDS accommodates the topology changes due to mobility of ad hoc nodes. For the construction of CDS a distributed algorithm runs in every node. There must be threads running to perform different activities in each node. These are demonstrated as follows:

Table 4.1.1: Running threads in every node.

CDS construction thread

```
While True do
    wait until round expires
     1. CDS_construction_SPAN()
     2. Antenna_Seletion_Rule1()
     // selects the directional antennas which
     must be kept open
     3. Antenna_Seletion_Rule2()
     // selects the directional antennas
     considering remaining energy of multiple
     coordinator nodes
end do
```

Data Message processing thread

```
While True do
    wait until notification of message receipt
     If RECEIVE_DATA_MESSAGE
         Forward message to open directional
         antenna regions
    endif
end do
```

The procedure *CDS_construction_SPAN* ( ) constructs a CDS according to the algorithm proposed in [1]. Detail of this algorithm is described in Appendix-A.

The methods *Antenna_Seletion_Rule*1( ) and *Antenna_Seletion_Rule*2( ) determine the directional CDS to conserve energy in an ad hoc network. We present these two algorithms in this chapter with detailed explanation, analysis and examples.

4.2 Directional Antenna Set Selection

Selection of directional antennas in an optimal way for a round which will ensure connectivity and coverage of the whole network based on locally available information is a non-trivial task. The non-triviality may be described with the following example.

In 360/k model of directional antenna, if $k = 4$, we may denote the directions in anti-clockwise manner as shown in Figure 6. Here, upper left antenna of U_1 is written as A_{11}, then A_{12}, A_{13} and A_{14} will follow anti-clockwise orientation. U_1, U_2 are coordinators or CDS members and v_1 is a non-coordinator waiting to be covered by any directional antenna of a coordinator. Possible covering nodes for v_1 are U_1 and U_2. To be more specific A_{13} and A_{22} are the two directional antenna regions where v_1 resides. Now we may denote this phenomenon as Cover (v_1) = { A_{13}, A_{22}}.

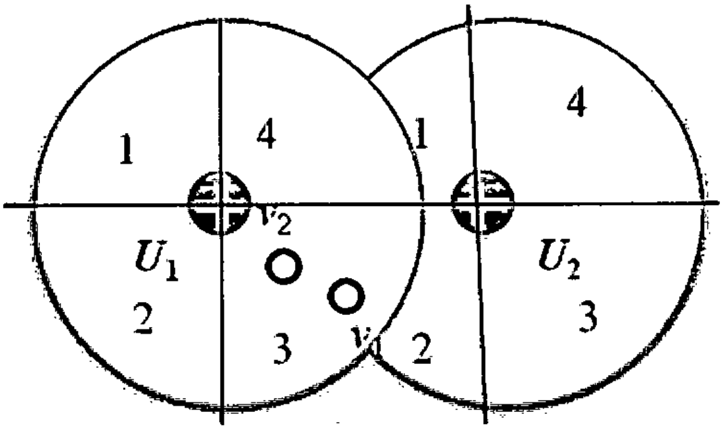

Figure 6: Selection of directional antenna.

Now, let us assume that in an expanded network (not shown in figure), there will be other non-coordinators v_2, v_3, v_4, etc.

Their coverage possibility may be shown as

Cover (v_1)={A_{13}, A_{22}, A_{34}, A_{42}}

Cover (v_2)={A_{23}, A_{21}, A_{44}, A_{32}}

Cover (v_3)={A_{13}, A_{23}, A_{31}, A_{32}}

Cover (v_4)={A_{13}, A_{22}, A_{34}, A_{42}}

From the list shown above, we see that if directional antennas covering the region A_{22}, A_{44} and A_{13} are kept open, all 4 non-coordinators will be covered. Our goal is to select such a set. Here we present some basic principles in selecting antennas:

- ➢ If some non-coordinators have unique coverage, that is, it can be covered by only one coordinator neighbor, the covering neighbor must be chosen.
- ➢ If there are more than one coordinator neighbors offering coverage to a non-coordinator, some other issues need to be considered.
- ➢ When a non-coordinator node receives offer from multiple coordinators, it will see whether the offering coordinator has some other non-coordinator to be covered in that region. For example, in Figure 6 we see A_{13} has two nodes v_1 and v_2 to cover in its region. Note that, v_2 does not have offer from any other coordinator as it is outside the coverage area of other coordinators. So U_1 must keep A_{13} antenna open. This message will reach v_1. Hence, v_1 will ignore the offer from A_{22}. In this way, every non-coordinator has to decide the acceptability of each offer.
- ➢ If such consideration of position of nodes and does not deduce decision, i.e. multiple coordinators offer with equal priority, remaining energy of the coordinators will be counted. All possible cases are considered in our described algorithm and examples are discussed with the help of Figure 7, 8 and 9.

4.3 Antenna model, Methods, Messages and Our Procedures

Our selected antenna model is ideally sectorized 360/k model. This is a generalized model where value of k may vary. More granularities (higher number of k) may increase number of closeable antennas, especially for network topologies with higher number of nodes. Still from hardware designers' point of view simpler antennas are preferred as processing overhead is reduced.

The following methods and message sending and receiving methods are used in our proposed algorithm:

Methods:

getLNN(n,α): Here n is a coordinator node and α is a directional antenna. This method returns a list of non-coordinator neighbors from antenna region α who are not covered yet by any coordinator. We may term the list as *List of Non-covered Non-coordinators* or *LNN* in short.

selectMostEligibleNode(n, request_list): Here n is a non-coordinator node. This method returns the coordinator with the highest eligibility to cover a non-coordinator neighbor. The coordinator is selected from available covering requests.

Messages:

must_open_message(n): This is an instruction from coordinator n to the receiver nodes to open the receiving antenna.

already_covered_message(n): This message indicates that a particular non coordinator n is covered already by a coordinator so that no other node wants to cover it later.

covering_request_message(n, α, List, E_r): This message expresses intention of a coordinator n to cover a non coordinator through antenna α by mentioning the *List* (this list contains non-covered non-coordinators of that antenna region) and the remaining energy of n *as* E_r. Non-coordinator nodes receive this message from coordinator neighbors and decide whether to accept it.

reply_message( ): This is the response to *covering_request_message* from a non-coordinator returning its best coordinator neighbor that wants to cover it.

Procedure *Antenna_Selection_Rule*1 (*n*)

```
// This procedure implements the antenna selection rules in the first phase. Here $n$ denotes the node where the algorithm is currently being executed
if $n$ is a coordinator
    Step 1:
    n.must_open = $\{\emptyset\}$ //must_open denotes list that contains antennas which should be open
    Step 2:
    for each antenna $\alpha$ do
        if $\alpha$ region has a coordinator neighbor $n_c$
            OR
        $\alpha$ region has a non-coordinator neighbor $n_x$ such that
        coordinator_neighbor($n_x$)=$\{n\}$
            //$n$ is the only coordinator_neighbor of $n_x$
          n.must_open=n.must_open $\cup \{\alpha\}$
        endif
    end for
    Step 3:
    for each $\alpha \in$ must_open do
        open antenna $\alpha$
        send must_open_message($n$) to all the nodes in the range of open antennas
        //messages are sent once through all open antennas so that overhead power consumption for multiple messages is reduced.
    end for
    Step 4:
    for each antenna $\alpha$ do
        if must_open_message($n_r$) is received
        // a must_open_message from $n_r$
          open antenna $\alpha$ for receiving direction
        endif
    end for
endif
if $n$ is a non-coordinator
```

```
        Step 1:
        for each antenna $\alpha$ do
              if must_open_message($n_r$) is received
                   open antenna $\alpha$
                   send already_covered_message ($n$) through all antennas
              endif
        end for
endif
end Procedure
```

Procedure ***Antenna_Selection_Rule2* (*n*)**

// This procedure implements the antenna selection rules in the second phase where number of coverable nodes and remaining energy of requesting coordinator neighbors are considered. Here n denotes the node where the algorithm is currently being executed.

```
if $n$ is a coordinator
        Step 1:
        for each antenna $\alpha$ do
              $LNN_\alpha$ =getLNN($n$, $\alpha$)
              if $LNN_\alpha \neq \varnothing$
                         send covering_request_message ($n$, $\alpha$, $LNN_\alpha$, $E_r$) in the direction of $\alpha$
              end if
        end for
        Step 2:
        wait until end(reply_message_threshold) //This statement halts execution until the timer
        for reply_message_threshold expires. Actually, it waits for the receipt of reply_messages.
        for each antenna $\alpha \notin$ must_open do
              $List\_Reply_\alpha$ = List of reply_message( ) received from antenna $\alpha$ from a non-
              coordinator neighbor
                        if $n \notin List\_Reply_\alpha$
                              close antenna $\alpha$
                        endif
```

```
        end for
endif
if n is a non-coordinator
        Step 1:
        request_list = ø
        Step 2:
        wait until end (covering_request_threshold) //This statement halts execution until the timer for covering_request_threshold expires. Actually, it waits for the receipt of all covering_request_messages.

        for each antenna $\alpha$ do
            if covering_request_message(n, $\alpha$, List, $E_r$) is received
                request_list = request_list $\cup$ covering_ request_message (n, $\alpha$, List, $E_r$)
            endif
        end for

        Step 3:
                $N_{max}$= selectMostEligibleNode(n, request_list)
        Step 4:
        send reply_message ($N_{max}$) to all directions
endif
```

end Procedure

```
Procedure selectMostEligibleNode (n, request_list)
        most_eligible_by_LNN=findNodeWithLargestLNN(request_list)
        most_eligible_by_$E_r$=findNodeWithMaxEnergy(request_list)
        for each l $\in$ request_list do
                if l.LNN $\underline{\in}$ most_eligible_by_LNN.LNN
                        return most_eligible_by_$E_r$;
                else
                        return most_eligible_by_LNN;
```

```
            endif
        end for
end Procedure
```

4.4 *Examples of CDS construction and antenna selection rules*

4.4.1 LNN Construction

List of Non-covered Non-coordinators (LNN) is prepared by each coordinator node for every antenna and consist of non-coordinator neighbors which are not covered by antenna selection rule 1.

