M.Tech. (Computer Science) Dissertation Series

Energy Efficient Routing by Node based Power Control in Wireless ad hoc Networks

a dissertation submitted in partial fulfilment of the
requirements for the M.Tech. (Computer Science)
degree of the Indian Statistical Institute

By

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Certificate of Approval

This is to certify that this dissertation thesis titled " ***Energy Efficient Routing by Node based Power Control in Wireless ad-hoc Networks***" submitted by Mr. Dinesh Layek, in partial fulfillment of the requirements for the M.Tech. (Computer Science) degree of the Indian Statistical Institute, Kolkata, embodies the work done under my supervision.

Nabanita Das

Dr. Nabanita Das 12/7/05
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Dinesh Layek

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Chapter 1

Ad hoc Networks

1.1 Introduction

A mobile ad hoc network is an autonomous system of mobile routers (and associated hosts) connected by wireless links--the union of which forms an arbitrary graph. There are no mobility restrictions on these routers and they can organize themselves arbitrarily resulting in rapid and unpredictable change in the network's topology. A mobile ad hoc network may operate in a standalone fashion or may be connected to the Internet. The property of these networks that makes it particularly attractive is that they don't require any prior investment in fixed infrastructure. Instead, the participating nodes form their own co-operative infrastructure by agreeing to relay each other's packets.

It is possible to construct large networks of fixed nodes today. Prominent examples include the telephone system and the Internet. The cellular telephone network shows how these wired networks can be extended to include large numbers of mobile nodes. However, these networks require a large investment in fixed infrastructure before they are useful---central offices, trunks, and local loops in the case of the telephone system, radio towers for the cellular network. Furthermore, upgrading these networks to meet increasing bandwidth requirements has proven expensive and slow. The fact that large fixed communication infrastructures already exist might seem to limit the usefulness of any competing approach. There are, however, a number of situations in which ad hoc networks are desirable. Users may be so sparse or dense that the appropriate level of fixed infrastructure is not an economical investment. Sometimes fixed infrastructure exists but cannot be relied upon, such as during disaster recovery. Finally, existing services may not provide adequate service, or may be too expensive. Mobile ad hoc networks are attracting a lot of attention these days due to little efforts needed to deploy them. These networks prove to be economical in sparse areas. In emergency services such as disaster recovery these networks are the only possible options. These networks are a valid substitution for local area networks as well. Nodes in a mobile ad hoc network forward packets to establish a virtual network backbone. The idea of forwarding each other's packets eliminates the need for a fixed network for communication. Zero configuration requirement is also an attractive point for mobile ad hoc network making it suitable for home networks or for users who either don't know how to configure a network or don't have an inclination to do so.

Though mobile ad hoc network are attractive, they are more difficult to implement than fixed networks. Fixed networks take advantage of their static nature in two ways. First, they proactively distribute network topology information among the nodes, and each node pre-computes routes through that topology using relatively inexpensive algorithms. Second, fixed networks embed routing hints in node addresses because the complete topology of a large network is too unwieldy to process or distribute globally. Neither of these techniques works well for networks with mobile nodes because movement invalidates topology information and permanent node addresses cannot include dynamic location information.

The idea of packet forwarding although works well in the case of small network, as and when the network size increases each node has to devote a significant amount of computing power for forwarding other node's packets. In the coming time these networks will need to support multimedia traffic such as voice, video and data. To fulfill these requirements, networks carrying data in real time and having high throughput, low delay and fault tolerance are desired which cannot be provided using existing methods. Another problem with mobile ad hoc network is their inefficiency to deal with the node density. If a cell becomes crowded, bandwidth share of each node will decrease and workload on each of them will increase due to increase in number of packets to forward and location updates to be done. If node density in a cell drops too low the probability of a message encountering dead-ends of the network increases.

In summary mobile ad hoc networks have the following characteristics:

- New members can join and leave the network any time
- No base station to provide connectivity to backbone hosts or to other mobile hosts
- Each node acts as a router, forwarding packets from others nodes
- Communication connectivity is usually fairly "weak"

1.2 Common Network Architectures

There are two common architectures of a mobile ad hoc network:

Hierarchical Network Architecture: This approach partitions the whole network into sub-networks. Each of these sub-networks then dynamically elects a node among themselves which acts as gateway to the other sub-network. All traffic to the sub-network is routed through these gateways. The nodes acting as gateways may again be partitioned and each of these partitions may elect a node to act as a second level gateway. This hierarchy can be extended to multiple layers. An example two-tier mobile ad hoc network is shown in the figure below.

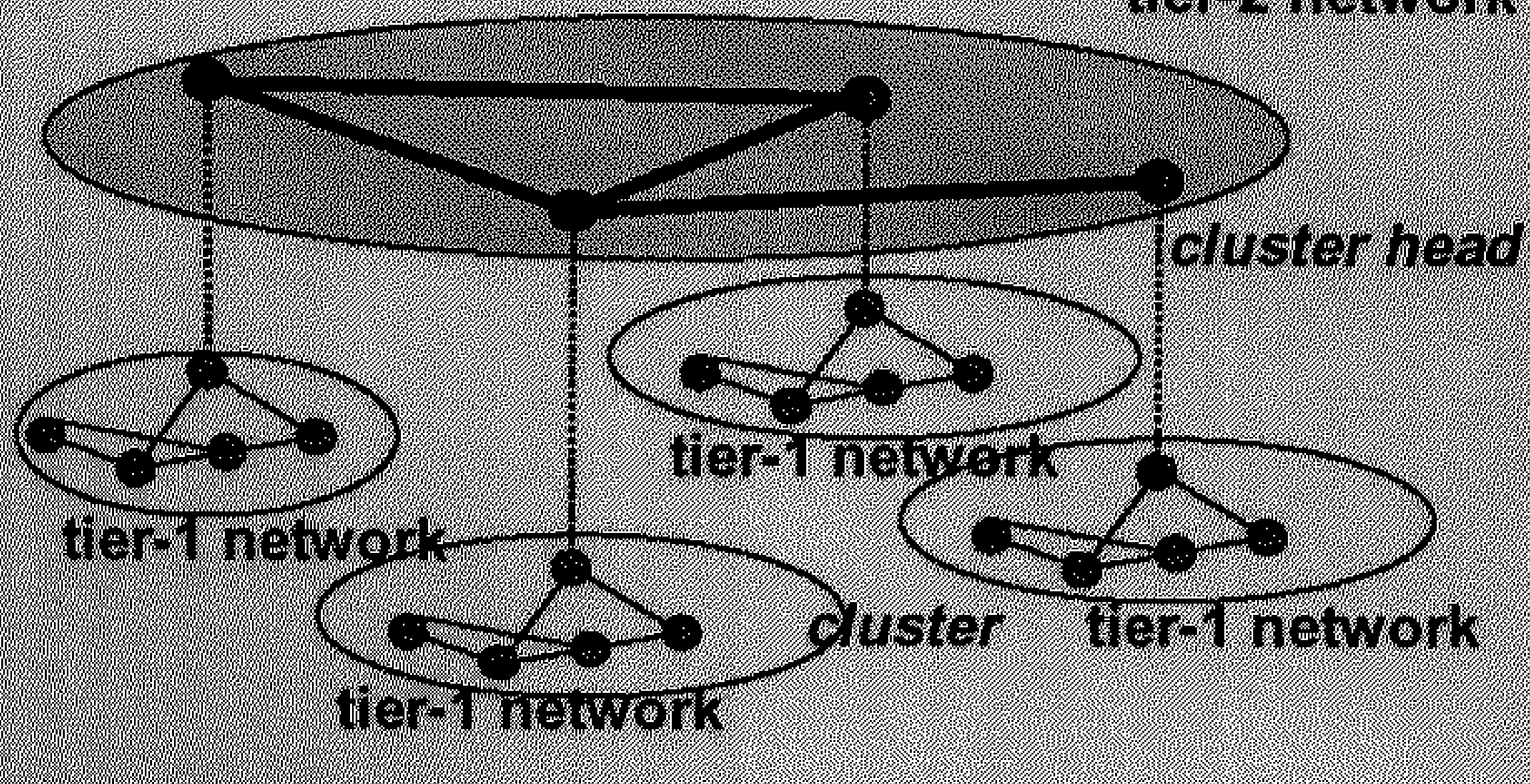


Figure 1.1
Hierarchical Network

II. Flat-routed Architecture: In this approach all the nodes are treated equally, and there is no concept of special gateways. An example flat-routed mobile ad hoc network is shown in the figure below.

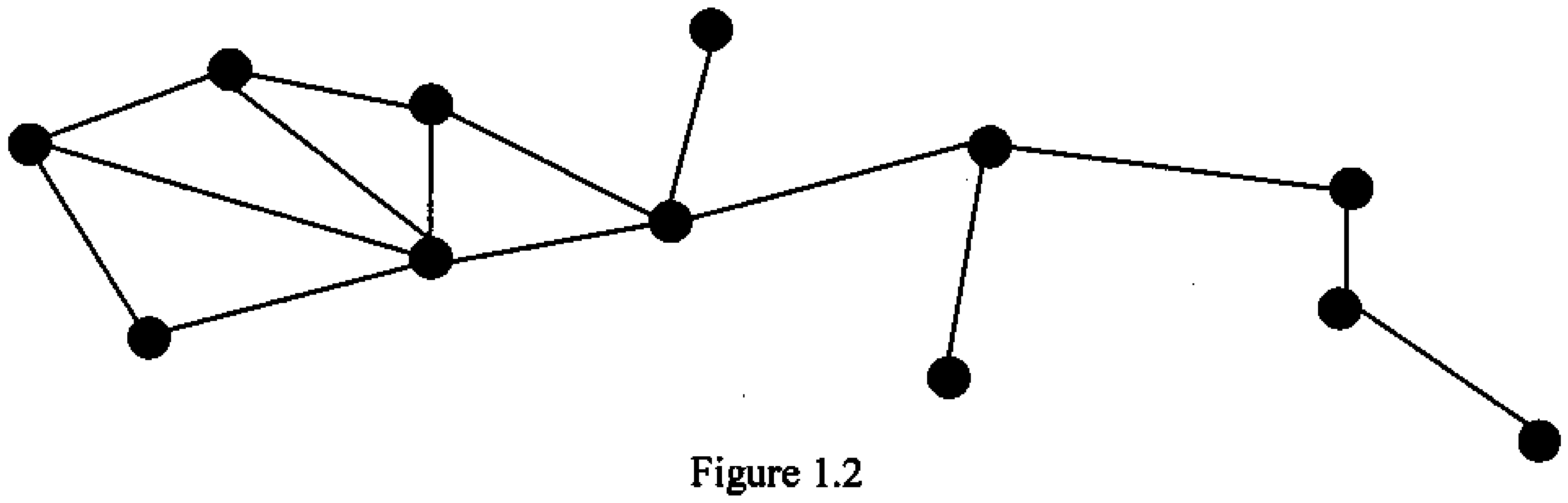


Figure 1.2
Flat Routed Adhoc Network

1.3 Routing in Mobile Ad Hoc Networks

As mentioned earlier, a mobile ad hoc network is a packet radio network in which the nodes themselves perform the routing functions. Due to the limited wireless transmission range, the routing is generally multi-hop. The nodes thus depend on each other to forward packets to a given destination. The nature of the networks places two fundamental requirements on the routing protocols. First, it has to be distributed and second since the topology changes are frequent it should computer multiple, cycle free routes while keeping the communication overhead to a minimum. Based on route discovery time, most routing approaches proposed for the mobile ad hoc networks can be classified into the following types:

I. Proactive Routing Algorithms: Like traditional fixed networks, these algorithms always maintain a route to all destinations. To transmit a packet, the route already present in the routing table is used. The transmission of the first packet in this case starts instantaneously, however, to maintain the routes to all nodes at all times is significant drain on the scarce power and bandwidth. Most of the proactive routing protocols are based on shortest path algorithms adapted to the mobile environment. In these protocols, routing tables are exchanged among neighboring nodes each time a change occurs in the topology of the network. Each exchange incurs a bandwidth and power overhead. Each node must re-compute the route, incorporating the new information, incurring a computation/power overhead. In each exchange a possibly large routing table need to be transmitted resulting in the bandwidth overhead. A large part of the bandwidth capacity of the network and the energy of the node is wasted in route maintenance. As a result, when the mobility rate of nodes is high, proactive protocols are infeasible since they cannot keep up with the changes in the topology.

