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Scalable energy-efficient routing in mobile Ad hoc network

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Abstract

The quick deployment without any existing infrastructure makes mobile ad hoc networks (MANET) a striking choice for dynamic situations such as military and rescue operations, disaster recovery, and so on and so forth. However, routing remains one of the major issues in MANET due to the highly dynamic and distributed environment. Energy consumption is also a significant issue in ad hoc networks since the nodes are battery powered. This report discusses some major dominating set based approaches to perform energy efficient routing in mobile ad hoc networks. It also presents the performance results for each of these mentioned approaches in terms of throughput, average end to end delay and the life time in terms of the first node failure. Based on the simulation results, I identified the key issues in these protocols regarding network life time. In this report, I propose and discuss a new approach "Dynamic Dominating Set Generation Algorithm" (DDSG) to optimize the network life time. This algorithm dynamically selects dominating nodes during the process of routing and thus creates a smaller dominating set. DDSG algorithm thereby eliminates the energy consumption from the non-used dominating nodes. In order to further increase the network life time, the algorithm takes into consideration the threshold settings which helps to distribute the process of routing within the network. This helps to eliminate a single dominating node from getting drained out by continuous transmission and reception of packets. In this report, the detailed algorithmic design and performance results through simulation is discussed.

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List of Acronyms

AODV	Ad Hoc On Demand Distance Vector
ATIM	Announcement Traffic Indication Message
DDSG	Dynamic Dominating Set Generation
DIFS	Distributed inter frame space
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
IBSS	Independent Basic Service Set
k-SPR	k-shortest path routing
k-SPRI	k-shortest path routing (I for ID)
k-SPRC	k-shortest path routing (C for covering number)
k-SPRE	k-shortest path routing (E for Energy)
MANET	Mobile Ad Hoc Network
MPR	Multipoint Relay
NDP	Neighbor Discovery Protocol
NON-PSM	Non Power Saving Mode
NP	Non-deterministic Polynomial time
OSPF	Open Shortest Path First
PSM	Power Saving Mode
SIFS	Short inter frame space
ZRP	Zone Routing Protocol

1 Introduction

In contrast to infrastructure based wireless networks, Mobile Ad-Hoc Networks are collections of nodes which are formed on the fly without the need of any existing network infrastructure or centralized control. This may be done either because it may not be economically practical or physically possible to provide the necessary infrastructure or because the situation does not permit its installation. Some typical applications of MANET include military, industrial and commercial applications involving mobile data exchange or satellite based information. MANET can be used for rescue operations or other situations which require rapidly-deployable communications with reliable dynamic networking. In such situations, devices communicate directly with each other and by forming chains of transceivers they relay information through other devices in order to reach the final destination. Each node in a MANET network itself acts as a router and is responsible for discovering and maintaining routes to other nodes.

2 Background and related studies

In the case where only two hosts within the transmission range are involved in the ad hoc network, no real routing protocol or routing decisions are necessary. But in many practical ad-hoc networks, two hosts that wish to communicate may not be close enough to be within wireless transmission range of each other. These hosts could communicate if the intermediate hosts between them in the ad-hoc network are willing to forward packets for them. The first generation of protocols called as the table driven protocols such as DSDV maintain the current routing information from every node to every other single node in the network with the main objective being increasing the throughput and decreasing the response time. The routing tables in these protocols are refreshed periodically to maintain the updated information.

But it was soon realized that every node maintaining route information to all other nodes in the network is not quite efficient. For example in a large ad hoc network consisting of thousands of nodes, the amount of routing information is proportional to the size of the network. Hence to achieve scalability, hierarchical routing protocols have been proposed. In this group of protocols, a network is divided and certain small set of nodes are selected. Only the selected smaller set of nodes has the responsibility of maintaining the complete view of the network while other nodes can maintain only a local view. Another way of achieving scalability is through the source initiated on demand protocols. Examples of this approach include AODV or DSR. In this case the path to reach a destination is discovered only on demand through a route discovery phase.