In Figure 7, U_1, U_2 and U_3 are coordinators. v_1 and v_2 are non-coordinators. We may analyze how U_1 and U_3 will construct LNN for third and fourth antenna region respectively. Here LNN (A_{34})={v_2} and *LNN*(A_{22})={v_2}. Although v_1 resides in A_{34} region, it does not contribute to *LNN* (A_{34}) as v_1 is already covered by A_{13} and A_{31} following *Antenna_Selection_Rule*1.

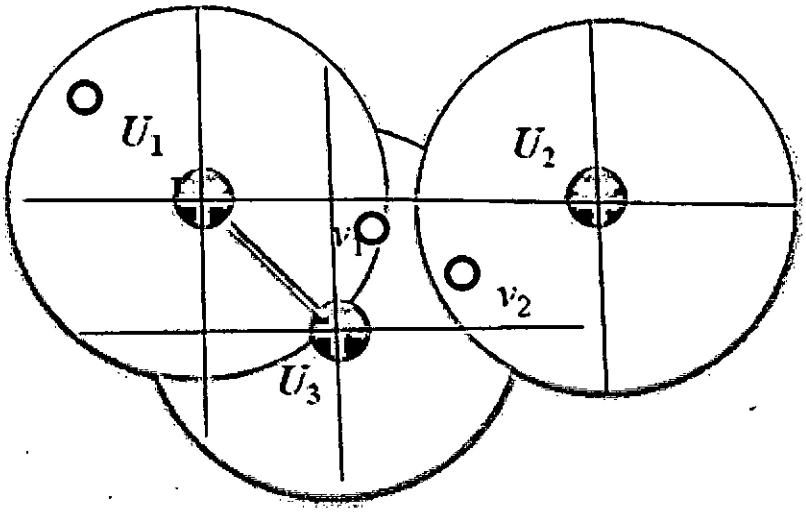

Figure 7: LNN construction.

4.4.2 Antenna Selection Rule 1

In the following example we shall see coordinator nodes must keep some antennas open to ensure coverage of non-coordinators which are not covered by any other coordinator. The antennas which connect coordinators must also be kept open. These types of antenna selection are ensured by antenna selection rule 1.

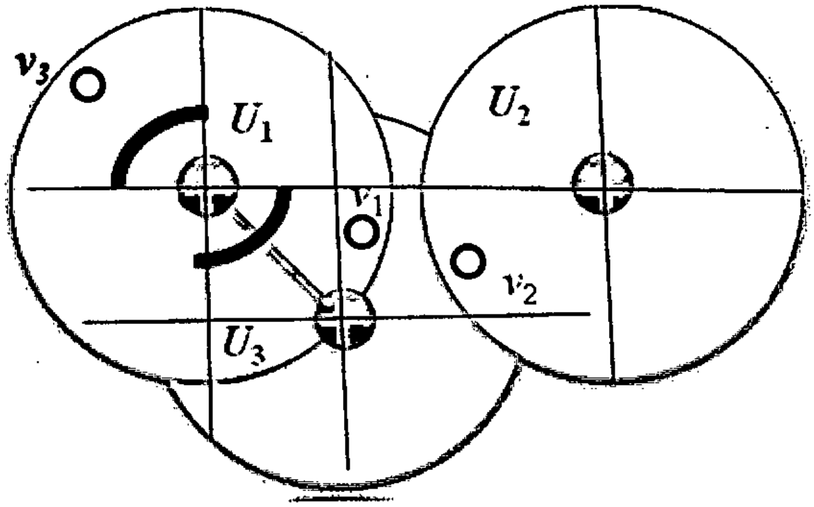

Figure 8: Example of must open antennas.

In Figure 8, U_1, U_2 and U_3 are coordinators. v_1, v_2 and v_3 are non-coordinators. Coordinator U_1 must open antenna A_{11} to cover non-coordinator v_3 and must open antenna A_{13} also for ensuring connectivity with coordinator neighbor U_3. Each coordinator node may take this compulsory decision according to antenna selection rule 1 described earlier.

4.4.3 Antenna Selection Rule 2

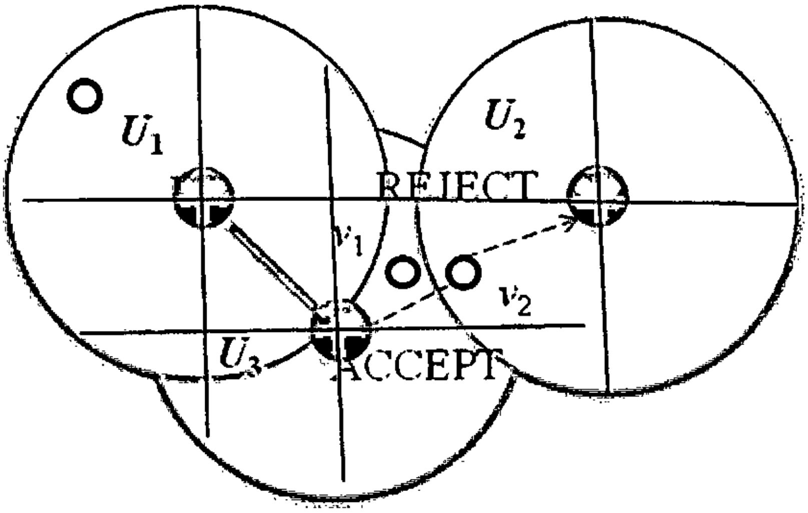

Figure 9: Example of Antenna Selection by Rule2.

In Figure 9, U_1, U_2 and U_3 are coordinators. v_1, v_2 and v_3 are non-coordinators. U_2 and U_3 are willing to cover v_2. So they will send LNN to corresponding regions A_{22} and A_{34} and these will be received by non-coordinators v_1, v_2. Here $LNN\ (A_{34})=\{v_1,v_2\}$ and $LNN(A_{22})=\{v_2\}$. That is, $LNN\ (A_{34})$ is superset of $LNN\ (A_{22})$. So both v_1 and v_2 will accept U_3 as its coordinator.

Here is an example of a random network topology shown in Figure 10 where coordinators are seen to have saved 13 out of their 36 antennas according to our proposed algorithm. Here dark curves imply the direction of coordinator nodes for which antenna may be closed.

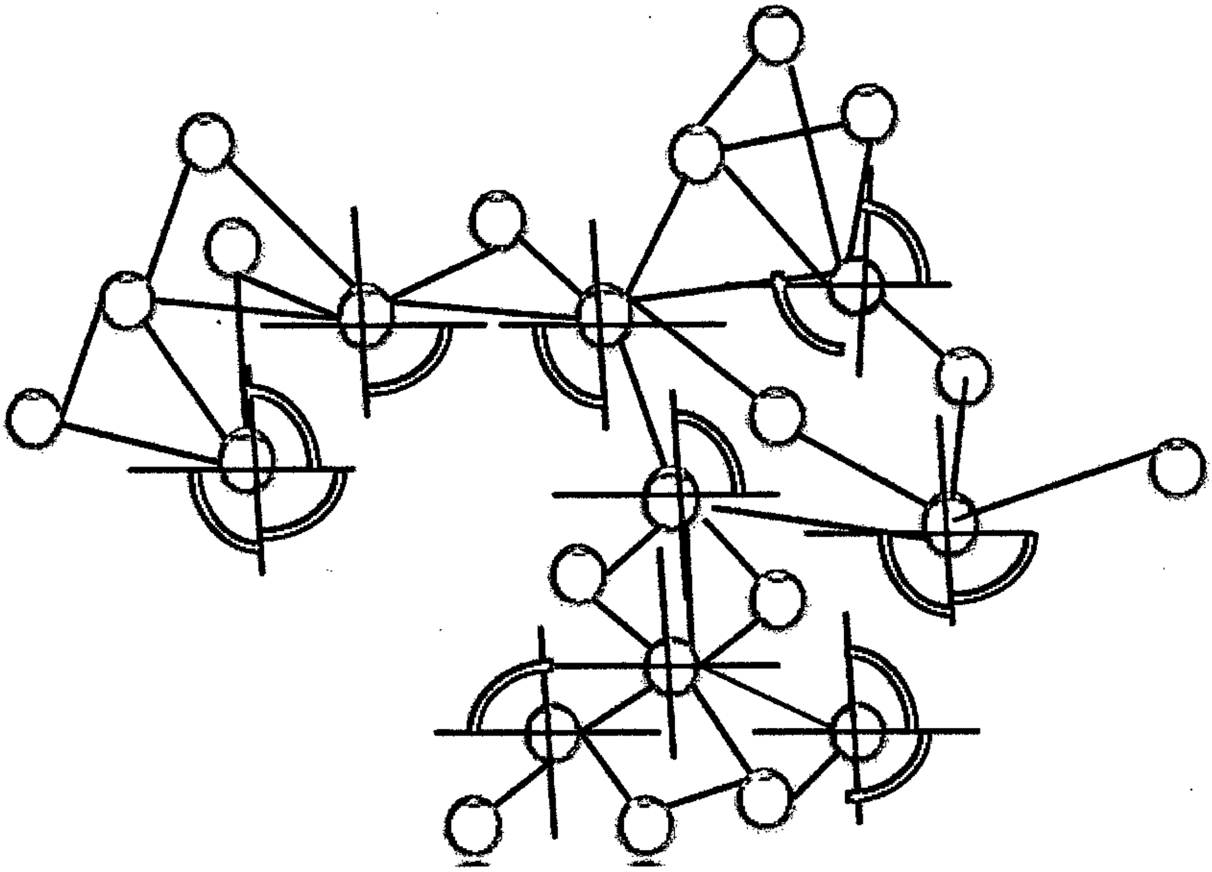

Figure 10: Example of selected antenna regions in a random topology.