II. Reactive Routing Algorithms: An attempt to overcome the limitations of proactive protocols is to look for a route in an "on-demand" fashion, i.e. only when it is needed to deliver a message. As the name suggests, in reactive routing algorithms, route discovery to a destination node is only initiated when a data packet needs to be transmitted to that node. Usually the route discovery phase precedes the actual send phase, slowing down the transmission of the first packet. This is the basic idea of reactive protocols, such as Dynamic Source Routing (DSR [24]) protocol, Temporally Ordered Routing Algorithm (TORA [25]), and Ad Hoc On-Demand Distance Vector (AODV [23]) routing protocol. In reactive protocols a control message is sent to discover a route to a given destination. This kind of control message is generally shorter than the control messages used in proactive protocols, leaving more bandwidth available for the transmission of data messages. However, since a route has to be entirely discovered prior to the actual transmission of the message, a sender may experience a long delay in waiting for the route to be computed. Furthermore, there is no guarantee that the route obtained is usable. It is possible that by the time the source node completes the route discovery; a change in network topology has invalidated the route. In case of high-speed mobile nodes this problem becomes more pronounced as the rate of change of the network topology increases. The route discovery mechanism is not able to adapt to the variations of the speed of the nodes. Even route caching or similar techniques, used to reduce the delay are ineffective when the mobility rate is high. The reactive routing algorithms are however efficient in terms of the data packet to routing control packet ratio saving battery power in the mobile nodes.

III Hybrid Approaches: Some proposed algorithms claim to have the best of these two classes. Protocol like ZRP [21] combines both a proactive and a reactive approach. Here, the route discovery phase is divided into an intra zone discovery, which involves all the nodes whose distance from the sender in number of hops < k, where proactive way is applied, and an inter zone discovery, which operates between zones using a reactive approach. The appropriate choice of the zone radius *k* depends on the mobility rate of the nodes and on the message arrival rate.

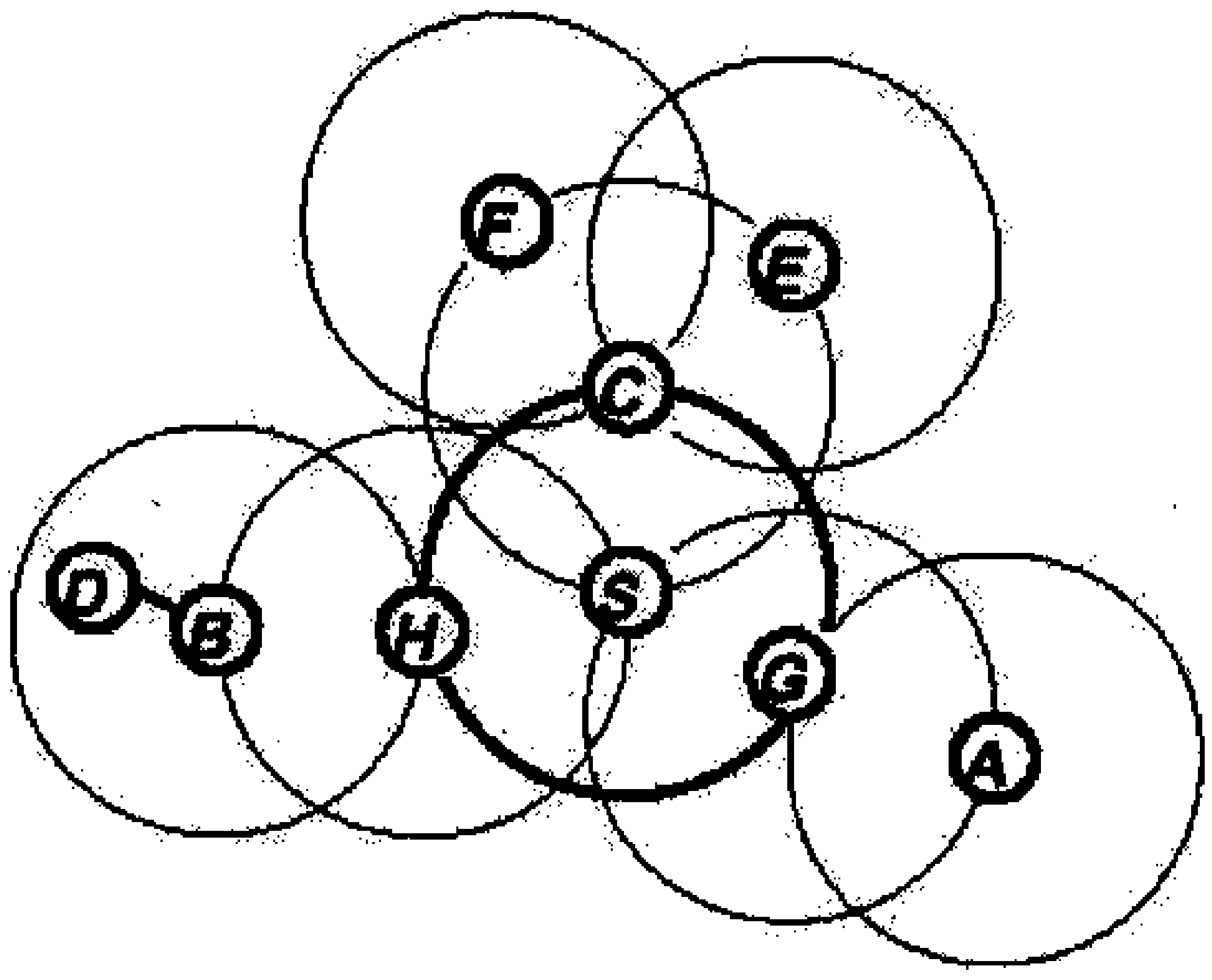


Figure 1.3
Zone Routing

In the Figure 1.3 shown above, the requirement is to send a message from S (Source) to D (Destination). The source node S first searches for D in its own routing zone (It knows about all the nodes in its routing zones). After recognizing that D is not in its routing zone it sends a query to its peripheral nodes namely C, H, and G. Now each of these nodes after verifying that D is not in their routing zone send a query to their peripheral nodes. Finally B gets the node D in its routing zone and replies with the path D-B-H-S. Number of hops up to which this query is transmitted is determined by the network diameter.

1.4 Issues and Challenges

Here we mention the important issues and challenges of ad hoc networks.

I. **Power Constraints:** Minimizing energy consumption is an important challenge in mobile networking. Since nodes are driven by battery so the lifetime of an ad-hoc network depends upon the residue power of every node. The nodes should consume minimum possible power for communication purpose. The power control and routing protocol should be such, which results homogeneous residue power distribution; otherwise the network may get partitioned into several parts.

II. **Bandwidth Constraints**: Most of the ad-hoc networks are of single channel, so bandwidth is very low in ad-hoc networks.

III. **Periodic Broadcast:** Most routing schemes proposed for mobile ad hoc networks are modifications/extensions of existing link-state or distance-vector routing protocols. Majority of these conventional protocols employ periodic broadcasts. In a power and bandwidth constrained environment periodic broadcasts put a heavy burden on individual nodes participating in the network.

IV. **Route Management in Mobile Environment:** A mobile ad hoc network has no base station to provide connectivity to backbone hosts or to other mobile hosts, instead the nodes themselves compute and maintain the routing information. As a result of mobility that results in frequent change in the network topology, the communication connectivity is "weak". A node migration invalidates all routes in which it was participating. A routing scheme that does not optimizes the routing table maintenance will be at best inefficient and result in low data throughput and high overhead of route computation. Prior to that, the possible types of ad-hoc mobile communications are examined.

In this work, we address the problem of transmission power control at each node that maintains the connectivity of the network but at the same time attempts to reduce the power requirement on every communication path between all pairs of nodes.

Chapter 2

Transmission Power Control

2.1 Introduction

Multi-hop wireless networks, such as radio networks [1], adhoc networks [2] and sensor networks [3] are networks where communication between two nodes may go through multiple consecutive wireless links. Unlike wired networks, which typically have a fixed network topology (except in case of failures), each node in a wireless network can potentially change the network topology by adjusting its transmission power to control its set of neighbors. The primary goal of topology control is to design power-efficient algorithm that maintains network connectivity and optimize performance metrics such as network lifetime and throughput.

For radio transmission, the power required to transmit between nodes increases as the *n*th power of the distance between them, for some $2 \leq n \leq 6$ [5], depending on the condition of surroundings media. Hence, a node *u* may require less power to relay messages through a series of intermediate nodes to the destination *v* than to transmit directly to *v*. In this work, it has been assumed that $n = 2$.

Generally, in ad hoc networks, it is assumed that each node transmits at a maximum power level P, covering a range R of transmission. However, it is undesirable to have nodes transmit with maximum power for two reasons. Firstly, if distance between two nodes u and v is less than R, u and v can communicate with power $p < P$. As nodes operate with limited battery power, it is very important to reduce the total power required for communication between any pair of nodes. In addition, the greater the power with which a node transmits, the greater the likelihood of the transmission interfering with other transmissions. Hence, it is a challenging problem to determine the transmission powers of the individual nodes that will maintain the connectivity of the network as well as reduce the total power required for communication.

2.2 Problem Formulation

Let us consider a set V of mobile nodes distributed over a two dimensional plane. It has been assumed that the maximum transmission power P is the same for every node corresponding to the maximum range of communication R. In general, each node transmits with the maximum power P to communicate to any of its adjacent nodes. However, it is evident that this much power is not always essential. Depending on the distance between the nodes it can be decided. For any two nodes u and v, at Euclidean distance $d(u,v)$, let the minimum power required for communication be $p(d(u,v))$. Hence $p(d(u,v))$ power is sufficient to maintain the link (u,v).

The objective of this work is to control the transmission power at individual nodes to reduce the communication cost in terms of transmission power required for end to end packet delivery maintaining the connectivity of the network

Definition 1: Given an ad hoc network with V nodes distributed over a two-dimensional plane, any node $v_i \in V$ transmitting with power $P_i \leq P$, the network topology is represented by a graph G(V,E), where E = {(v_i, v_j) | v_i, v_j $\in$ V and p(d(v_i, v_j)) $\leq$ min {P_i , P_j }, d(v_i, v_j) is the Euclidean distance between v_i and v_j and p(d(v_i, v_j)) is the minimum power required for covering distance d(v_i, v_j). G(V, E) is defined as the *topology graph* of the given ad hoc network. □

However, if each node transmits with the maximum power *P*, i.e., all the node pairs (u,v), for which d(u,v) $\leq R$, are connected, the topology graph is represented as G_R(V,E). It is obvious that given any ad hoc network all possible topology graphs G(V,E) $\subseteq$ G_R(V,E).

Definition 2: A topology graph G(V, E) with each edge (v_i, v_j) labeled with weight P_i is defined as the power graph G_L(V,E). □

It is to be noted that since the links in the topology graph G(V, E) are bi-directional, they are so in power graph G_L(V,E) also, but the weights on a link may be different in two directions.

Example 1: Figure 2.1.a shows an arbitrary topology graph G_R(V,E), where each node transmits at a power level 16. Figure 2.1.b shows the modified topology graph G(V,E′), where each node transmits at different power levels. The power levels are shown as node labels.