Nodes in an ad-hoc network can be heterogeneous with different computation, storage and communication capabilities. Power consumption is yet another critical issue, since nodes in ad hoc networks are constantly involved in forwarding packets sent by other nodes. Mobile nodes are often powered by batteries that have a finite amount of energy. As a consequence, the conservation of energy is of primary concern for ad hoc networks. Taking this into consideration a third group of protocols have been proposed in which routes are selected based on the energy required to deliver the packet from the source to the destination.

There are various approaches adopted by energy efficient protocols. The following section discusses them in brief.

2.1 Energy aware routing protocols

Energy aware routing protocols can be divided into four categories [9]:

- Minimum transmit power protocols
  These set of protocols determine the least power consuming path for an end to end transmission of packet.

- Transmit power control protocols
  These protocols vary the transmission power to reduce power consumption based on the distance to the receiver.

- Maximum lifetime protocols
  As the name suggests, these protocols increase the network lifetime by avoiding the nodes with less energy.

- Power save protocols
  For protocols that belong to this category, each node saves the idle energy consumption by switching to low power/sleep mode whenever the node has no data to transmit or receive.

3 Summary of CS297 Study: Dominating Set Based Routing in Ad hoc Networks

3.1 Motivation:

Conventional wired network protocols usually make use of link-state routing protocol or distance vector routing protocol. However, these protocols can not be used in an ad hoc environment. In a mobile network, mobile nodes act as routers. Thus the convergence to fresh, stable routes using these protocols for frequent topological changes will be slow. Also this process will be expensive since bandwidth is limited in case of an ad hoc network. To accommodate these topological changes a number of messages have to be sent/received which would again require a lot of energy. Thus this results in the need for localizing the routing information after host movements. One of the approaches to achieve this is to select certain set of nodes from the ad hoc network known as gateway nodes for routing. These gateway nodes form a dominating set and are responsible for maintaining the routing information for the network. Hence there is no requirement for the nodes in the sub network to recalculate the routing tables. These gateway nodes can be connected to reduce the process of routing within the connected dominating set.

Thus to achieve scalability, many protocols have been proposed which make use of this dominating set concept in an ad hoc network. I will discuss some of them in detail in the next few sections. Since the mobile devices are powered by batteries, energy is a key issue and maintaining network connectivity a significant task. So these protocols make use of IEEE 802.11 Power Saving Mode for ad hoc network where only selected set of nodes (dominating nodes in this case) are awake throughout the network life time and rest of the nodes conserve energy by going to sleep mode.

3.2 Dominating set

Ad hoc networks are typically represented by a connected graph where the links are bi-directional, in which nodes represent devices and links between the two nodes represent that the hosts are within their transmission ranges.

It is quite evident that routing together with gathering and maintaining route information poses heavy burden on the ad hoc network devices since transmission power and bandwidth are major constraints. Thus in order to achieve scalability only a subset of all nodes chosen for the routing tasks, could lead to a more efficient use of the network resources. Routing based on dominating set seems to be a promising approach for this.

Definition for dominating set [13]: “A subset of the vertices of a graph is a dominating set if every vertex not in the subset is adjacent to at least one vertex in the subset.”

The desirable features of dominating set formed for an ad-hoc network is as follows [15]:

- The formation process should be simple.
- The resulting dominating set needs to be connected and small in size
- It should contain shortest paths

Many researchers have used minimal connected dominating set to induce a virtual backbone in an ad-hoc network. Although the task of finding the minimal connected dominating set is NP-complete, Wu and Li proposed an algorithm that finds a connected dominating set in a given graph. In the next few sections, four such algorithms based on dominating set are discussed with two of them in detail.

3.3 Wu & Li’s algorithm - Marking Process

J. Wu and H. Li proposed a simple and efficient distributed algorithm to form a dominating set based on the local neighborhood information. To further reduce the number of dominating nodes in a network two refinements were added.

This section explains the marking process [14] for a graph G = (V, E) where V represents a set of wireless mobile hosts and E represents a set of edges between them. Edges between the wireless hosts indicate that they are within the wireless transmitter range of each other. Every vertex will be marked as T (marked) or F (unmarked). It is assumed that all vertices are unmarked initially. N(v) represents the open neighbor set of vertex v.