4.5 Expected Number of Open Antenna

Let there be n nodes in a topology. Let n_c be the total number of coordinators and n_x be the total number of non-coordinators. Again, assume R be the whole region around a coordinator node and α be an antenna of that node. Let r be the radius of transmission range of a node.

Then, region covered by a directional antenna of model $360^0/k$ is $\dfrac{\pi r^2}{k}$.

Let P (a coordinator has at least one coordinator neighbor in its direction α) = 1- P (all other coordinators are outside region in direction of α) = P_c

Now, P (all other coordinators are outside region in direction of α) = $\dbinom{n_c - 1}{n_c - 1}(P(S))^{n_c - 1}(P(F))^0$

where S = a coordinator is outside region in direction of α

and F= a coordinator is not outside region in direction of α

Hence $P(S) = \left(1 - \dfrac{\pi r^2}{kR}\right)$

Then, P (all other coordinators are outside region in direction of α) = $\left(1 - \dfrac{\pi r^2}{kR}\right)^{n_c - 1}$

So, P_c = 1- $\left(1 - \dfrac{\pi r^2}{kR}\right)^{n_c - 1}$

Again, P (a coordinator has at least one non-coordinator neighbor in direction of α that has no other coordinator neighbor)

= P(a coordinator has at least one non-coordinator neighbor in direction of α)×P(that non-coordinator has no other coordinator neighbor) $=P_1 \times P_2 = P_s$

P_1= 1- $\left(1 - \dfrac{\pi r^2}{kR}\right)^{n_x}$

P_2= P (all other coordinators are outside range of non-coordinator) $= \begin{pmatrix} n_c - 1 \\ n_c - 1 \end{pmatrix} (P(S))^{n_c - 1} (P(F))^0$

where S = a coordinator is outside range of a non-coordinator

and F= a coordinator is not outside range of a non-coordinator

Hence $P(S) = \left(1 - \frac{\pi r^2}{R}\right)$

Then, P_2= $\left(1 - \frac{\pi r^2}{R}\right)^{n_c - 1}$

So, P_x= $\left\{1 - \left(1 - \frac{\pi r^2}{kR}\right)^{n_x}\right\} \times \left(1 - \frac{\pi r^2}{R}\right)^{n_c - 1}$

Hence, P ($a \in must\_open$) $= P_C + P_X$.

Total number of antennas of all coordinators is kn_c.

So expected number of antennas of coordinators that must be open is $E_c = kn_c (P_C + P_X)$.

Again each non-coordinator must open at least one antenna to be covered by a coordinator.

Hence expected number of antennas of non-coordinators that must be open is $E_x = n_x$.

Some coordinators have to keep other antennas open according to procedure antenna selection rule 2 described earlier. These open antennas depend on the instant position of non-coordinator nodes and remaining energy of coordinators. Let us assume this number is θ.

Hence the ratio of number of open directional antennas after and before applying our approach may be presented as $(E_c + E_x + \theta)/(kn_c + kn_x)$.

Considering the best case scenario, where all non-coordinators will be covered by the must open antennas, value of θ is 0. Then the ratio of number of open directional antennas after and before applying our approach is $(E_c + E_x)/(kn_c + kn_x)$.

Now, we may derive the following table for the best case scenario described above. Here we assume that a network has approximately one third nodes as coordinators and coordinators. We also assume the whole region R=1000×1000, radius of transmission range of a node r = 250 and number of directional antennas in a node k =4.

Table 4.5.1 Ratio of open antennas for networks with different number of nodes.

Total number of nodes	**Estimated number of coordinators**	**Ratios of the open antennas** $=(E_c + E_x)/(kn_{c+} kn_x)$
25	8	0.31
50	16	0.35
100	33	0.43

Theorem 1: Antenna Set Selection algorithm achieves full reachability.

Proof: Let s be the source node for a particular broadcast. By Contradiction, suppose u be a node that does not receive this broadcast.

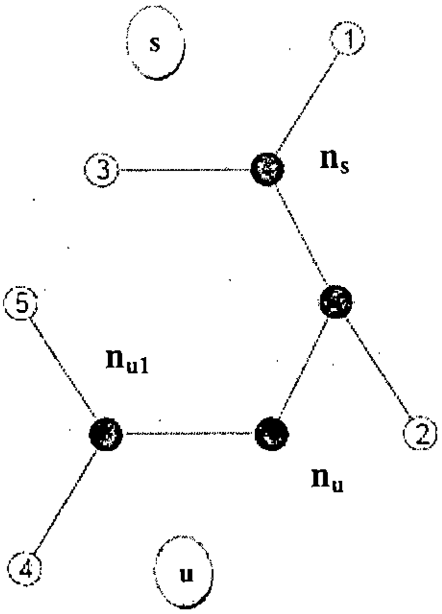

Figure 11: An example of full coverage.

By definition of CDS, s has at least one coordinator neighbor. Let s has only one coordinator neighbor n_s. Then s will be covered by n_s according to antenna selection rule 1. If s has more than one coordinator neighbor, it will be covered by at least one of them according to antenna selection rule 2.

So n_s will receive the message and forward it to nearest CDS member and ultimately every node in CDS will receive it [5]. So, if u is a CDS member, it will receive the message.

If u is not a CDS member, it will be covered by at least one CDS member. If u has only one CDS neighbor, it will be selected as coordinator by execution of antenna selection rule 1. If u has more than one coordinator neighbor, for example, n_{u1} and n_{u2} in Figure 11, the more suitable one in terms of relative coverage of other nodes and remaining energy will be accepted as coordinator. This will be selected by antenna selection rule 2.

4.6 Connectivity Issues:

For a CDS based algorithm, maintenance of connectivity is a very important issue. SPAN ensures connectivity of CDS. Our approach reduces number of connections existing in omni-directional CDS by closing some of the directional antennas. Thus it runs the risk of breaking connectivity. Here we prove that connectivity is ensured by our proposed approach.

Theorem 2: A Dominating Set does not lose connectivity after directional antenna selection.

Proof: By contradiction, let there be a node n which is not connected.

If n is a coordinator, it will be connected according to approach described in procedure *Antenna_Selection_Rule*1 by receiving *must_open* message from all coordinator neighbors. So it cannot remain disconnected.

If n is a non-coordinator, then consider a situation where antenna α is open which does not have any coordinator within its transmission/reception range and all other antennas of it are closed. However, according to definition of CDS, it has one coordinator within its transmission/reception range. Let, it resides in antenna region β of n. By procedure *Antenna_Selection_Rule*1, n will receive *must_open* message from direction β from that coordinator and will keep this antenna open. If n has more than one coordinator nodes in multiple antenna regions, it will receive covering requests from all of them. It will accept one of those requests considering relative coverage capacity and energy of the requesting coordinators according to steps described in procedure *Antenna_Selection_Rule2*. So, *n* will keep at least one antenna open which connects itself to at least one coordinator.

4.7 Analysis of Potential Routing Redundancy

The heuristic we proposed was based on localized information collected during CDS construction phase. It is specially made for broadcasting and performance improvement is demonstrated through simulation. Incorporation of directional antenna is likely to minimize energy consumption in case of routing as well. So the applicability of our approach for routing should be analyzed.

There is a possibility of suffering from local minima as it is dependent on local information and the only metric considered for routing is energy. Routing distance in terms of hop count or other usual criteria like load, bandwidth are not considered for best path determination. As a result, a longer path to reach destination may be chosen by a source node as it selects the next hop coordinator with higher energy or coverage. This will ultimately cause more energy consumption by additional retransmissions as the path involves more nodes.

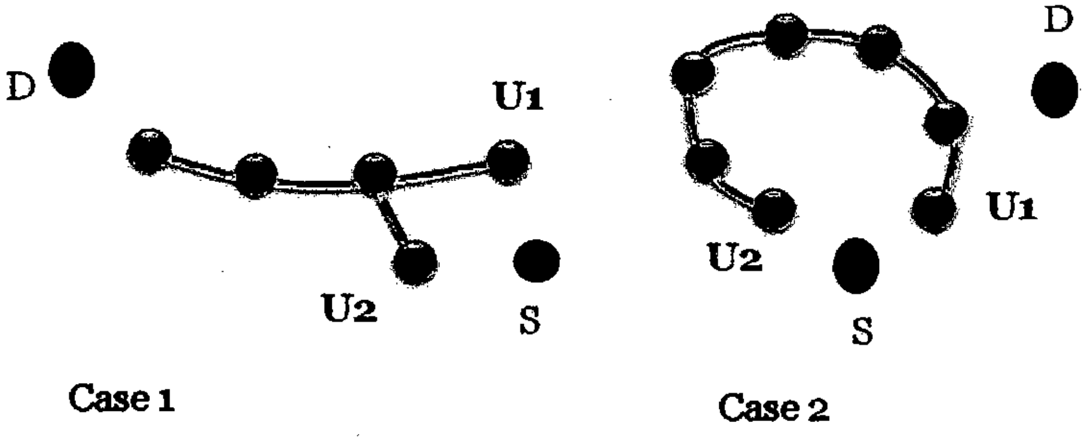

Figure 12: Analysis of potential routing redundancy.