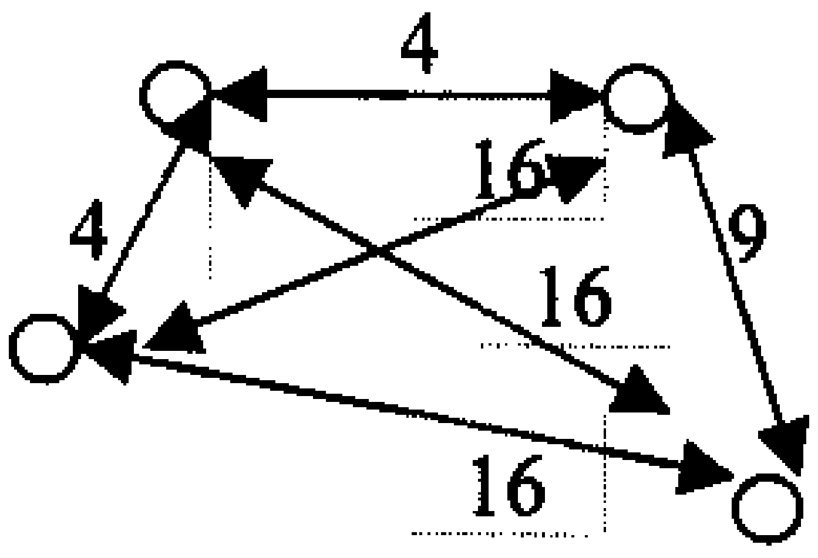


Figure 2.1.a
Topology Graph G_R

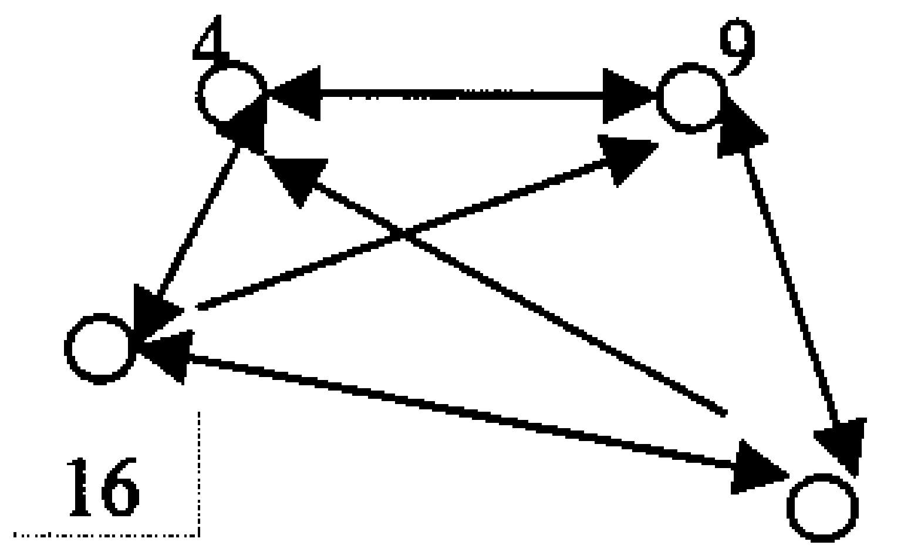


Figure 2.1.b
Modified Topology Graph G

Definition 3: Given a power graph G_L(V,E), the shortest-path-power for any two nodes v_i and v_j, SPP(v_i, v_j) is defined as the sum of weights on the links along the shortest path from v_i to v_j. □

Definition 4: Given a power graph G_L(V,E), the all-pair-shortest-path-power APSP is defined as:

$$\text{APSP} = \Sigma\ \text{SPP}(v_i, v_j), \forall (v_i, v_j) \in V. \quad □$$

If it is assumed that for message transmission all source destination pairs occur with equal probability, and routes in general follows the shortest paths, APSP can be considered as a good measure of the total transmission power required for communication in the network. The objective of this paper is to reduce this all-pair-shortest-path-power APSP to enhance the load capacity, and the lifetime of the network.

Given the original topology graph $G_R(V, E)$, which is a connected one, the proposed algorithm tries to find a new topology graph $G(V, E')$ in a distributed way, such that:
G consists of all the nodes in G_R but has fewer edges. i.e., $E' \subseteq E$
$G(V, E')$ remains connected
Every node $v_i \in G$ is assigned a transmission power $P_i \leq P$ such that for any pair of nodes, $SPP(v_i, v_j)$ is less than that required in the power graph of G_R, where each node transmits with the maximum power P.

It is evident that the graph G satisfying the above criteria will finally reduce the APSP consumed in the network for completing all pair shortest path communications.

The challenge is that we require a distributed algorithm without any central control. Therefore, nodes will not be aware of the whole topology. So, the objective is that with minimum local information, how nodes may assign their individual power levels so that the APSP can be minimized.

2.3 Previous Work

Various routing and topology control algorithms have been proposed for wireless ad-hoc networks in the literature. Those algorithms are mainly focused on establishing routes, and maintaining these routes under frequent and unpredictable connectivity changes [17], [18]. The implicit assumption in most of the earlier work is that nodes' transmitted powers are fixed. To the best of our knowledge, there is no prior known work that proposes the concept of mobile ad-hoc nodes using different transmit powers. It is evident that this approach is restricted to ad-hoc networks of relatively low mobility patterns. If the nodes are highly mobile, the power management algorithm might fail to cope with the fast and sudden changes due to fading and interference conditions. In [16], Bambos refers to power control as being widely accepted in the context of cellular (both channelized and CDMA) systems and satellite systems. On the other hand, he refers to the limited attention that power control has received in mobile ad-hoc networks. This work investigates the benefits, and possibly the tradeoffs; of deploying different transmit powers in the wireless ad-hoc environment.

Narayanaswamy et all [6] describes an algorithm that does topology control by assigning a common power level to all the nodes. Hu [8] describes an algorithm that does topology control using heuristics based on a Delauney triangulation of the graph. There seems to be no guarantee that the heuristics preserve connectivity. Ramanathan and Rosales-Hain [9] describe a centralized spanning tree algorithm for achieving connected and bi-connected static networks, while minimizing the maximum transmission power. (They also describe distributed algorithms that are based on heuristics and are not guaranteed to preserve connectivity.) Rodoplu and Meng [10] propose a distributed position-based topology control algorithm that preserves connectivity; their algorithm is improved by Li and Halpern [11]. Relative neighborhood graphs [14] and their relatives (such as Gabriel graphs, or Gί graphs [15]) are similar in spirit to the graphs produced by the cone-based algorithm.

Many of the previous papers on topology control have utilized position information, which usually requires the availability of GPS at each node. There are a number of disadvantages with using GPS. In particular, the acquisition of GPS location information incurs a high delay, and GPS does not work in indoor environments or cities. The cone-based algorithm [19] requires the directional information. That is, it must be possible to estimate the direction from which another node is transmitting. Also most of these algorithms use common transmission power for all the nodes, which can be further optimized significantly.

2.4 Our Contribution

Our objective is to study the problem of assigning transmission ranges to the nodes of a wireless multi-hop network so as to maximize the traffic carrying capacity of the entire network, extending battery life through providing low power routes under the constraint that adequate power is provided to the nodes to ensure that the network is strongly connected. These low power routes reduce the total power required for communicating between pairs of nodes.

We have developed a distributed algorithm by which each node gathers local information about the topology and based on that determines its transmission power with the objective to reduce the total transmission power T of the network. Our algorithm does not require any GPS information or directional information. It assigns the power-level of a node based on its local information only. When u receives a message from its adjacent neighbor v, it notes the reception power p'. We assume that from the transmission power p, and the reception power p', the node u can calculate the required power to reach v.

Our algorithm tries to find a subgraph G of G_R such that (1) G consists of all the nodes in G_R but has fewer edges, (2) if u and v are connected in G_R, they are still connected in G, and (3) a node u can transmit to all its neighbors in G using less power than is required to transmit to all its neighbors in G_R, where each node transmits with the maximum power P.

Since proposed **Node-Based-Power-Control** algorithm does not assign any common power-level for all the nodes so it may create many uni-directional links. But our subgraph is generated in such a way that if we ignore these uni-directional links from the resultant subgraph G then also the subgraph G remains connected. However it may result a marginal increase in T. Many of the existing routing protocols (e.g., AODV [23] and TORA [25]) were primarily designed only for bi-directional networks. While a few protocols (e.g., DSR [20] and ZRP [21]) have the capability to route packets using unidirectional links many others route packets only along the bi-directional links. Several problems in routing with unidirectional links are examined in [22].

We have studied the performance of our proposed algorithm by simulation. The performance is compared with the already proposed works. The performance of our algorithm is better compared to Common-Power [6] algorithm. Our algorithm is a distributed one and very simple which can be implemented easily. Also, nodes will transmit with a constant power provided the topology remains static. However, if topology changes due to the mobility or failure of nodes, our algorithm can adapt with the changes and re-compute the power levels at the affected nodes.

Chapter 3

Node-Based-Power-Control algorithm

3.1 Introduction

It has been already mentioned that the power required for communicating between nodes directly increases as the *n*th power of the distance between them, for some $2 \leq n \leq 6$ [5]. Therefore, it may require less power to relay messages from a source *u* through a series of intermediate nodes to destination *v* than to transmit it directly from *u* to *v*. Using this concept the proposed algorithm tries to reduce the range of every node such that the resultant graph remains connected, and APSP, the total power consumption gets reduced. By the proposed *Node-Based-Power-Control* algorithm, each node *u* discovers its local neighbors in a distributed fashion. Here follows a definition.

Definition 5: In a topology graph G, the set of all the nodes, which are reachable from a given node *u* by traversing at most *k* edges by the shortest route, is defined as the *k*-hop neighbor-set of *u* ($N^k(u)$).

In the initialization phase, each node transmits with the maximum power P, and discovers its 1-hop neighbors in G_R. Every node collects the weighted adjacency list from all its 1-hop neighbors in G_R. The weighted adjacency list of a node v is the list of all the 1-hop neighbors of v in G_R, along with their distances (in terms of required power) from v. It is assumed that when u receives a message from v, it measures the reception power p'. From the transmission power P, and the reception power p', the node u calculates the required power to reach v which is pr(u,v). This way the weighted adjacency list is generated.

So once u had the weighted adjacency list, it can delete all the edge (u, v), $v \in N(u)$, if there exists a vertex $k \in N(u)$, such that $pr(u, v) > pr(u, k) + pr(k, v)$.

Here follows the distributed algorithm for power control based on the information of 2-hop neighbors (k=2).