3.3.1 Marking process [14]:

1. Initially, assign marker F to each v in V
2. Each v exchanges its open neighbor set N(v) with all its neighbors'
3. Each v assigns its marker m (v) to T if there exists two unconnected neighbors.

The dominating set formed by the above marking process has the following properties. Below we just list the properties without any discussion of proof.

Theorem 1: Given a graph G = (V,E) that is connected, but not completely connected, the vertex subset V1, derived from the marking process, forms a dominating set of G.

Theorem 2: The reduced graph G1= G [V1] is a connected graph.

Theorem 3: The shortest path between any two nodes does not include any non-dominating node as an intermediate node.

Refinements:

Rule #1: Consider two vertices v and u in G1. If N[v] $\subseteq$ N[u] in G1 and id(v) < id(u), change the marker of v to F if node v is marked, i.e., G1 is changed to G1-{v}

Rule #2: Assume u and w are two marked neighbors of marked vertex v in G1.
If N(v) $\subseteq$ N(u) U N(w) in G and id(v) = min{id(v), id(u), id(w)}, then change the marker of v to F.
Example:

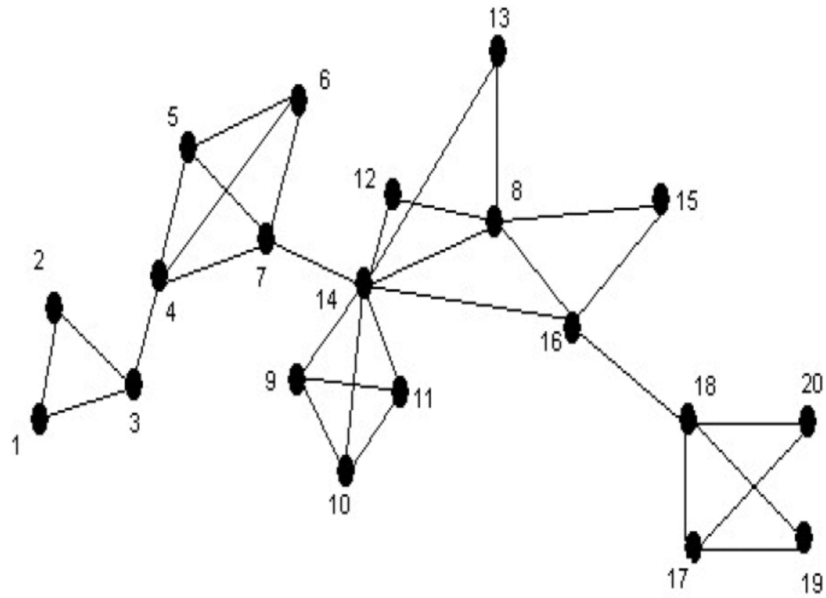


Figure 1: Initial graph of ad-hoc wireless network

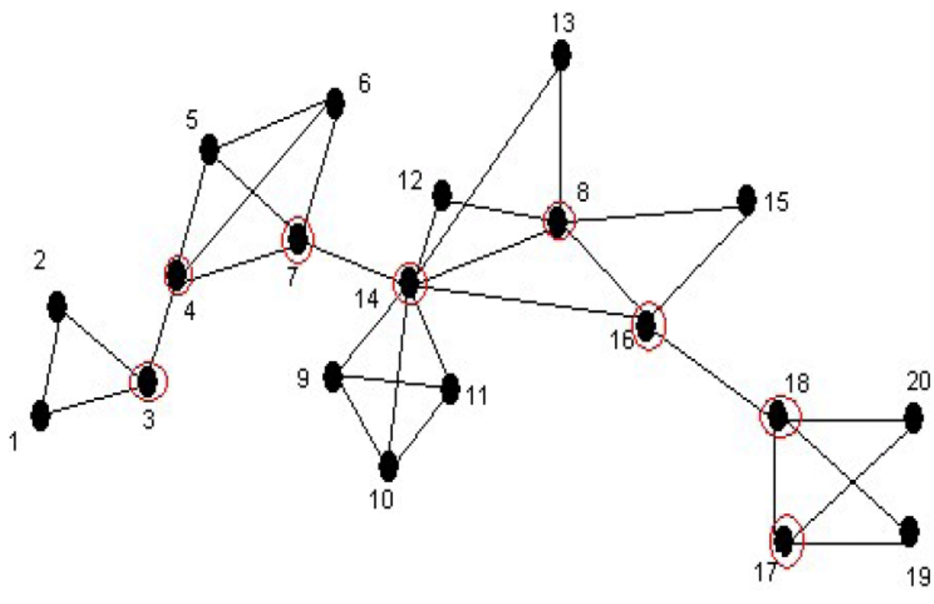


Figure 2: After marking process

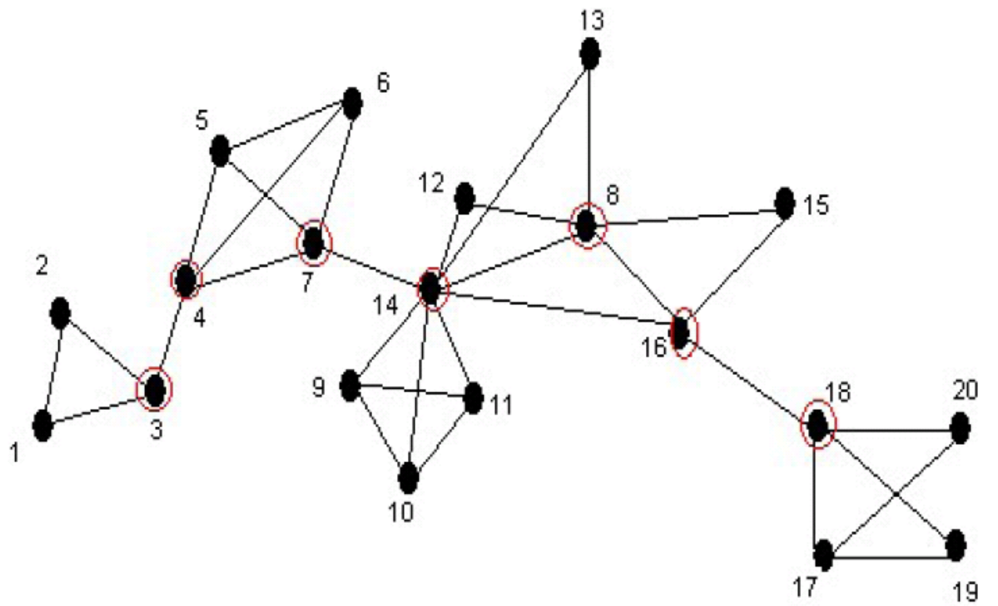


Figure 3: After applying Rule#1

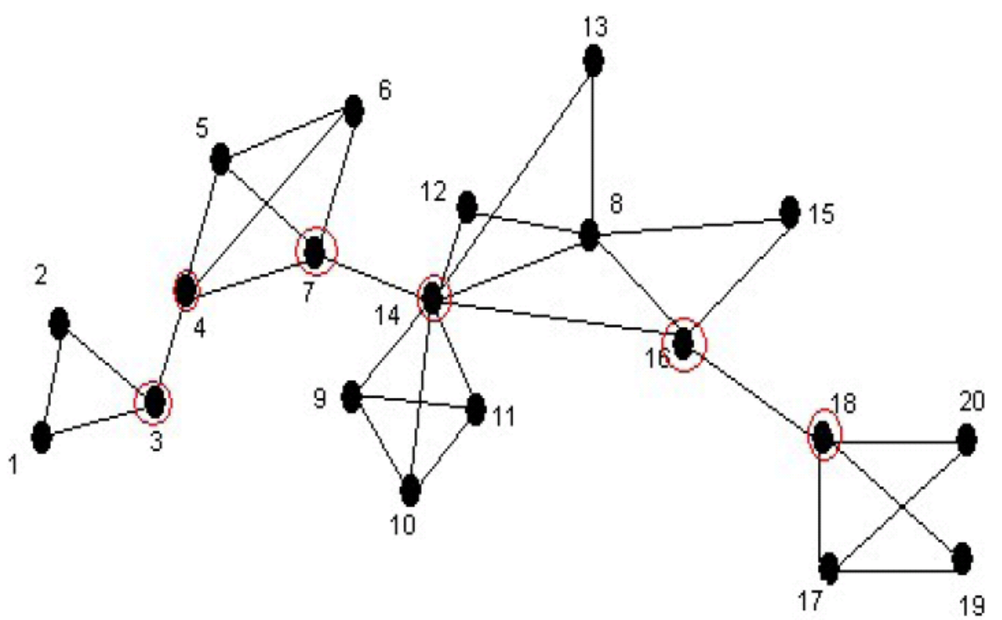


Figure 4: After applying Rule# 2.

3.4 KSPR-I Algorithm

B. Liang and Z. Haas proposed a greedy algorithm to obtain a k-dominating set, in which every node in the network is within k-hops of a node in the dominating set [10]. S. Dhar, M. Rieck, S. Pai, and E. Kim proposed similar kind of approach for forming k-SPR dominating set. In addition to the one proposed by Liang and Haas, this resulting dominating set [4] is k-hop connected and has k-shortest path property. In this approach every node requires to know about every other node within k+1 hops [4].