In Figure 12, Case 1 shows a topology where the source node S may choose U_1 or U_2, any of the nearest coordinators, to send packet to destination D and the distance will be the same for each selection. However, in Case 2 if U_2 is preferred by S to forward data with ultimate destination D, a much longer path has to be traversed in comparison with the path starting with U_1.

5 Simulation

We have simulated ad hoc network using Network Simulator 2 (NS2). We calculate energy consumption of traditional CDS developed according to SPAN with omni-directional antennas. We also incorporate our algorithm implementing directional model of the antenna for the same network topology and energy model. We present the change in energy consumption with incorporation of our new algorithm.

5.1 Simulation Program

5.1.1 Changes Required in NS2

NS2 is an event driven network simulator developed at UC Berkeley that simulates variety of IP networks [37]. Its features and architecture are discussed in detail in Appendix-B. This simulator is widely used for simulation of networking protocols as it simulates many real-world scenarios with its already implemented protocols. So incorporation of proposed protocols by researchers gives realistic results with this simulator. For our simulation program we have used NS2 version 2.31 as the simulation platform.

In an NS2 simulation application, we can customize the simulation by making changes in 3 layers as described below. On top of the MAC layer, the agent actually takes routing decision. AODV is commonly used for wireless ad hoc networks in this layer. Finally, at the topmost layer, there is an application which generates packet to be forwarded through the two lower layers. Apart from this, a tcl script generates the topology of network and initializes the nodes according to the set parameters.

Here we have an application named application_broadcast.cc which actually generates packets to be broadcasted. We have implemented an agent to work at the middle layer named Directional_CDS_Agent.cc which has a procedure *broadcast*( ) that interfaces with upper layer application. The packet received from application is forwarded according to the routing table constructed by our proposed directional CDS. All simulation timers are also defined in Directional_CDS_Agent.cc file. The activities of our implemented agent are depicted with the help of a sequence diagram shown in Figure 13 where two adjacent nodes participate in CDS construction and antenna selection process.

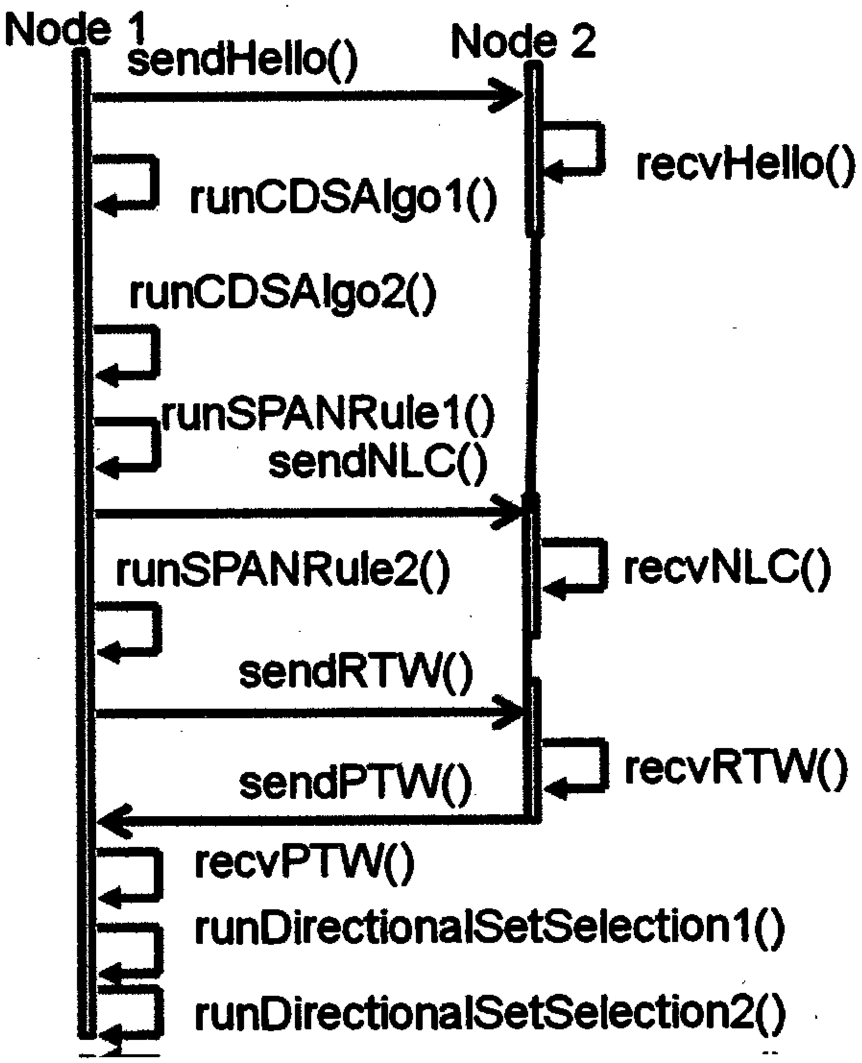

Figure 13: Sequence diagram for our implemented agent.

Last two procedures shown in this diagram are for directional antenna selection and described in Section 4.3. Other procedures are used to construct CDS following SPAN. We have presented details of these in *Appendix A*.

5.1.2 Implementation of Directional Antenna Model in the Simulation

Since the transmission and reception scheme implemented in NS2 do not support directional antenna model, we had to improvise the model. After execution of antenna selection rule 2 of our algorithm, when set of open antennas is selected for every node, each node will forward data packets to the *open antenna* regions. In our simulated directional scheme, the receiver nodes will decide whether to receive the packet or drop it. In the real scenario the receipt of a packet is determined through antenna automatically. But here sensing through antenna is done by determining whether there is an open antenna in a particular region. A receiver node calculates direction from coordinates of the sender node and its own *open antenna list*. If the sender node falls within the range of at least one antenna from the *open antenna list*, the packet will be received, otherwise packet will be dropped. In this way, it is ensured that if the packet comes from a region where antenna is supposed to be closed, the packet is ultimately dropped and not forwarded further. The extra loss of energy for reception of the packet, which ultimately will not occur in real world where the directional reception is maintained in hardware level, is excluded in energy consumption calculation.

Use of directional antennas actually reduce alternative paths and thereby increases potential collisions. So quantity of energy likely to be saved in ideal case may not be the same in practical situation where extra retransmission may consume more energy. NS2's underlying protocol 802.11 considers this and simulates necessary retransmission so that realistic energy consumption may be compared.

5.1.3 Performance Measures

In power savings research there are two important approaches: the maximization of the lifetime of a single node and the maximization of the whole network life [1]. In our simulation we have measured the performance both in terms of overall energy consumption of the network and lifetime of the most vulnerable node in the network. We have also compared the gain of using our approach for networks with different number of nodes. Here the comparison is made in percentage gain of energy after using directional antennas with respect to traditional omnidirectinal approach calculated as $((\text{Energy}_{\text{directional}}-\text{Energy}_{\text{omnidirectional}})/\ \text{Energy}_{\text{directional}})\times 100$. That is, the difference of remaining energy of a node with or without directional antenna with respect to remaining energy of directional node is expressed in percentage.

5.2 Simulation Settings

To set the wireless ad hoc network environment for our simulation we set the following parameters as shown in the table:

Table 5.2.1 Values of some important parameters of the Ad hoc Networks

Item	**Settings value**
Simulation area	1000×1000
Transmission range	250 units
Link speed	2 Mbps
Broadcast interval	Random interval following poison distribution with average λ =2 time units
Number of node	Varies from 25 to 100
Speed of the nodes	0 to 10 meter/unit
Pause time of the nodes	500 unit

5.2.1 Energy Model

For power consumption, we used the same settings used for the experiment of SPAN [5]. Power consumption of the Cabletron 802.11 network card is shown in the following table.

Table 5.2.2 Values of some important parameters related to energy consumption

Mode or events	**Power consumption**
Transmission of message	1400 mW
Reception of message	1000 mW
Idle	830 mW
Sleeping	130 mW

Since we have used link speed of 2 Mbps, effective bandwidth (Considering CSMA/CA) = 2/1 = 1Mbps. All nodes are initially given energy randomly in the range of 50 to 70 Joule. Nodes will lose energy due to transmission or receive of packets and also for remaining idle or in sleep mode in proportion presented in Table 5.2.2. Nodes may transmit packets with data in broadcast mode or for protocol execution, i.e. Hello packet. Different types of packet sizes are given below.

Hello packet: 2 (packet type) + n (number of neighbors) × 32(IP address) + 16 (total energy)+ 16(remaining energy)+ 1 (own coordinator) bits

Considering n=2, average size of a Hello packet is 100 bits

Data packet in broadcast mode: 2 KB

NLC (No longer a coordinator): 1 byte

PTW (Permission to withdraw): 1 byte

RTW (Request to withdraw): 1 byte

Nodes send Hello packets at interval of 1 second. All nodes will broadcast packets at random interval following poison distribution with average $\lambda = 2$.