3.2 A Distributed algorithm for k = 2

Algorithm: Node-Based-Power-Control

Procedure for node u:

```
Broadcast (Hello(u))
While u receives a Hello-Message from v
in a certain TIMEOUT period
do
    add v to its 1-hop neighbor-list,
    calculate pr(u, v).
    add the edge (u, v, pr(u, v)) to its adjacency list.
```

```
Broadcast (1-hop-neighbor-list (u))
While u receives a 1-hop-neighbor-list message from v
do
    if there exist an edge (v, k, pr(v, k)) in this list, such that
    (u, k, pr(u, k))> (u, v, pr(u, v))+ (v, k, pr(v, k))
    then
        delete the edge (u, k, pr(u, k)) from its adjacency-list

Fixed the power level as the maximum of pr(u, v),
where (u, v, pr(u, v)) exists in its adjacency list.
```

Examples:

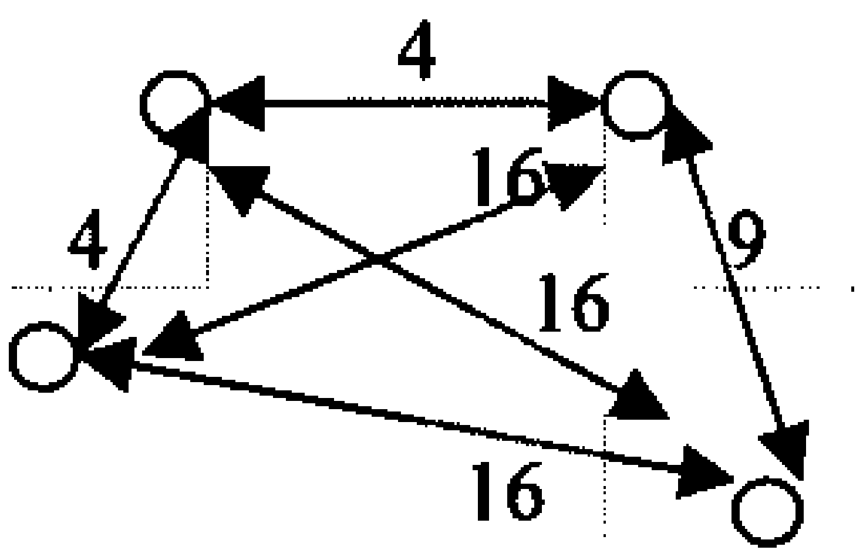


Figure 3.1.a
Topology Graph G_R

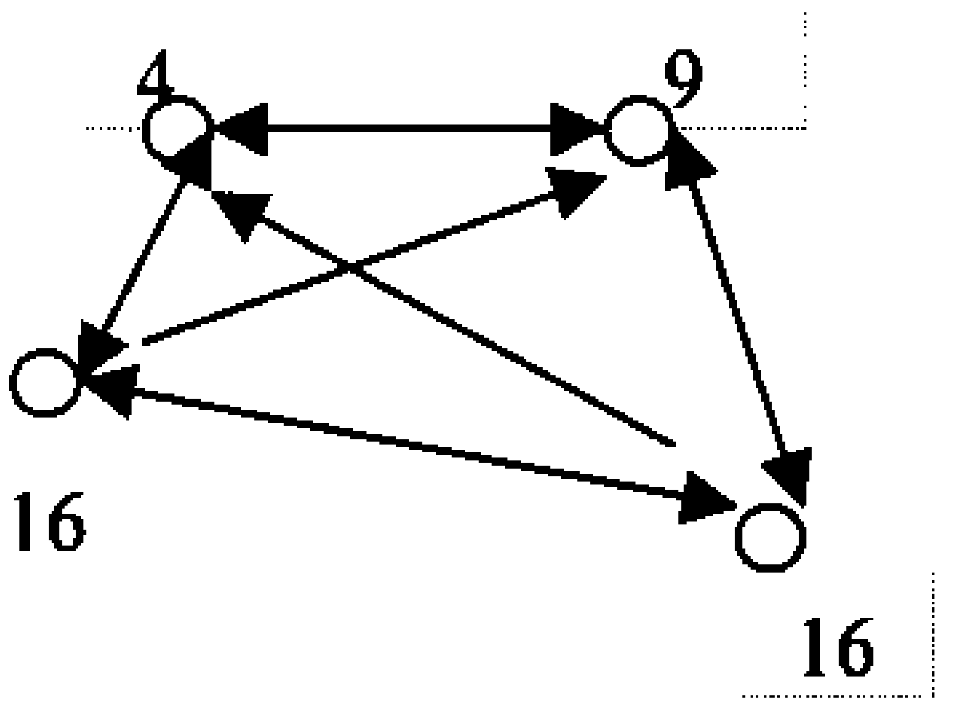


Figure 3.1.b
Reduced Subgraph G

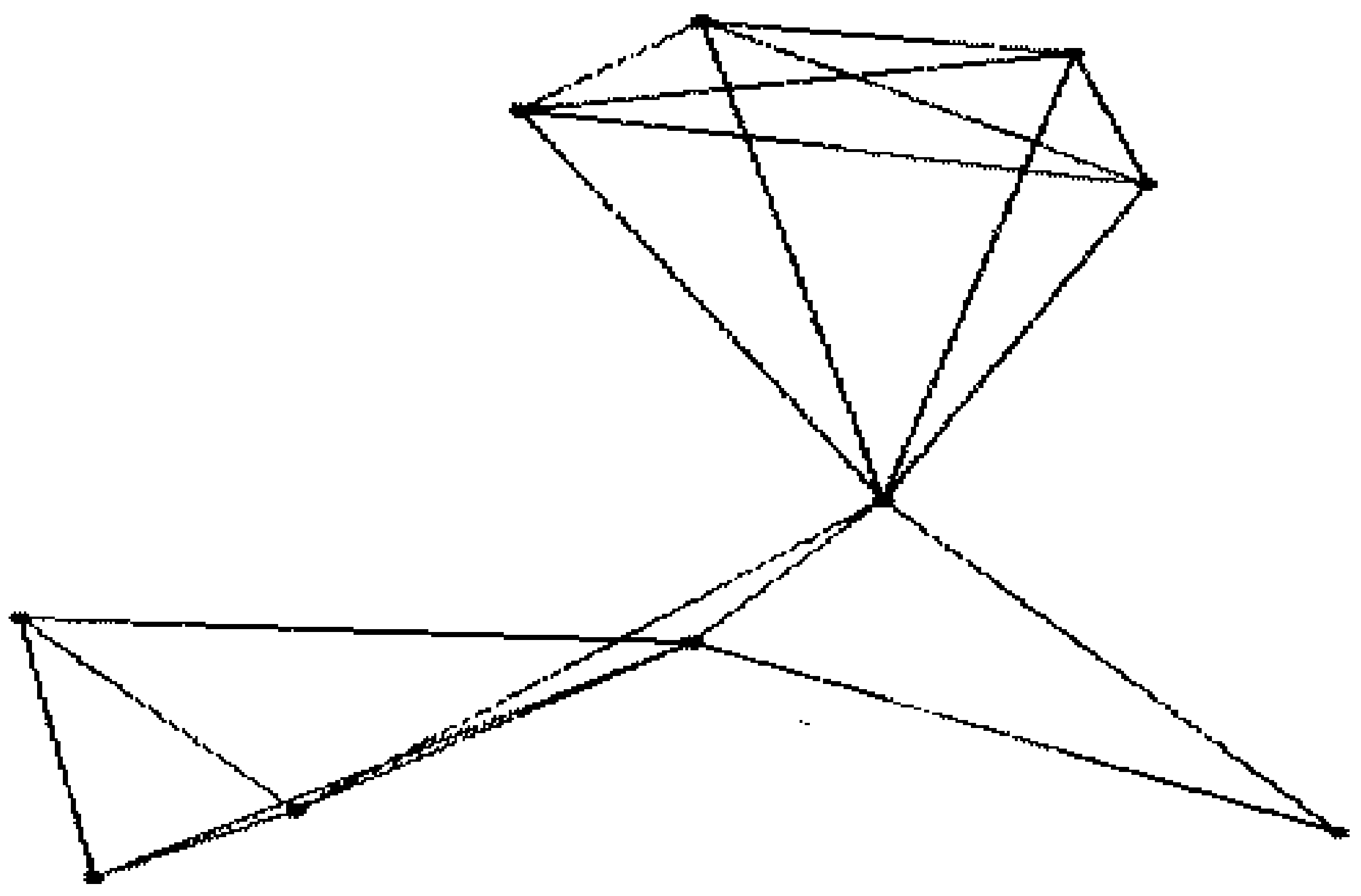


Figure 3.2.a
Program Generated Topology Graph G_R

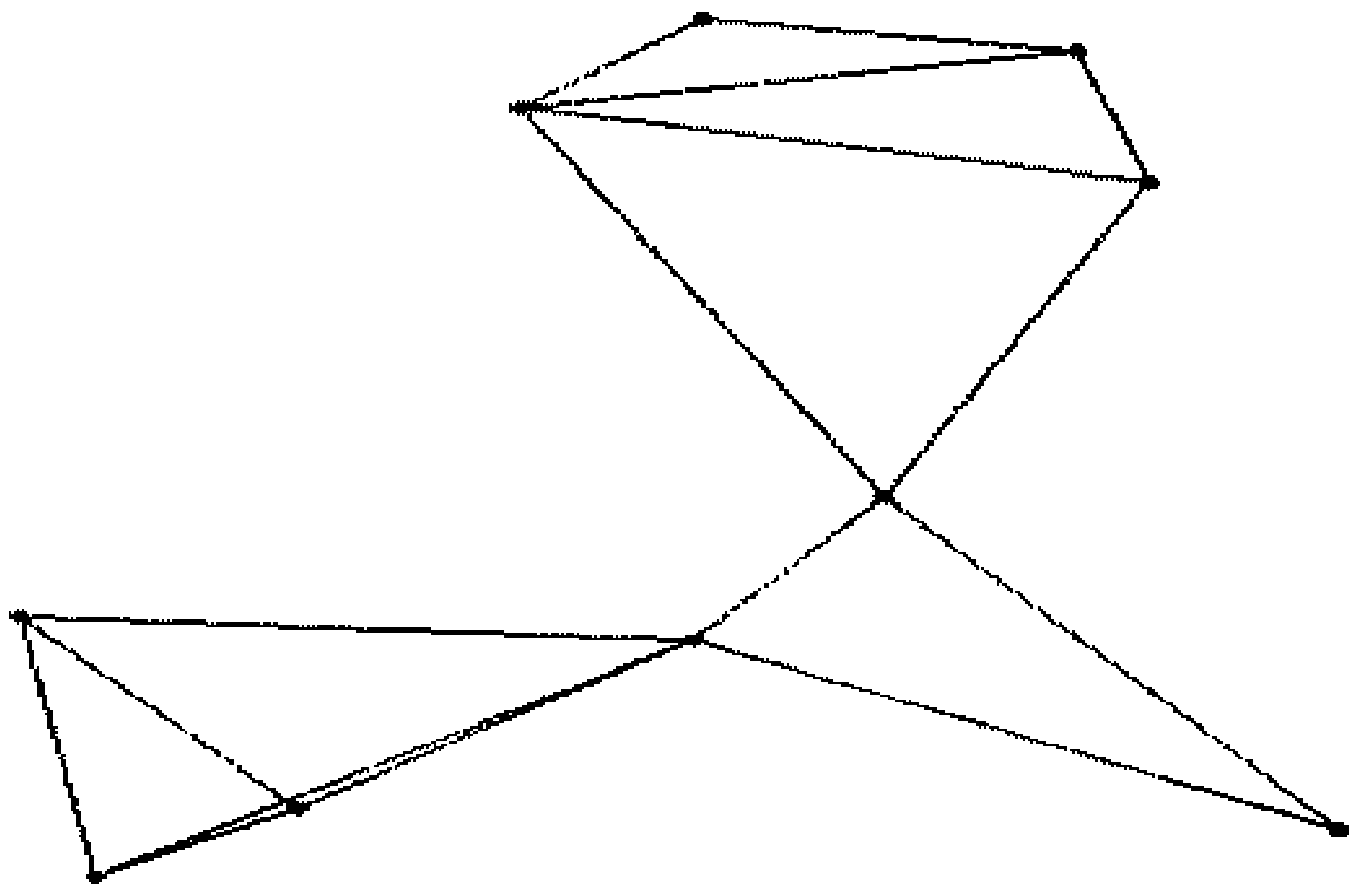


Figure 3.2.b
Reduced Subgraph G

3.3 Power-Control by k-hop Neighbors

Instead of considering only 2-hop neighbors, if each node collects information about farther neighbors, say, k-hop neighbors, $k>2$, it is expected that it would be able to remove power-inefficient edges to reduce its power level in a more efficient way. With this idea, an algorithm is developed and presented below.

In the proposed algorithm every node *u* collects information about its *k-hop* neighbor set $N^k(u)$ in G_R. Next, it constructs the induced subgraph $g^k(u)$, consisting of nodes $v \in N^k(u) \cup u$. It is termed here as the *k-hop graph* of u. It computes the shortest path routes to all the vertices of $N^k(u)$ from u. Next it removes all the edges from $g^k(u)$, which does not belong to any shortest path route. Finally, u decides its power-level $P_u = \max\{p(d(u, v)) | v \in N^1(u)\}$.