Considering k-dominating ($k > 1$) rather than mere dominating, results in smaller number of backbone nodes and hence each node is responsible for covering wider area of neighboring nodes. "k-hop connected" means that given any two nodes u and v in the set, there is a path beginning with u and ending with v, such that the hop count between consecutive nodes along the path that belong to the set never exceeds k[4]. In fact the set produced has the additional special property that there exists a path as just described between any two nodes u and v, and that this path is a shortest (possible) path in the sense that any other path connecting u and v requires at least as many hops[4]. In k-SPR, "SPR" stands for shortest path routing.

Different variants of k-SPRX such as k-SPRI, k-SPRE and k-SPRC were proposed of which we will be studying k-SPRI explained next in detail.

Basically every node in the network has been assigned a unique positive integer ID.
The mathematical representation for the algorithm is as follows.
For each pair $\{x, y\}$ in B, let $A\{x, y\} = \{w \mid \partial(x, w) + \partial(y, w) = k+1, w \neq x, w \neq y\}$. This consists of the interior nodes for the pair $\{x, y\}$. Now, using k-SPRI, the node v in $A\{x, y\}$ with the highest ID is selected to cover this pair. The resulting set of elected nodes is clearly a k-SPR set. To implement this approach initially each node learns about its (k+1) local view by using k+1 rounds of local broadcasting. After this broadcasting phase each node decides to join the k-SPR set if it finds that there is some pair (x, y) in B that it covers for which it has the highest id among all the nodes that cover this pair. The resulting dominating set is k-hop connected k-dominating set and has the desirable k-shortest path property.

The other variant of k-SPRI, k-SPR-C was proposed. In k-SPRC, every node is selected based on another set of information known as the covering number. Basically every node is given a priority based on lexicographical ordering of (covering number, ID). The node with the highest priority is selected into the k-SPRC set. Based on a similar idea they [8] proposed an energy efficient routing protocol known as k-SPRE where E stands for energy. The k-SPRE set is formed where every node's priority is based on (residual energy level, ID) instead of the covering number. In k-SPRE set formation, priority is based on each node's remaining battery life. Also they suggest re-electing the dominating nodes in k-SPRE at periodic intervals of time so that nodes with higher energy are currently active as dominating nodes.

Once the dominating set is formed based on either of these approaches mentioned above, a two-level hierarchical routing protocol is applied on the network [9]. The routing protocol is based on a two-level structure where the dominating nodes form the top level hierarchy and the rest of the nodes form the bottom level. The "local routing" component enables a non-dominating node to send a packet to a destination node which is within "k" hops from the sender. "Global routing" component is used to route data packets among the router (dominating) nodes. They propose to use IEEE 802.11 IBSS Power saving mode (PSM) for non-dominating nodes to follow a synchronized sleep/wakeup cycle and for dominating nodes to continue to remain awake throughout the beacon period.