So, broadcast transmission rate= 0.5 packet/sec

Packet transmission time = $\frac{\text{Packet size}}{\text{Effective bandwidth}}$

Update interval (when idle and sleeping power consumption are calculated) = 1ms

Computational overhead for directional model= 20 % (Remaining 80 % is distributed over each of the 4 antennas in equal ratio)

Directional multiplier = $\frac{\text{Power Consumed by a directional antenna}}{\text{Power Consumed by omni-directional antenna working for the same distance}}$

Transmission: calculated when transmitting packet

For directional antenna model:

Consumed energy= Packet transmission time × (open antenna count × directional multiplier + Computational overhead) × transmit power

For omni-directional antenna model:

Consumed energy = Packet transmission time × transmit power

Energy = energy – Consumed energy

Reception: calculated when packet received

Consumed energy = Packet transmission time × receive power

Energy = energy – Consumed energy

Constant consumption: calculated at every expiration of Update Interval

Idle = Idle power × (Open antenna count ×Directional multiplier + Computational overhead)

Sleep = Sleep power × ((Total antenna – Open antenna count) × Directional multiplier + Computational overhead)

Consumed energy = (Idle + sleep) × Update interval

Energy = energy – Consumed energy

5.2.2 Packet Transmission and Procedure Execution Interval

- Hello packet: This packet is used for keeping all nodes informed of any sort of topology change including arrival or departure of a node. In our simulation we have defined 1 unit interval for transmission of hello packets.
- CDS construction: For construction of CDS, procedures of SPAN algorithm are executed at an interval of 5 units.
- Directional antenna set selection: Our procedures of directional antenna selection are executed at intervals of 2 units. For an already constructed CDS, directional antennas are selected multiple times. This strategy ensures that if a mobile node changes its position in such a way that it goes out of covered antenna range, it is covered again by another directional antenna in the new selection process.

5.3 Simulation Result

In this section we are going to discuss our simulation result with the help of figures of various topologies and comparison graphs.

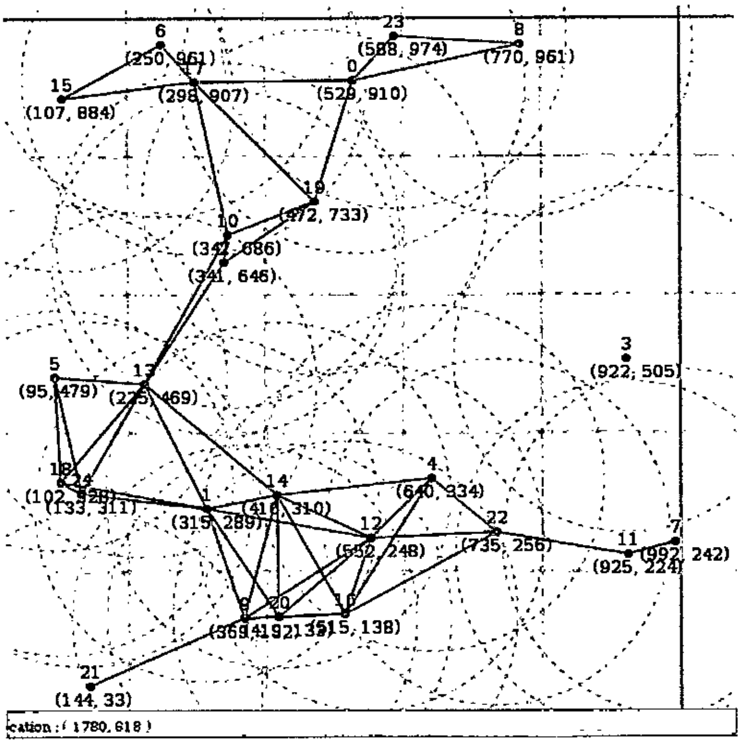

Figure 14: Topology with 25 nodes.

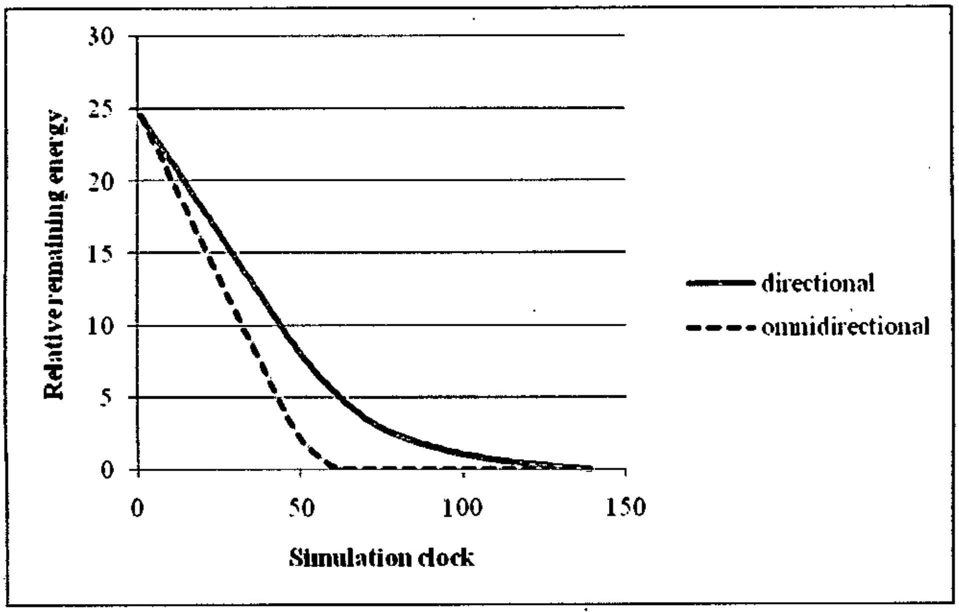

Figure 15: Overall energy consumption for 25 nodes.

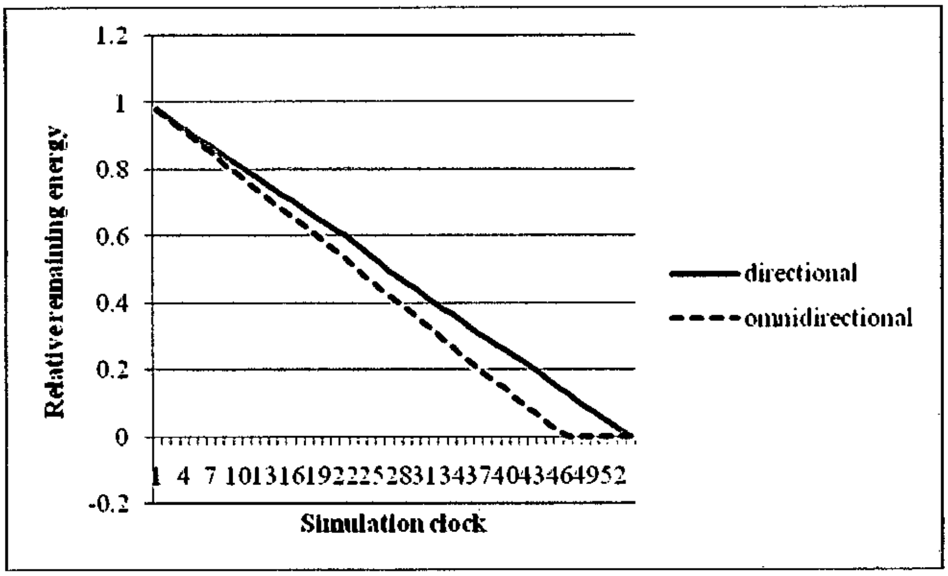

Figure 16: Energy consumption of the first node that dies in network of 25 nodes.

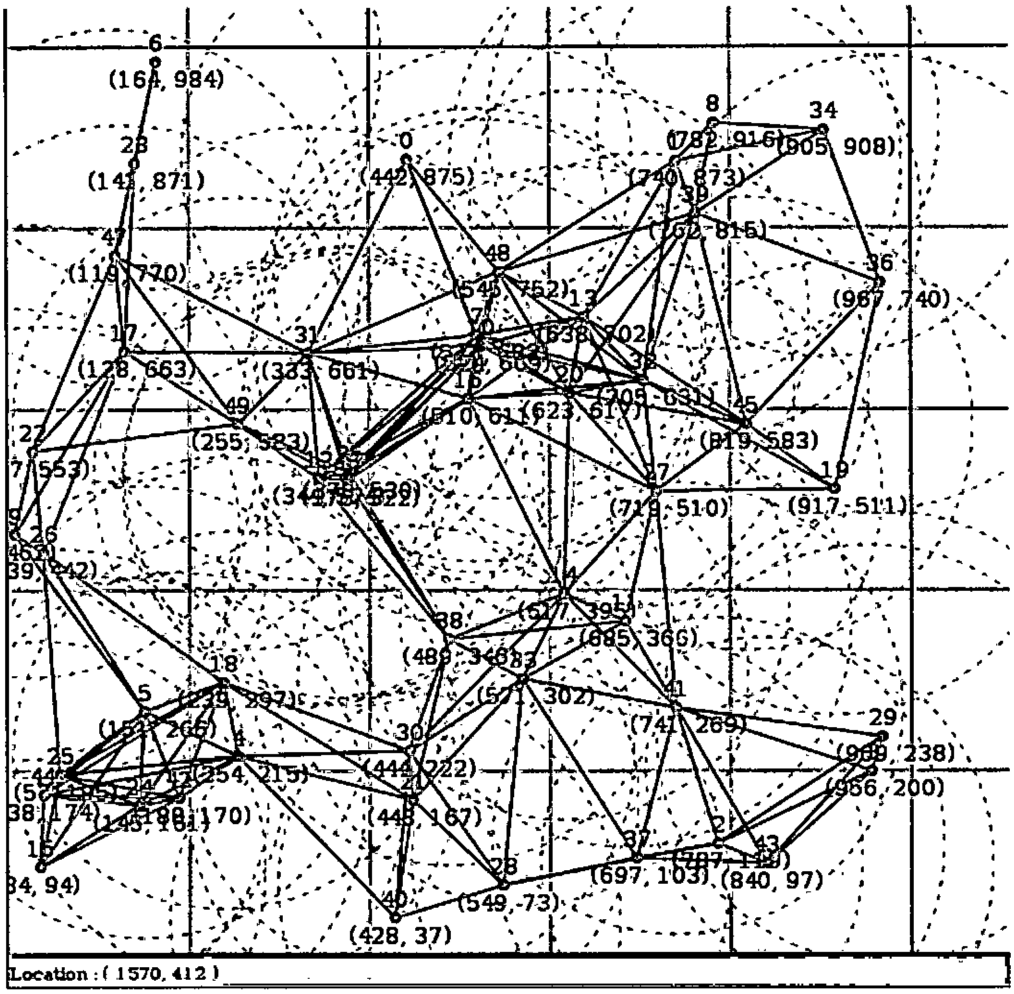

Figure 17: Topology with 50 nodes.