An outline of the procedure is given below.

Algorithm Power-Control: k-hop

```
For all the node u
        Find its k-hop neighbor set $N(u)$
        Build the k-hop graph $g(u)$
        Find the shortest path routes from u to all the vertices of $g(u)$
        Delete all the edges of $g(u)$ which does not occur in any shortest path route.
        Assign the range of $u$ as $\max\{p(d(u, v)) | (u,v) \in g(u)\}$
```

Example: for k=3

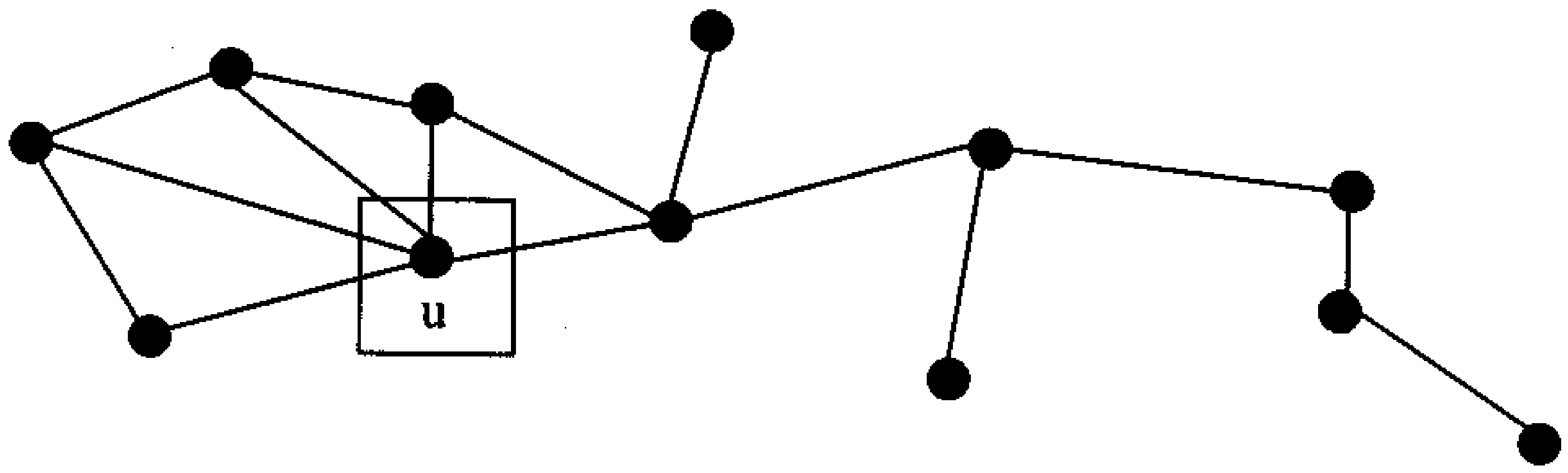


Figure 3.3.a
Initial Graph G

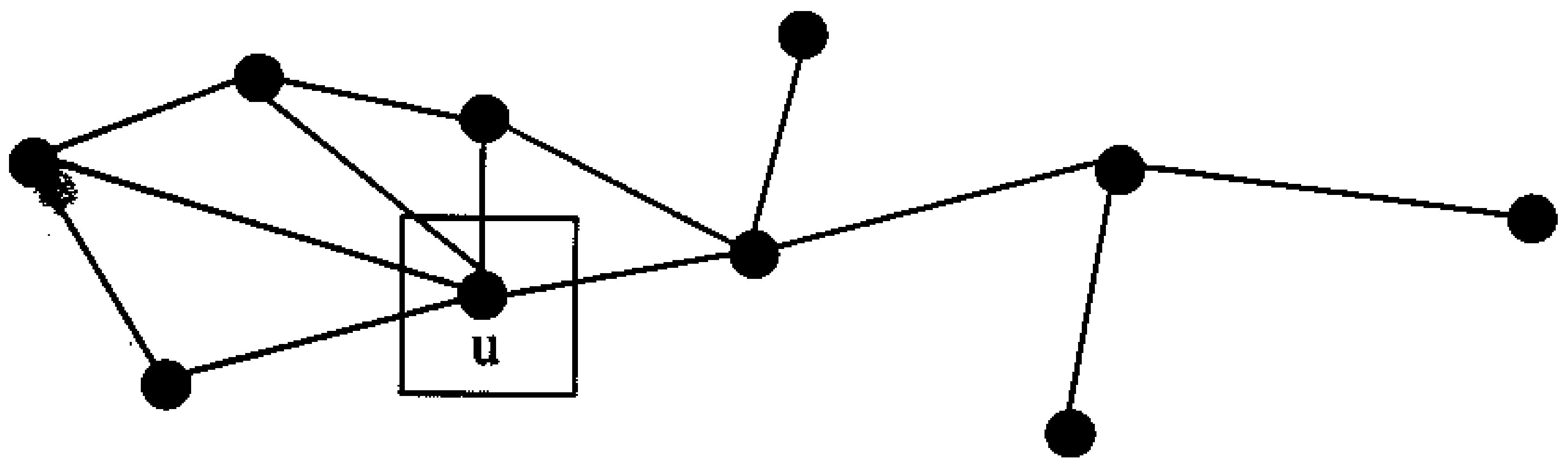


Figure 3.3.b
g(u) for 3-hop neighbor set

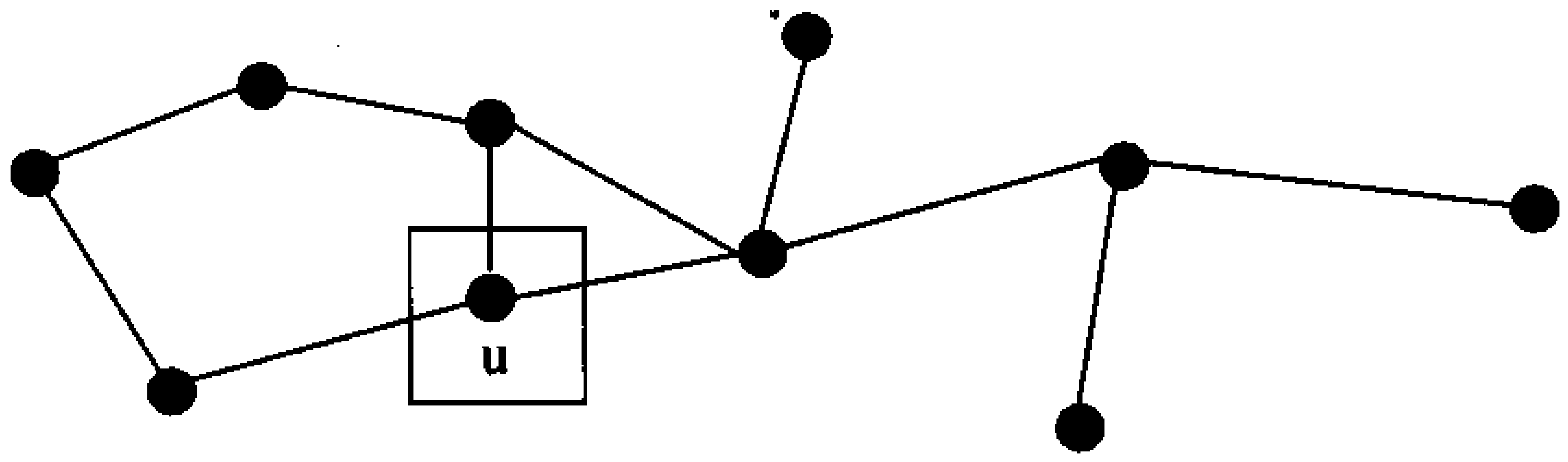


Figure 3.3.c
Reduced g(u)

3.4 Some Characteristics of the Reduced Graph

Some interesting characteristics of the reduced subgraphs generated by the proposed algorithm are presented below.

Lemma-1:

When Node-Based-Power-Control algorithm is applied to a graph G_R, it produces a directed graph G, which is strongly connected if and only if G_R is connected.

Proof: If G_R is not connected then G cannot be connected since we are only deleting edges; there is no addition of edges. So this part is trivial.
Now we have to show that if G_R is connected then G is also connected.
Let (u, v) be an edge in G_R. we are deleting (u, v) only when there are edges (u, k) and (k, v) such that pr(*u*, v))> pr(*u*, *k*)+ pr(k, v). So after the deletion of (u, v) they are still connected through the intermediate node k. Now the problem comes when (u, k) is also gets deleted. Similarly after the deletion of (u, k), there will be another vertex k' by which they will be connected. And it is clear that two lower weight edges are the cause of the deletion of a higher weight edges. So there is no cyclic effect means a lower weight edges will not be deleted because of a higher weight edge. So whenever an edge (u, v) is gets deleted we have two lower weight edges (u, k) and (k, v), so u, v is still connected in G. So the resultant graph is strongly connected.

Lemma-2:

When Node-Based-Power-Control algorithm is applied on a graph G_R, it produces a directed graph G, which contains all the shortest path edges of G.

Proof: Let the shortest path route of G_R from u to v is u, v_1, ... , v_k, v. Our claim is all these edges (u, v1),..., (v_k, v) are present in G. Otherwise let the edge (v_m-1, v_m) is not present in G, 2 ≤m≤k, that means there exists at least one intermediate node A such that d(v_m-1, v_m) < d(v_m-1, A) + d(A, v_m), but that contradicts the property of shortest path. Hence the proof.

3.5 Simulation Studies

The algorithm have been simulated for *k=2, 3, 4, and 5* on random graphs, and the performance metrics are compared. Random graphs have been generated by generating the coordinates of the nodes randomly on a 2-dimensional plane with corners (0, 0) and (400, 400). Simulation has been done by varying the number of nodes (*n*). Here we have considered n = 10,20,40,60,80, and 100. For each value of *n*, we have generated 50 random graphs, and then we took the average APSP, H, and S of these 50 graphs. The maximum transmission range for a node is assumed to be 150 for all the cases