3.5 802.11 Ad hoc Power Saving Mode

IEEE 802.11 ad-hoc power-saving mode uses periodic beacons to synchronize nodes in the network. Beacon packets contain timestamps that synchronize the nodes in the network. Every beacon period starts with an ad-hoc traffic indication message window (ATIM window), during which all nodes wake up and hear for pending traffic transmissions. A node that receives and acknowledges an advertisement for uni-cast or broadcast traffic must stay on for the rest of the beacon interval. Nodes that do not hear or transmit any announcements can turn themselves off at the end of the ATIM window, until the beginning of the next beacon period.

3.6 Performance Evaluation

Various k-SPRX variants and the Wu Li algorithm with rule 1 and 2 applied are implemented and the results compared in this section. Also local and global routing components are integrated with each of these algorithms. Dijkstra's algorithm is used to implement the local routing [9] and Geographical forwarding to implement the global routing. Dominating set size produced by each of these algorithms is compared. Also throughput, average end to end delay/packet and the time of the first node failure is recorded for all the four algorithms.

3.6.1 Simulation Settings

A network of 100 ad-hoc nodes is set up on an area of 1000m x 1000m.
The nodes generate data at 5.12Mbps. Transmission range of the nodes is 250 m. Initial energy of the node is varied and results are collected for both 3000mJ and 6000mJ.

Simulation parameter values are represented in a Table 1s.

Parameter	Value
No of nodes	100
Transmission Range	250 m
Packet Size	320 bytes
Traffic Load	5.12 Mbps