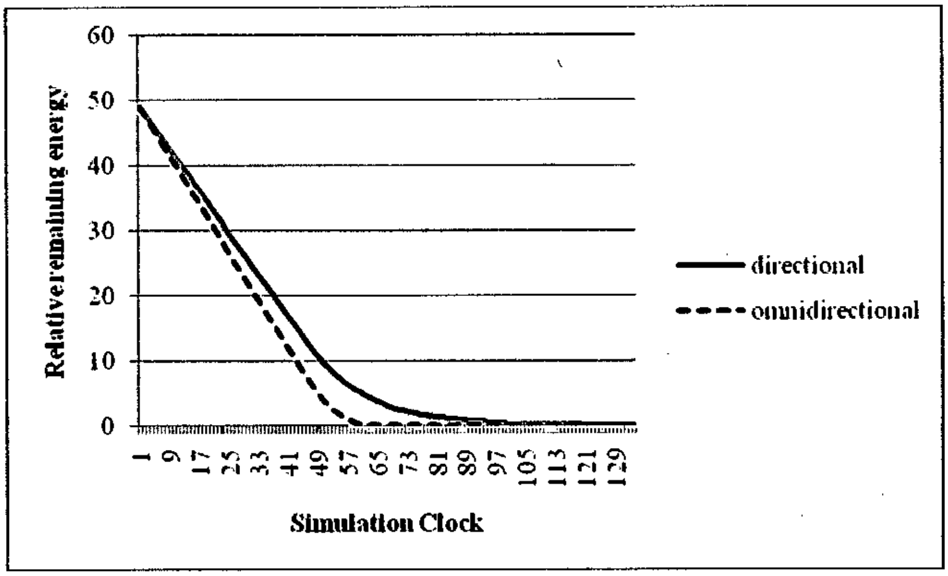

Figure 18: Overall energy consumption with 50 nodes.

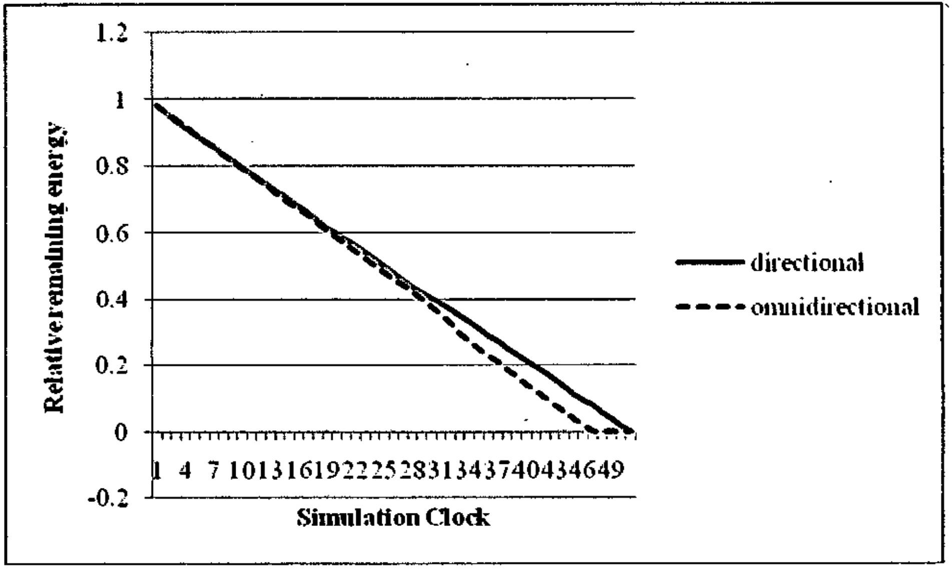

Figure 19: Energy consumption of the first node that dies in network of 50 nodes.

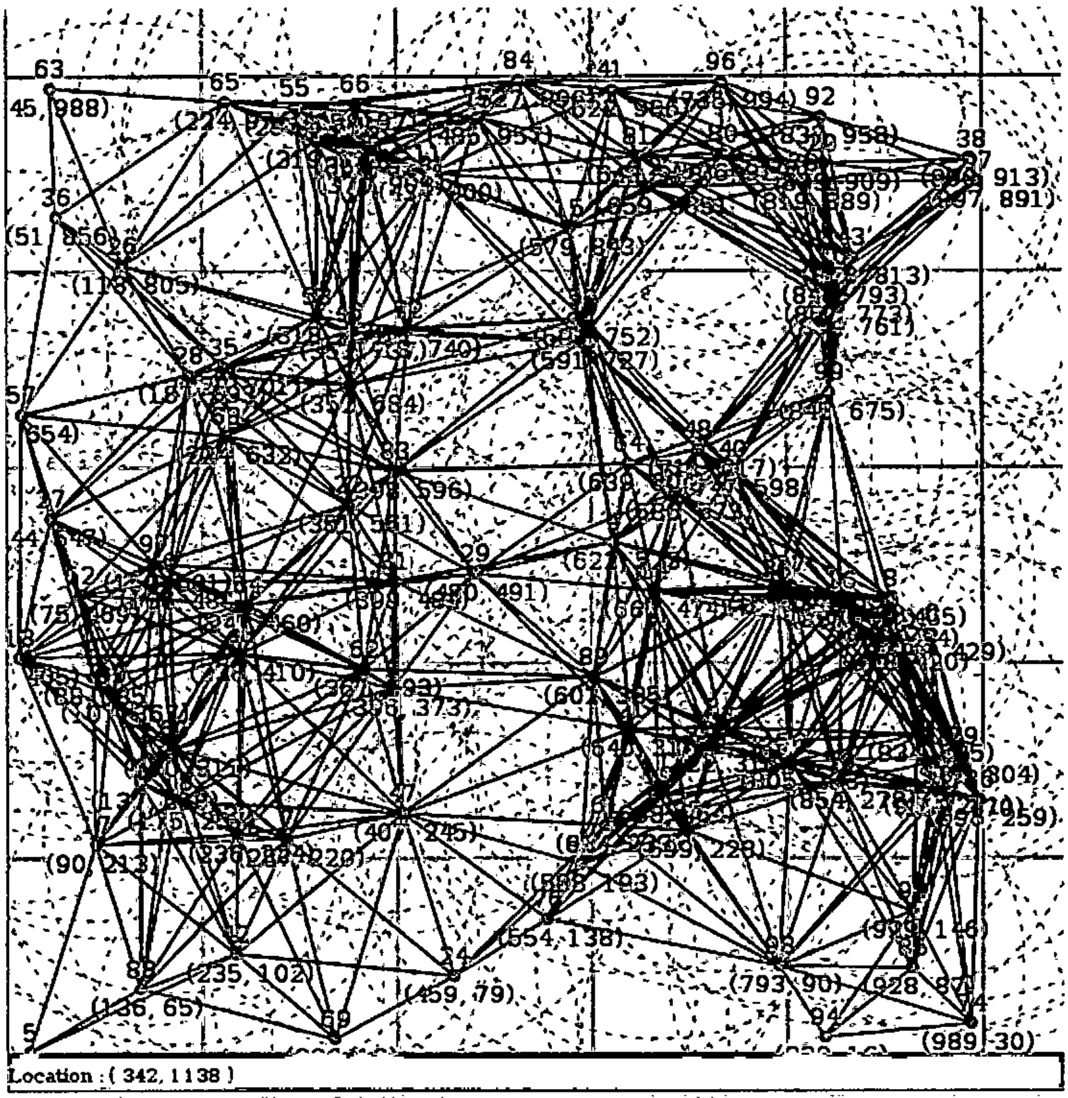

Figure 20: Topology of 100 nodes.