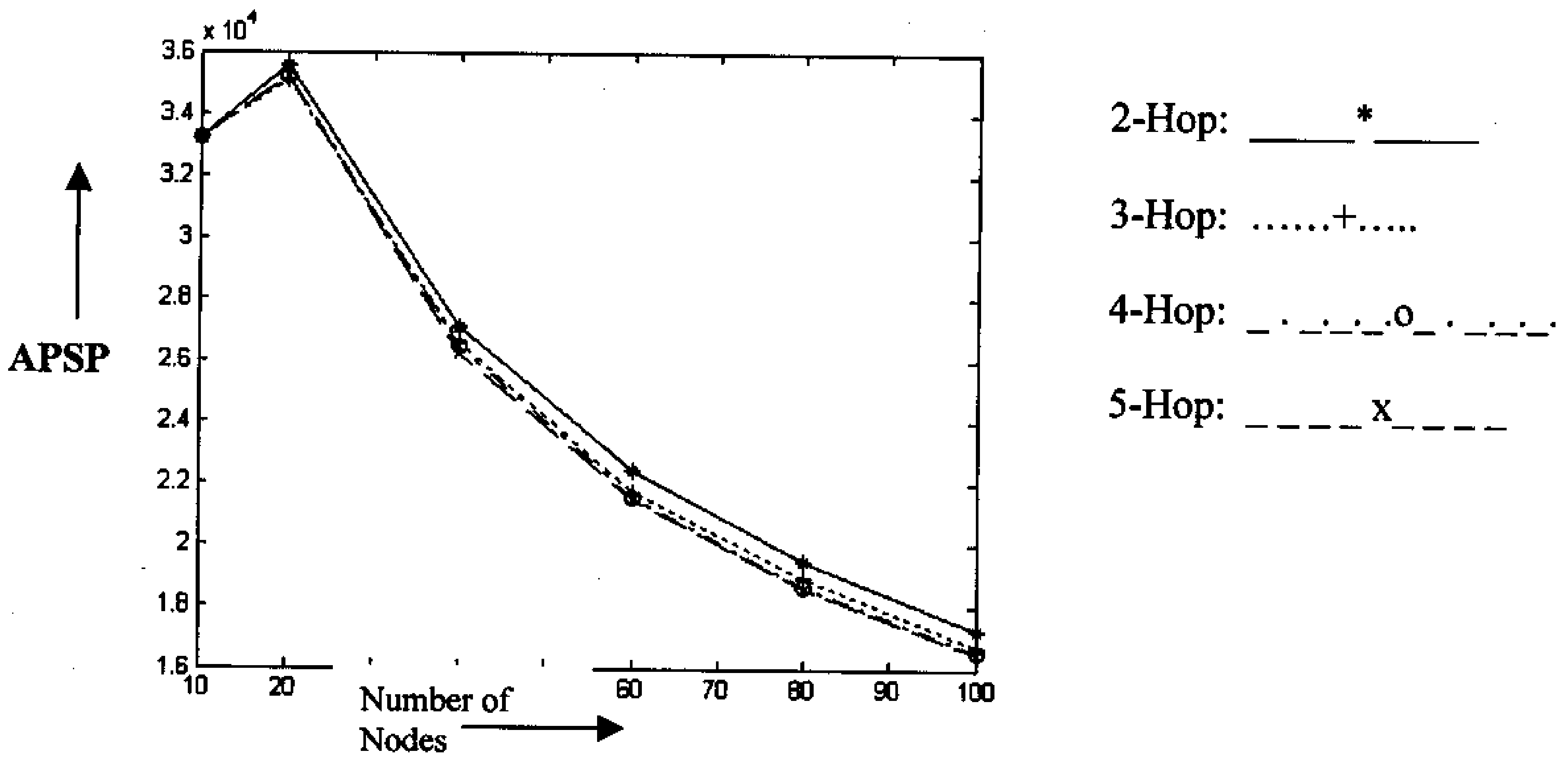


Figure 3.4
APSP Vs. Number of Nodes

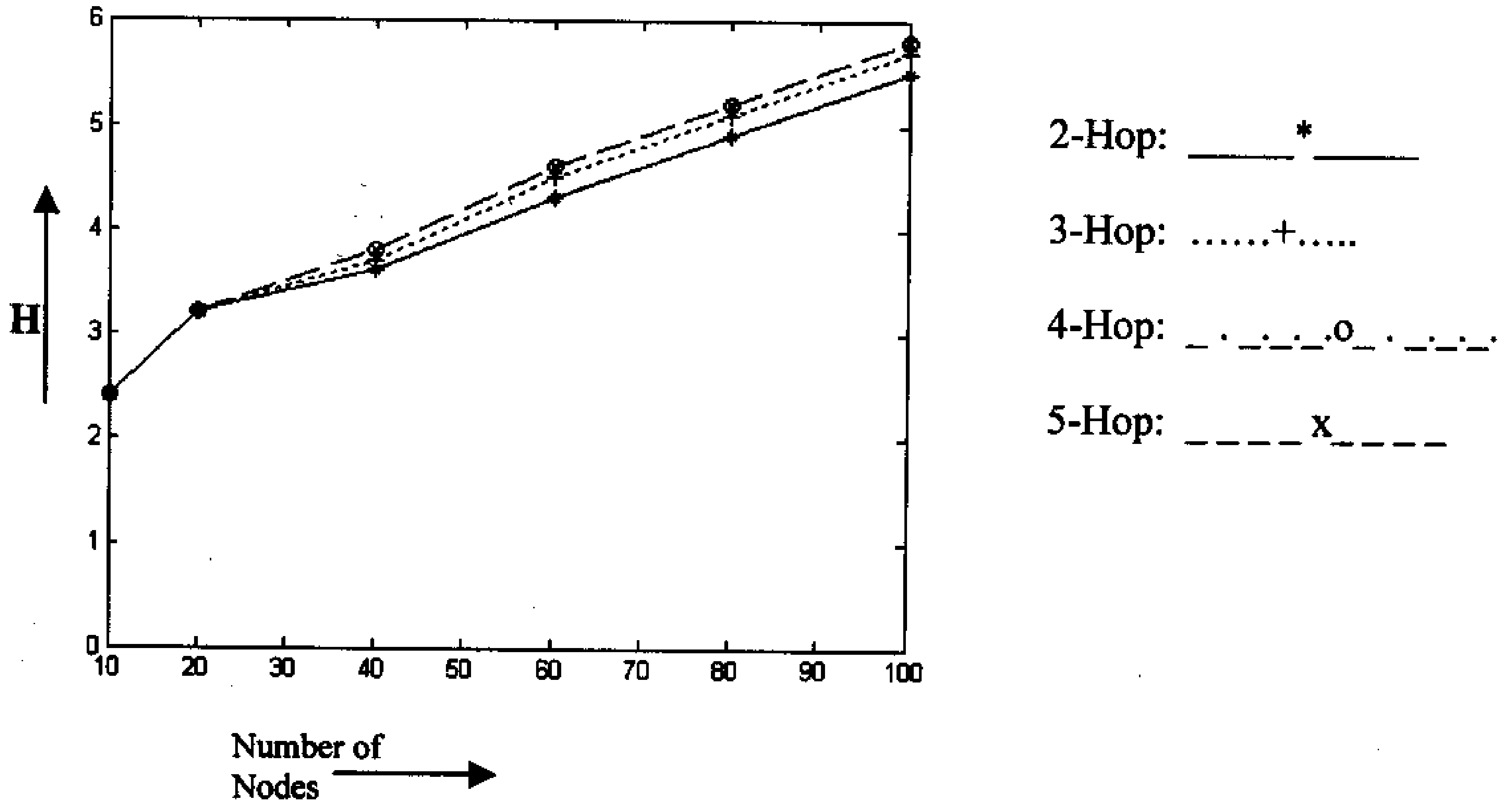


Figure 3.5
Hop Count Vs. Number of Nodes

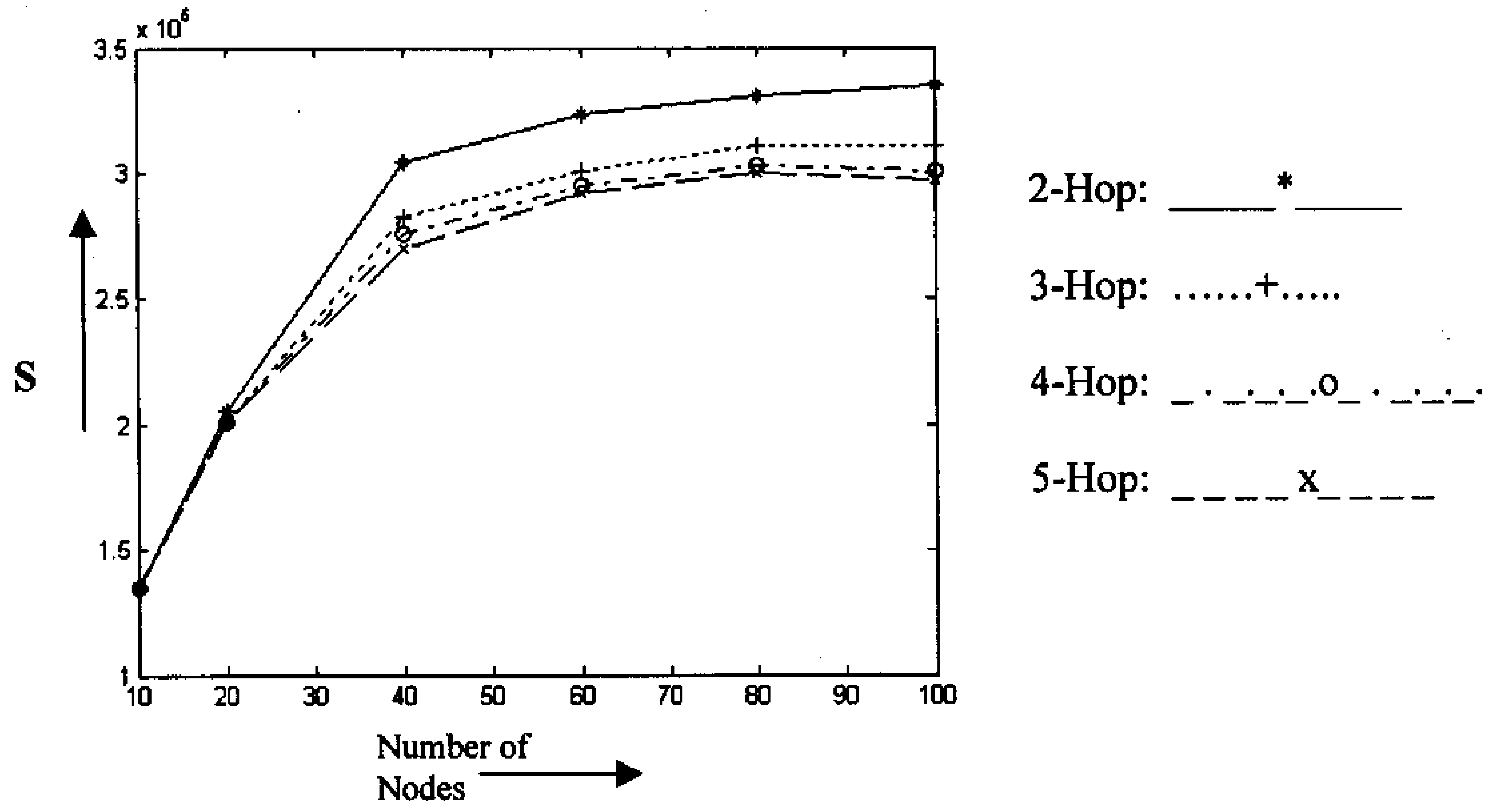


Figure 3.6
Sum of Power Vs. Number of Nodes

It is obvious that if greater value of k is used, a node can remove its redundant links, i.e., the links that require more power and hence is not included in any shortest route in a more efficient way. Hence, the node can optimize its power level in a better way. However, since nodes are allowed to fix its power level at a constant level, instead of using a link-level control, where a node controls its power level according to the requirement of each of its link, the power saving in each path is not maximized. Also, in an ad hoc network it is not very easy to discover nodes at 3-4 hops away in a distributed way, since it requires more message-passing, and more collision, making the procedure more complex and time consuming. From the simulation results it is clear that the improvement in performance is marginal for k >2. So, in the study of the performance evaluation of the proposed algorithm presented in the next section only the distributed algorithm for k=2 have been considered.

3.6 Routing

The common routing protocols for ad hoc networks, in general, assume bi-directional links. However, the protocols like DSR [20] and ZRP [21] have the capability to route packets using unidirectional links. Routing with unidirectional links is examined in [22].

AODV routing technique, with a little modification, can be used with this topology control algorithm. The modification is necessary because of the reduced subgraph G is a directed graph, so links are unidirectional. In the route discovery phase of AODV the forward direction will remain same, but while sending the acknowledgement there may arise a problem. Let (u, v) is a forward link by which a packet came from u to v, now while sending the acknowledgement the link (v, u) may not exist, since the links are not bi-directional. As (*u*, *v*) exist in G, so (*u*, *v*) was there in G_R so (*v*, *u*) was also there in G_R, so node *v* has deleted the link (*v*, *u*), that means there is a vertex *k* adjacent to *v* in G by which it can send back the acknowledgement to *u*. The modified AODV routing is implemented and simulated on random graphs.

However, in MAC layer, as IEEE 802.11 is the default protocol, and it always assumes bi-directional links, it is advantageous to provide only bi-directional links, so that the protocol can be used unaltered. Keeping that in mind, we have shown that if we delete the unidirectional links (means (u, v) is an edge but not (v, u)) of G then also G remains connected. So after deletion of unidirectional edges all the remaining links of G are bi-directional and G is still connected. In this case the total power consumption will increase slightly but existing algorithms, which works for bi-directional links, can be used.