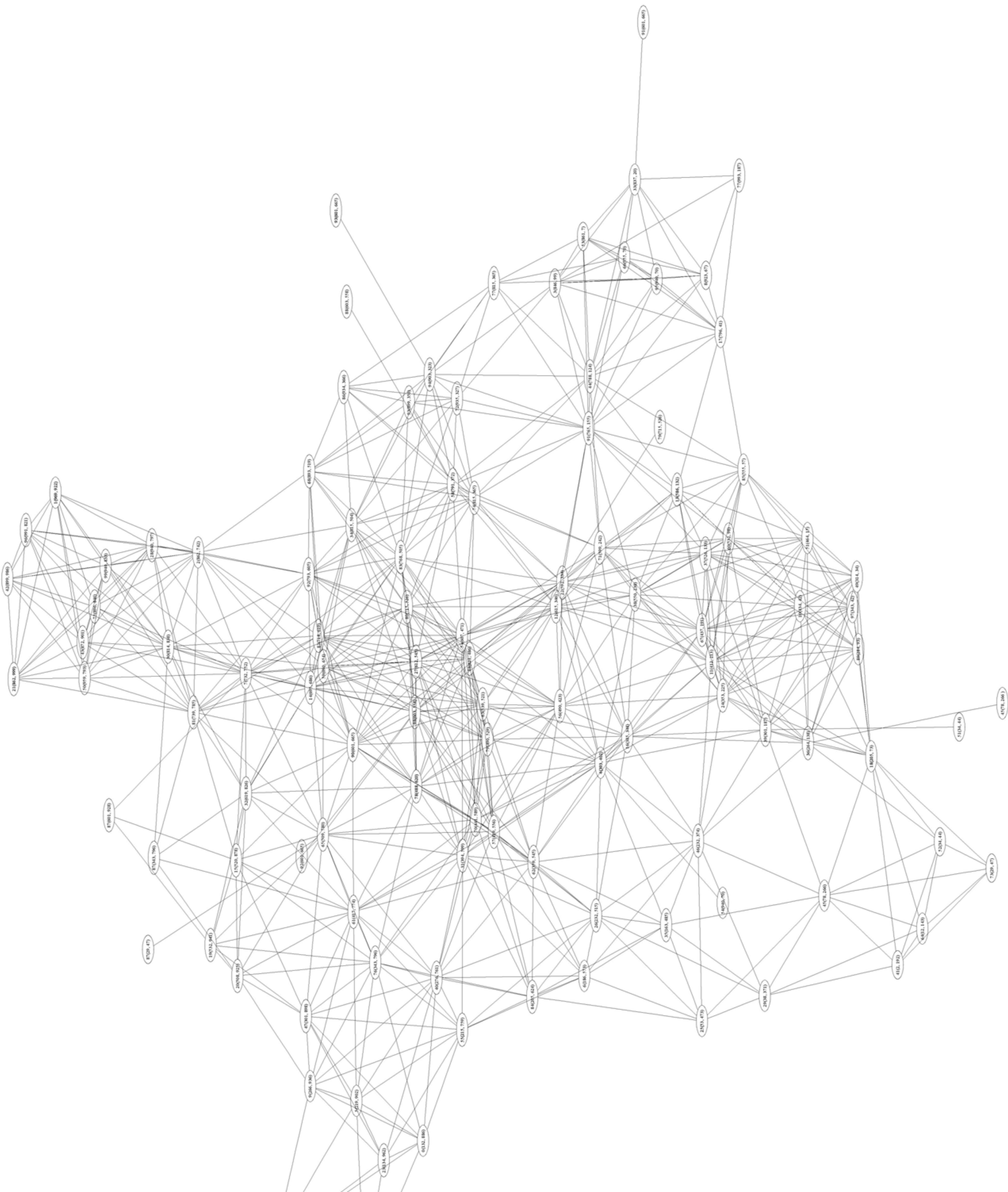
Table 1: Simulation Parameters

Standard parameter values for 802.11 PSM mode is considered for simulation.

Parameter	Value
sifs	0.028 ms
difs	0.128 ms
Beacon period	200 ms
ATIM window	10 ms

Table 2: Simulation parameters for 802.11 PSM

Figure 5: Network Graph



3.6.2 Radio Model

The radio model used is shown in Table 3 below. Radio transceiver dissipates E_{elec} = 50nJ/bit and uses ϵ_{amp} = 100pJ/bit/m^2. Energy dissipation for a k-bit message over distance d is shown in Table 3.

Operation	Energy Dissipation
Transmission	$E_{Tx}(k,d) = E_{elec} * k + \epsilon_{amp} * k * d^2$
Reception	$E_{Rx}(k) = E_{elec} * k$

Table 3: First Order Radio Model [3]

Energy consumption for idle listening is considered as 0.0135 mJ/ms and sleep = 15nJ/ms.

3.6.3 Results and discussions

Variants of K-SPRX and Wu-Li are applied to the same input graph of 100 nodes and the number of dominating nodes formed in each case is noted. Wu-Li with rules 1 and 2 applied has fewer dominating nodes in comparison to the k-SPRX variants. This is expected since k-SPRX may add more nodes into the dominating set to guarantee the k-shortest path property.