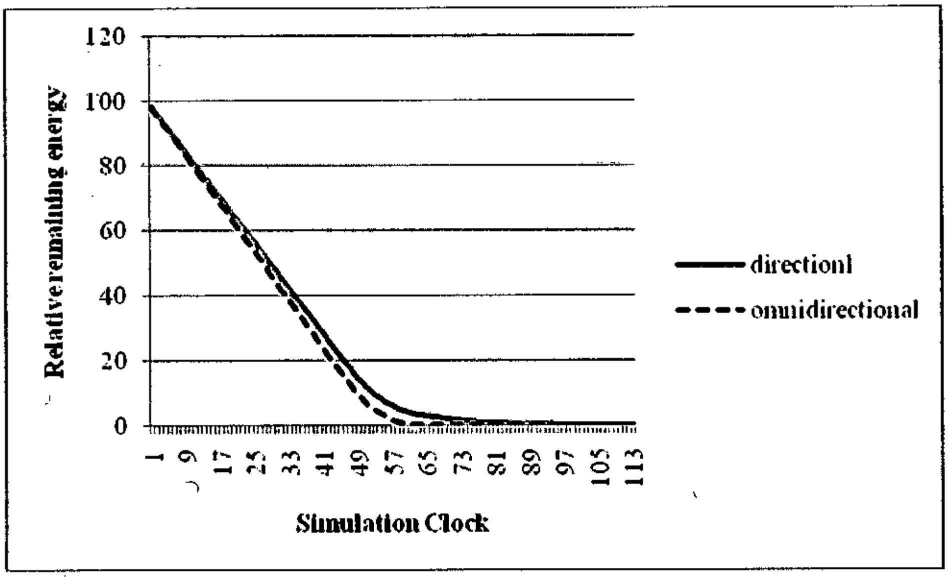

Figure 21: Overall energy consumption with 100 nodes.

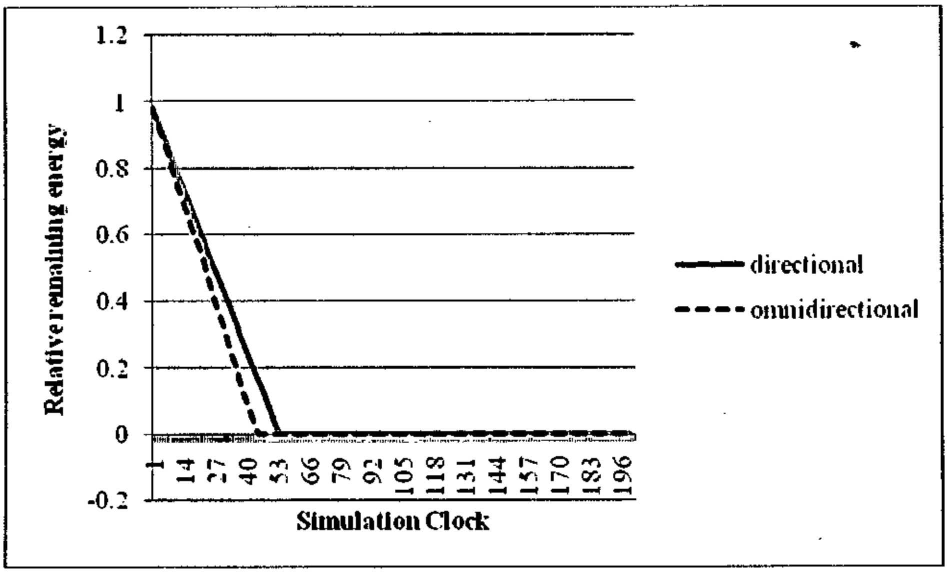

Figure 22: Energy consumption of first node that dies in network of 100 nodes.

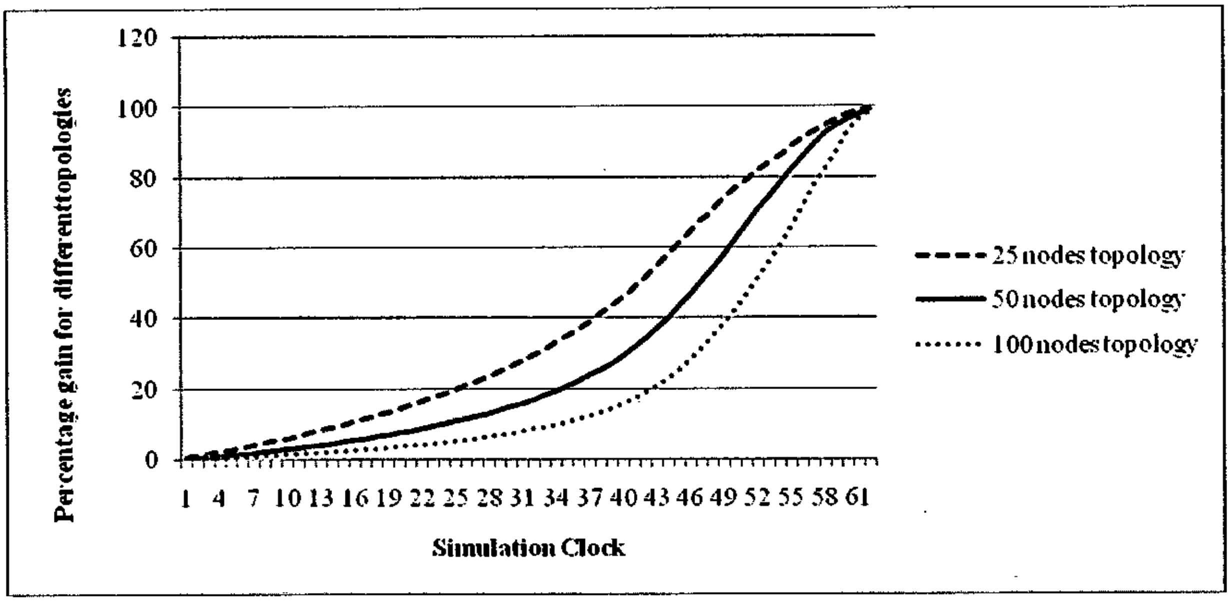

Figure 23: Comparison of percentage gain for 3 types of topologies.

Figure 14 shows a randomly generated network with 25 nodes. Figure 15 shows the effect of our algorithm on this topology. Initially, each node was randomly given energy in the range of 50 to 70 units. Total energy was consumed for traditional CDS in 60 simulation clock unit where as after applying our algorithm it took almost double the time, i.e. 120 units. In figures, relative remaining energy implies the ratio of remaining energy with respect to initial energy given. In our second comparison, as shown in Figure 16, we find that in terms of lifetime of the most vulnerable node, our proposed approach also performs considerably better by extending lifetime by 7 units which is almost 15% increase of the traditional CDS approach.

Figure 17 shows our topology with 50 nodes, Figure 18 and 19 depict similar comparisons of Figure 15 and 16 respectively for this topology.

For the topology with 100 nodes in same restricted area of 1000×1000 (as shown in Figure 20), where density becomes very high, overall lifetime improvement is small (see Figure 21), but the most vulnerable node shows significant improvement (almost 11%, see Figure 22).

With increased density scope of closing directional antenna is reduced as nodes exist in more antenna regions. The change of performance with respect to density (number of nodes in the topology in same restricted area) is depicted in Figure 23. Here remaining energy for whole network is compared in percentage with or without operation of directional antenna for explained in Section 5.1.3. Here 100 percent gain implies that overall energy (i.e., $\text{Energy}_{\text{omnidirectional}}$) is consumed in traditional CDS. Then the term $((\text{Energy}_{\text{directional}}-\text{Energy}_{\text{omnidirectional}})/\ \text{Energy}_{\text{directional}})\times 100$ yields 100% gain as $\text{Energy}_{\text{omnidirectional}}$ is 0. Careful observation of Figure 22 shows that $\text{Energy}_{\text{omnidirectional}}$ becomes zero at the interval of simulation clock between 59 from 62 for each of the adhoc network. Experimental data shows that $\text{Energy}_{\text{omnidirectional}}$ for larger networks becomes zero earlier although it is not directly visible from plotted data in Figure 22.

The presented performance gain in Figure 23 justifies the theoretical calculation (Table 4.5.1) of the ratio of expected number of open antennas in the best case where there is only one directional antennas open for each non coordinator in the network. In Table 4.5.1we find that the ratio of open antennas in our directional CDS and traditional omni-directional CDS increases with the increase of number of nodes in the ad hoc network. This proportion of open antennas in larger network increases relative energy consumption with respect to the traditional approaches. This is rightly reflected in the simulation result presented in Figure 22. Moreover the performance gain in highly dense network seems to be reasonable to motivate the users in directional CDS algorithms.

6 Conclusion

Energy conservation of wireless ad hoc network is a mature, yet live research issue. This thesis consists of a detail study of related work with necessary background discussion and proposes a new approach for energy efficient broadcasting by constructing directional Connected Dominating Set (CDS). The use of directional antenna in an efficient manner reduces redundant message passing and thereby conserves energy of participating nodes. The approach may cause increase of packet retransmission due to extra collisions for reducing alternative paths which ultimately consumes extra energy. However, simulation results for various topologies shows that it works considerably well in terms of energy efficiency in case of broadcasting.

6.1 Major Contributions of the Thesis

- *Concept of Directional Antenna based CDS:* In this thesis we have proposed the use of directional antennas with traditionally built CDS to reduce number of unnecessary broadcasts and thereby to conserve energy.

- *New algorithm and complexity analysis:*. We have proposed an algorithm to select directional antennas that has to be kept open. The selection is based on available local information. An analysis of expected number of open antennas and proof of network coverage are presented.

- *Simulation and Performance analysis:* Simulation of our proposed algorithm is done using NS2 and performance is analyzed in terms of energy consumption compared to the traditional CDS constructed by SPAN.