Chapter 4

Performance Evaluation

Basically, the distributed algorithms proposed here for power control in individual nodes, attempts to control the topology of the network to reduce the total power consumption in the network. Reducing energy consumption has been viewed as perhaps the most important design metric for topology control. There are two standard approaches to reduce energy consumption: (1) reducing the transmission power of each node as much as possible, i.e., minimizing ΣP_i , and, (2) reducing the total energy consumption through the preservation of minimum-energy paths in the underlying network. These two approaches may conflict: reducing the transmission power required by each node may not result in minimum energy paths (see [7] for a discussion) or vice versa. Furthermore, there are other metrics to consider, such as network throughput and network lifetime (This is particularly true if the main reason that nodes die is due to loss of battery power). In this section we will show the performance of our algorithm with respect to other algorithms for power control proposed so far. Here we have assumed that all source-destination pairs are equi-probable, so by calculating the **APSP** in some randomly generated graphs can test the performance. We are also computing the average number of hops (**H**) per message and sum of power $\mathbf{S=\Sigma P_i}$, where $\mathbf{P_i}$ is the power level of $\mathbf{i^{th}}$ node.

We have considered the performance metrics **APSP, H,** and S for the performance comparison of the following four algorithms:

I. Least-Power: In this case nodes does not have any fixed transmission power, it can vary depending upon the distance of the next node in the route. Here we have used all-pair shortest path routing algorithm in the original graph G and the weight of edge (u, v) is pr(u, v). This gives us the least possible total power consumption for all-pair shortest path communication.

II. Maximum-Power: In this case we didn't use any power control algorithm. The nodes always transmit in the maximum power. Here also we have used all-pair shortest path routing algorithm in the original graph G, but in this case the edge weights are always equal to the maximum power.

III. Common-Power: Common-Power [6] algorithm assigns a common power level to all the nodes which is the minimum one required to keep the reduced graph G2 connected. Then in this reduced graph G2 we have applied all-pair shortest path routing algorithm to route the packets. In this case all the nodes transmits with a common power.

IV. Node-based Power Control: Our node-based-power-control algorithm is applied in G to get the reduced graph G1. Then in this reduced graph G1 we have applied all-pair shortest path routing algorithm to route the packets. In this case a node transmits in a fixed power, but the transmission power of two different nodes may be different.

Example:

The performance measures **APSP, H,** and **S** for the following graphs are:

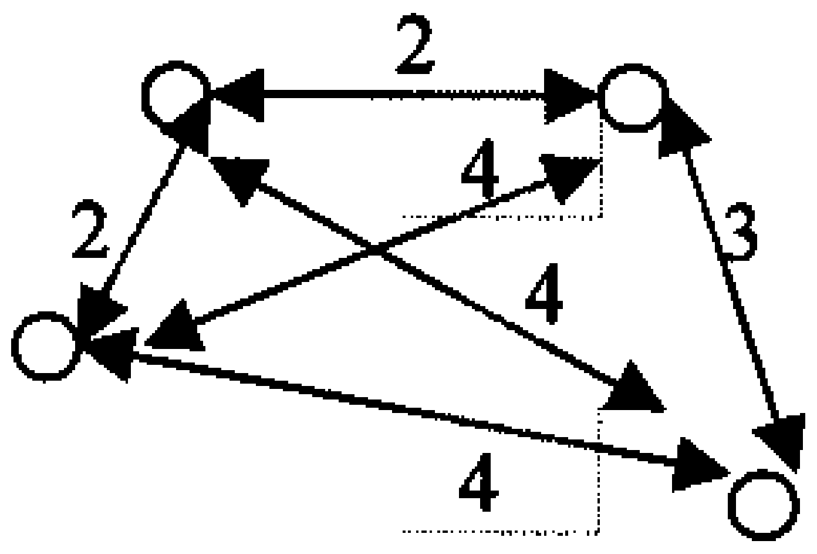


Figure 4.1.a
Initial Graph

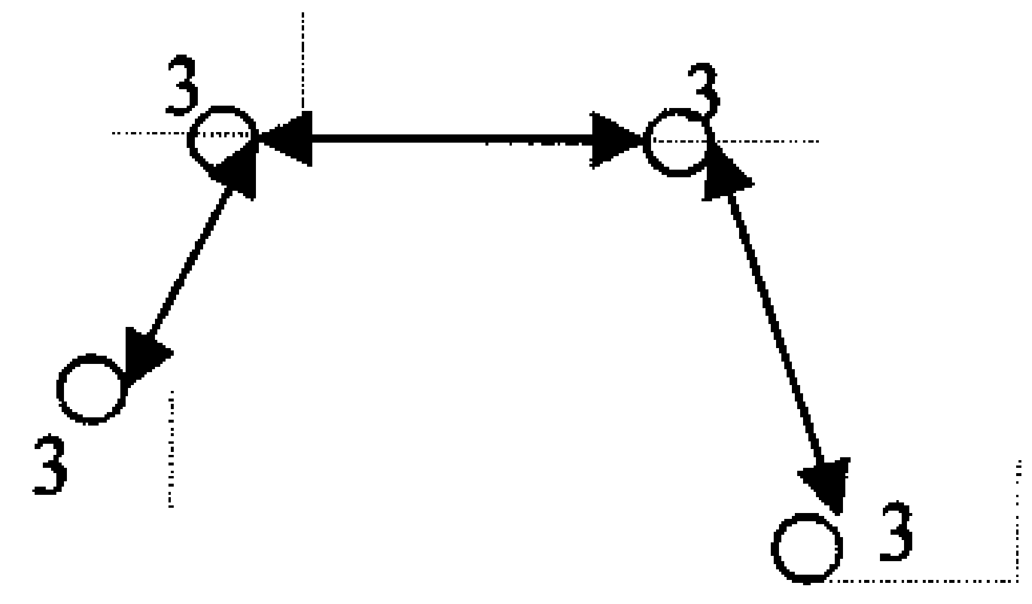


Figure 4.1.b
Reduced graph for common power algorithm

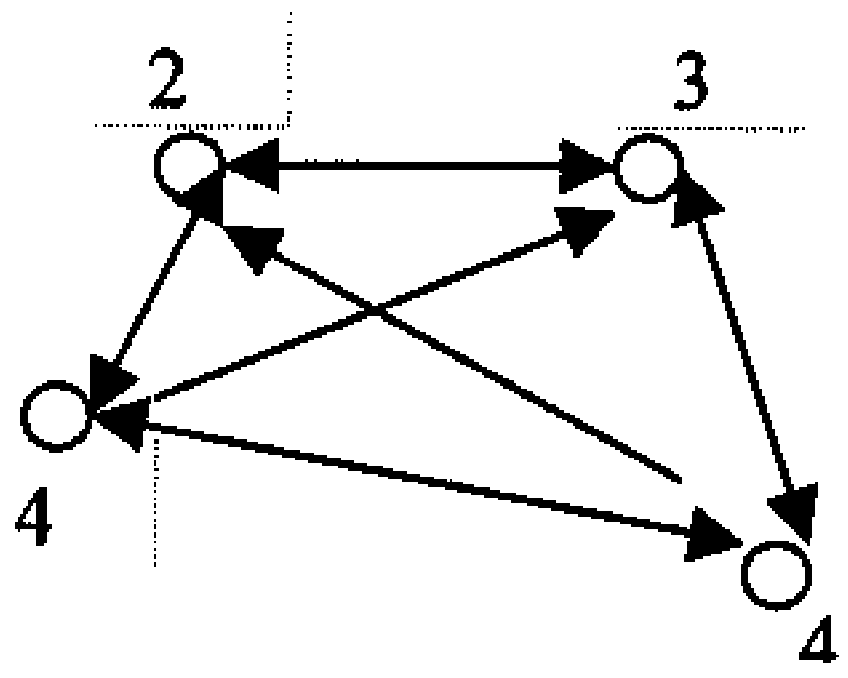


Figure 4.1.b
Reduced graph for node based power control algorithm

Table I: Comparison of Performance for the above graph

Algorithms Performance Measures	Least-Power	Maximum-Power	Common-Power	Node-Based-Power-Control
APSP	108	192	180	148
Average Hop Count	1.25	1.0	1.67	1.17
Sum of Power	--	64	36	45

Comparison of Total Cost

The four algorithms have been simulated on random graphs, and the performance metrics are compared. Random graphs have been generated by generating the coordinates of the nodes randomly on a 2-dimensional plane with corners (0, 0) and (400, 400). Simulation has been done by varying the number of nodes (*n*). Here we have considered n = 10,20,40,60,80, and 100. For each value of *n*, we have generated 50 random graphs, and then we took the average APSP, H, and S of these 50 graphs. The maximum transmission range for a node is assumed to be 150 for all the cases.

Table II: Comparison of APSP

Algorithms Number of nodes	Least Power Path	Maximum-Power	Common-Power	Node-based-Power-Control
10	24190	36654	41248	33202
20	23190	42678	47461	35562
40	16155	41231	37910	27100
60	13011	41475	29620	22419
80	11234	41525	24906	19499
100	9940	41599	23361	17253

Table III: Comparison of Hop Count (H)

Algorithms Number of nodes	Least Power Path	Maximum-Power	Common-Power	Node-based-Power-Control
10	2.6	2.0	2.3	2.4
20	3.9	2.3	3.0	3.2
40	5.2	2.1	3.4	3.6
60	6.4	2.0	4.7	4.3
80	7.5	2.0	5.0	4.9
100	8.5	2.0	6.1	5.5

Table IV: Comparison of Sum of Power-level of all the nodes (S)

Algorithms Number of Nodes	Maximum-Power	Common-Power	Node-based-Power-Control
10	225000	180608	134842
20	450000	321230	205750
40	900000	469928	304349
60	1350000	401319	323541
80	1800000	409996	330864
100	2250000	411185	334837