6.2 Future Direction

- *Applicability analysis in routing:* Our proposed scheme is for broadcasting in wireless ad hoc network. Analysis of routing redundancy with this approach and its effect on energy consumption as future work. ID generation of nodes based on their relative position may facilitate routing decisions throughout our directional antenna based CDS.

- *Observation of increased granularity of directional antenna:* Although increasing granularity of directional antenna model is not feasible from current hardware designers' viewpoint, it may be theoretically interesting to analyze the case with k= 6 or k=8 for 360/k model.

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Appendix – A

The following algorithm is proposed to construct a coordinator set which will act as a backbone. We have used this approach for our basic CDS construction.

Let the network be represented as a connected graph $G = (V, E)$. The backbone consists of a smaller graph G' subset G such that G' remains connected.

Let:

1. $N(v)$ be the *open neighbor set* of vertex v i.e.

$N(v)= \{u \mid \{v, u\} \in E\}$.

2. n (v) be the cardinality of $N(v)$

3. $p(v)$ be the power metric defined as $p(v) = E_r/E_t$ where

E_t is the maximum amount of energy available at the node

and E_r is the remaining energy at the node

4. $ID(v)$ be the unique node ID of v

A tuple is constructed such as tuple, $T(v) =< N(v), p(v), n(v), ID(v)>$

To compare two such tuples we use the following rule $T(v) < T(u)$ if and only if

1. $N(v) < N(u)$

2. If $N(v) = N(u)$ then we compare the other elements lexicographically.

The two tuples are equal if and only if all their elements are equal.

The sequence of operation within a node and major message passing are shown with the help of a sequence diagram below. The following sequence of operation is repeated in a distributed manner.

sendHello() and recvHello()

Each of the nodes in the network periodically sends a HELLO message containing a list of all its neighbors. All the nodes maintain a list of their neighbors and the neighbor list of each neighbor. Receiving a HELLO, a node updates its neighbor and neighbors' list.

RunCDSAlgo1

The nodes in the neighbor table are marked as coordinators or non-coordinators. If any 2 neighbors of node v are not connected then node v declares itself as the coordinator.

RunCDSAlgo1

This algorithm reduces the backbone size by executing the following two rules.

Rule 1:

For the coordinator node v:

If $T(v)$ is a complete subset of $T(v_1)$, where v_1 is another coordinator, then node v withdraws as a coordinator and sends NLC (No Longer a Coordinator) to all neighbors

Rule 2: For the coordinator node v:

1. If

(a) all coordinator neighbors of node v are connected to each other directly or through one coordinator and

(b) all the non-coordinator neighbors of v are connected to at least one other coordinator other than v then send RTW (Request to Withdraw)to all neighboring coordinators including itself.

2. If node v receives PTW (Permission to Withdraw) from all its neighboring coordinators then node v withdraws as coordinator and sends NLC (No Longer a Coordinator) to all neighbors including itself.

3. If node v receives RTW from one or more node; wait till the end of the round and then send PTW to the node with the minimum of all values of T received.

Appendix-B

NS implements network protocols such as TCP and UDP, traffic source behavior such as FTP, Telnet, Web, CBR and VBR, router queue management mechanism such as Drop Tail, RED and CBQ, routing algorithms such as Dijkstra, and more. NS also implements multicasting and some of the MAC layer protocols for LAN simulations. The NS project is now a part of the VINT project that develops tools for simulation results display, analysis and converters that convert network topologies generated by well-known generators to NS formats. Currently, NS (version 2) written in C++ and OTcl (Tcl script language with Object-oriented extensions developed at MIT) is available.

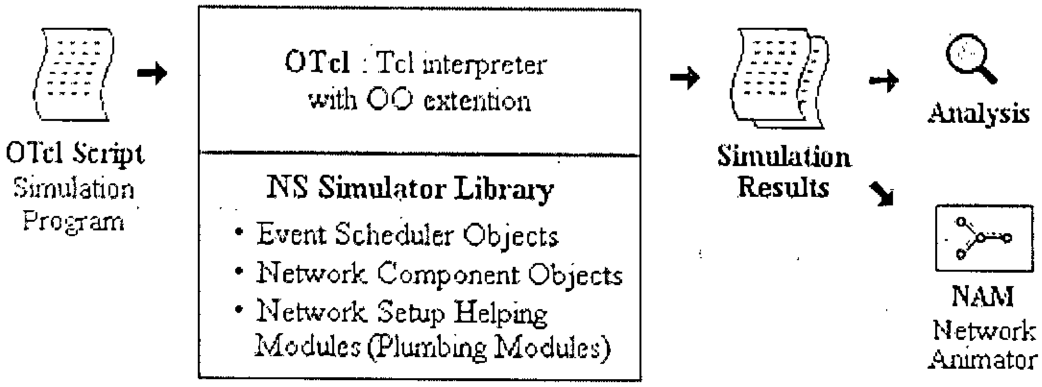

Figure 24: Simplified User's View of NS.

As shown in Figure 24, in a simplified user's view, NS is Object-oriented Tcl (OTcl) script interpreter that has a simulation event scheduler and network component object libraries, and network setup (plumbing) module libraries (actually, plumbing modules are implemented as member functions of the base simulator object). In other words, to use NS, one has to program in OTcl script language. To setup and run a simulation network, a user should write an OTcl script that initiates an event scheduler, sets up the network topology using the network objects and the plumbing functions in the library, and tells traffic sources when to start and stop transmitting packets through the event scheduler. The term "plumbing" is used for a network setup, because setting up a network is plumbing possible data paths among network objects by setting the "neighbor" pointer of an object to the address of an appropriate object. When a user wants to make a new network object, he or she can easily make an object either by writing a new object or by making a compound object from the object library, and plumb the data path through the object. This may sound like complicated job, but the plumbing OTcl modules actually make the job very easy. The power of NS comes from this plumbing.

Another major component of NS beside network objects is the event scheduler. An event in NS is a packet ID that is unique for a packet with scheduled time and the pointer to an object that handles the event. In NS, an event scheduler keeps track of simulation time and fires all the events in the event queue scheduled for the current time by invoking appropriate network components, which usually are the ones who issued the events, and let them do the appropriate action associated with packet pointed by the event. Network components communicate with one another passing packets, however this does not consume actual simulation time. All the network components that need to spend some simulation time handling a packet (i.e. need a delay) use the event scheduler by issuing an event for the packet and waiting for the event to be fired to itself before doing further action handling the packet. For example, a network switch component that simulates a switch with 20 microseconds of switching delay issues an event for a packet to be switched to the scheduler as an event 20 microsecond later. The scheduler after 20 microsecond dequeues the event and fires it to the switch component, which then passes the packet to an appropriate output link component. Another use of an event scheduler is timer. For example, TCP needs a timer to keep track of a packet transmission time out for retransmission (transmission of a packet with the same TCP packet number but different NS packet ID). Timers use event schedulers in a similar manner that delay does. The only difference is that timer measures a time value associated with a packet and does an appropriate action related to that packet after a certain time goes by, and does not simulate a delay.

NS is written not only in OTcl but in C++ also. For efficiency reason, NS separates the data path implementation from control path implementations. In order to reduce packet and event processing time (not simulation time), the event scheduler and the basic network component objects in the data path are written and compiled using C++. These compiled objects are made available to the OTcl interpreter through an OTcl linkage that creates a matching OTcl object for each of the C++ objects and makes the control functions and the configurable variables specified by the C++ object act as member functions and member variables of the corresponding OTcl object. In this way, the controls of the C++ objects are given to OTcl. It is also possible to add member functions and variables to a C++ linked OTcl object. The objects in C++ that do not need to be controlled in a simulation or internally used by another object do not need to be linked to OTcl. Likewise, an object (not in the data path) can be entirely implemented in OTcl. Figure 25 shows an object hierarchy example in C++ and OTcl. One thing to note in the figure is that for C++ objects that have an OTcl linkage forming a hierarchy, there is a matching OTcl object hierarchy very similar to that of C++.

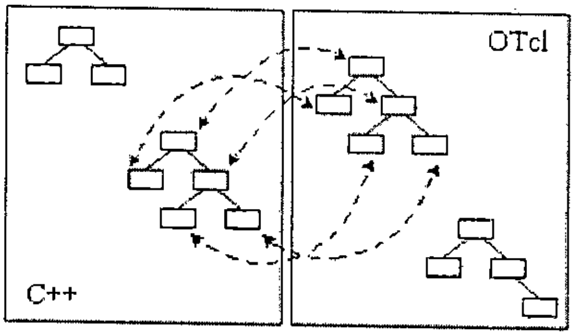

Figure 25: TCL and C++ : the duality.

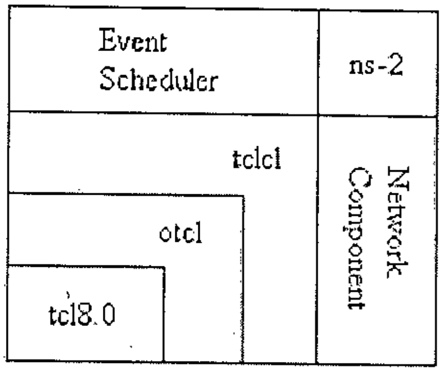

Figure 26: Architectural View of NS.

Figure 26 shows the general architecture of NS. In this figure a general user (not an NS developer) can be thought of standing at the left bottom corner, designing and running simulations in Tcl using the simulator objects in the OTcl library. The event schedulers and most of the network components are implemented in C++ and available to OTcl through an OTcl linkage that is implemented using tclcl. The whole thing together makes NS, which is an Object Oriented extended Tcl interpreter with network simulator libraries.

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