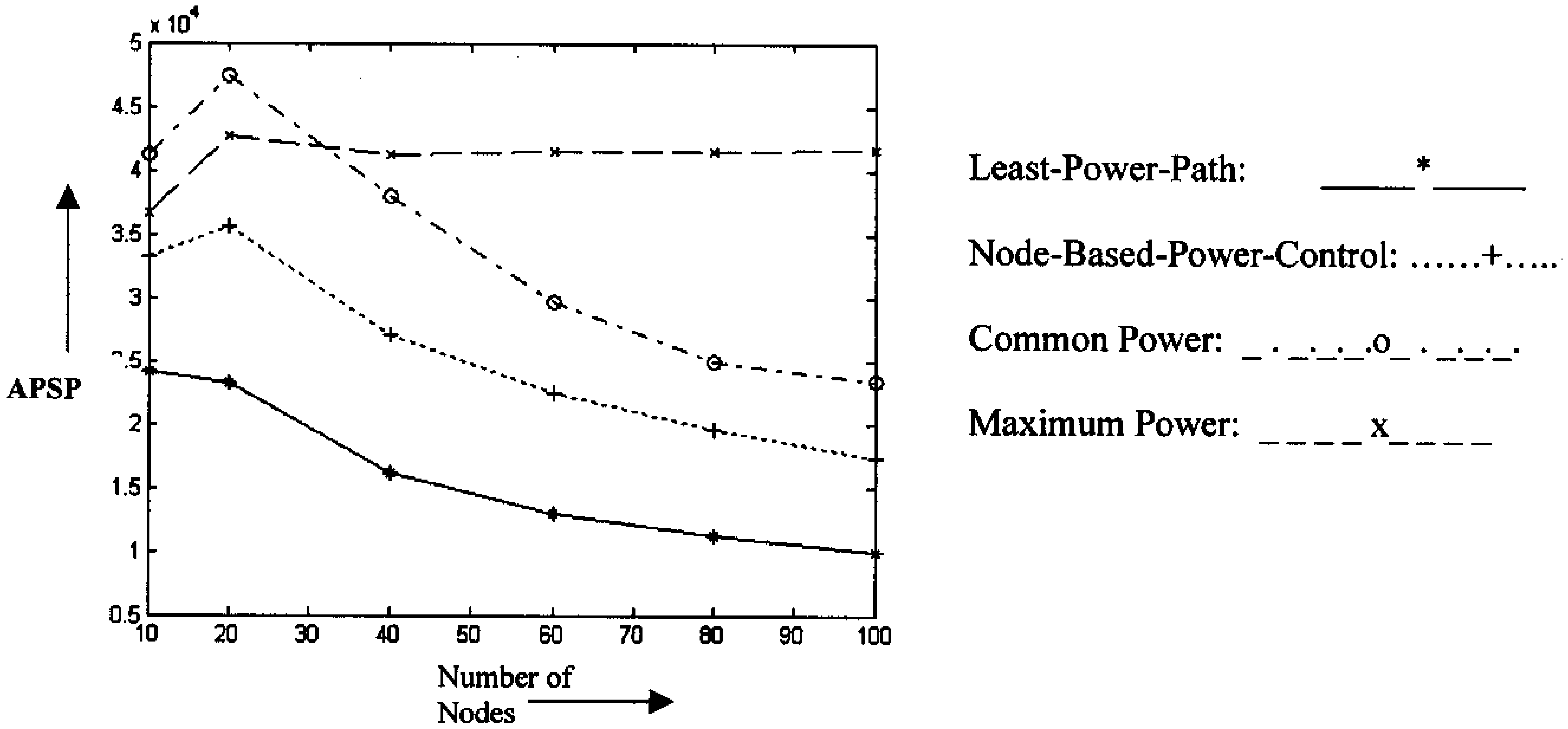


Figure 4.2
APSP Vs. Number of Nodes

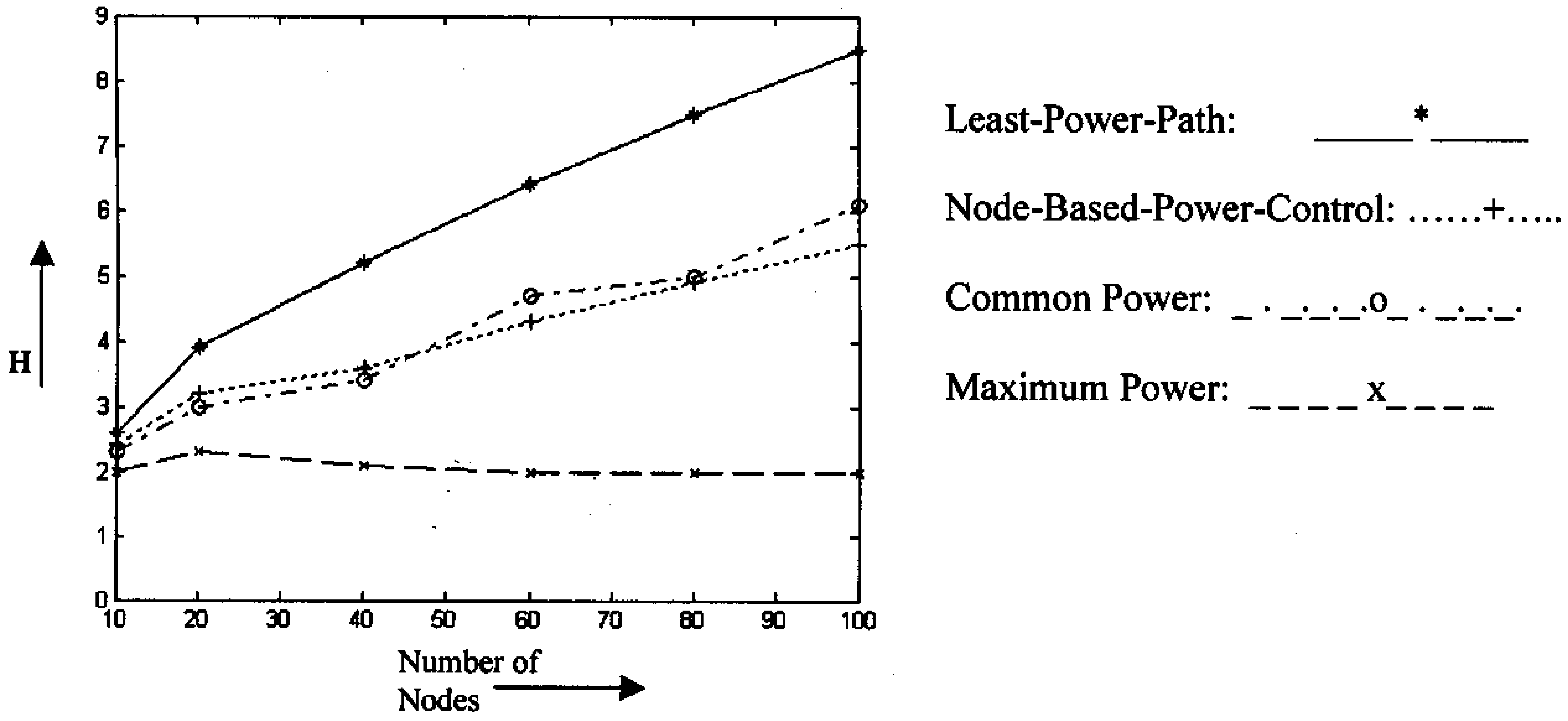
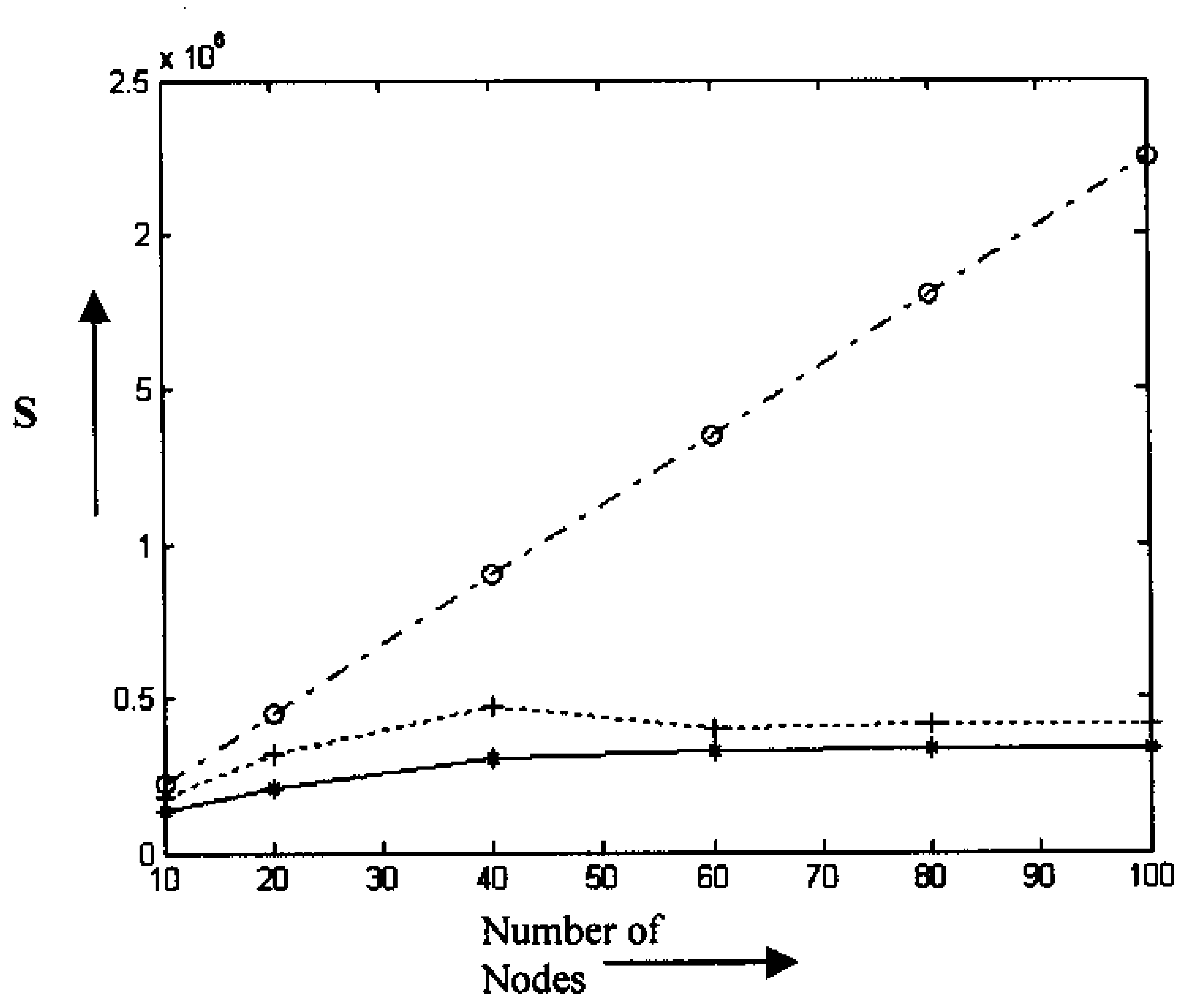


Figure 4.3
Hop Count Vs. Number of Nodes



Maximum Power: _____*_____

Node-Based-Power-Control: ......+.....

Common Power: _ . _._._.o_ . _._._.

Figure 4.4
Sum of Power Vs. Number of Nodes

Chapter 5

Conclusion

The power control is a promising technique for enhancing the performance of wireless ad-hoc networks. However, few power control objectives in the network contradict with each other. For example, throughput and energy, link quality and throughput, delay and throughput, and energy and link quality, are some orthogonal requirements in ad-hoc networks. The power control has become a necessity for the present communication networks and the future broadband wireless networking will rely on power control. Achieving the power control in a distributed technique is challenging. We have provided a distributed power control algorithm, in which every node decides its power level based on the local information. Most importantly simulation results show that it is very effective in reducing total power consumption.

Reducing energy consumption has been viewed as perhaps the most important design metric for topology control. There are two standard approaches to reduce energy consumption: (1) reducing the transmission power of each node as much as possible; (2) reducing the total energy consumption through the preservation of minimum-energy paths in the underlying network. These two approaches may conflict: reducing the transmission power required by each node may not result in minimum energy paths (see [7] for a discussion) or vice versa. Furthermore, there are other metrics to consider, such as network throughput and network lifetime (This is particularly true if the main reason that nodes die is due to loss of battery power). However there is no guarantee that it will. For example, using minimum-energy paths for all communications may result in hot spots and congestion, which in turn may drain battery power and lead to network partition. If topology control is not done carefully, network throughput can be hurt. As eliminating edges may result in more congestion and hence worst throughput, even if it saves power in short run. The right tradeoffs to make are very much application dependents. We hope to explore these issues in more details in future work. Since proposed Node-Based-Power-Control algorithm does not assign common power-level for all the nodes so it may create many uni-directional links. But our subgraph is generated in such a way that if we ignore these uni-directional links from the resultant subgraph G then also the subgraph G remains connected. However it may result a marginal increase in T. Many of the existing routing protocols (e.g., AODV [23] and TORA [25]) were primarily designed only for bi-directional networks. While a few protocols (e.g., DSR [24] and ZRP [21]) have the capability to route packets using unidirectional links many others route packets only along the bi-directional links. Several problems in routing with unidirectional links are examined in [22].

We have studied the performance of our proposed algorithm by simulation. The performance is compared with the already proposed works. The performance of our algorithm is better compared to Common-Power algorithm [6]. Our algorithm is a distributed one and very simple which can be implemented easily. Also, nodes will transmit with a constant power provided the topology remains static. However, if topology changes due to the mobility or failure of nodes, our algorithm can adapt with the changes and re-compute the power levels at the affected nodes.

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