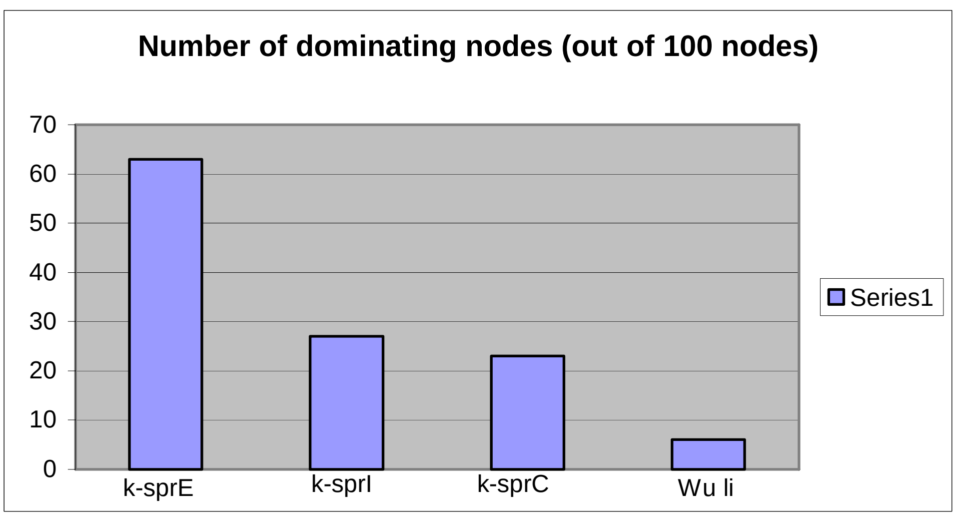


Figure 6: Dominating nodes set size when k = 3

Data – 10 flow
Simulation data is collected for two cases where 10 flows are generated.

Case 1:
Throughput for each of the k-SPRX variants and Wu–Li is measured both in Power Saving Mode (PSM) and NON-PSM case. K-SPRE demonstrates higher throughput than

the other algorithms since K-SPRE has a bigger dominating set size and hence there is more number of dominating nodes lying on the path. No ATIM packets need to be sent to a dominating node since they remain awake throughout the beacon interval. Hence the actual data is sent as soon as it is received (thus being faster) and thereby results in higher throughput (since packets do not encounter ATIM delay).

Average end to end delay for all the packets in each of the cases is calculated in the following manner.
End-to-end delay =
(Time at which packet is received at the destination – Time at which the packet was sent)

Average end to end delay is calculated using
(Sum of end-to-end delays of the packets received)/Total no of packets received

Based on the same reasoning for the throughput results as discussed above, we see in Figure 8, that the average end-to-end delay for K-SPRE (PSM) is the lowest when compared to other algorithms. Wu-Li (PSM)shows a higher average end to end delay since there are fewer dominating nodes as a whole in the network and hence on the path chosen and thus would have more ATIM delay introduced all along the path.

However in the NON- PSM case (no ATIM window hence no ATIM packet) the throughput and average end to end delay remained the same for all the algorithms since the paths followed by each of the algorithms in case 1 is the same. The throughput in NON-PSM case is higher than PSM case (all algorithms) and average end to end delay is lower than PSM case (all algorithms) since all the nodes will remain awake throughout the beacon interval and continuously receive and forward the packets.

Results for 10 flows (Nodes with initial Energy of 3000mJ)

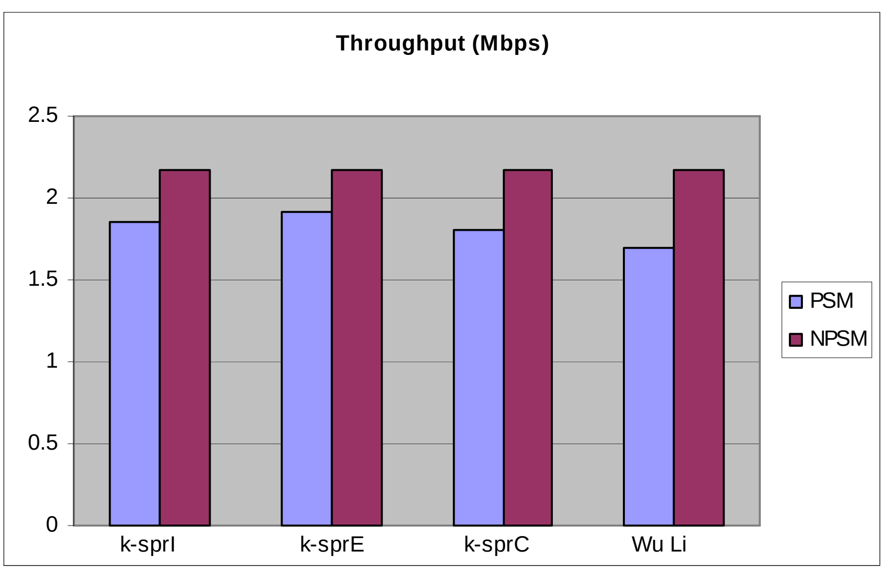


Figure 7: Throughput (Mbps)

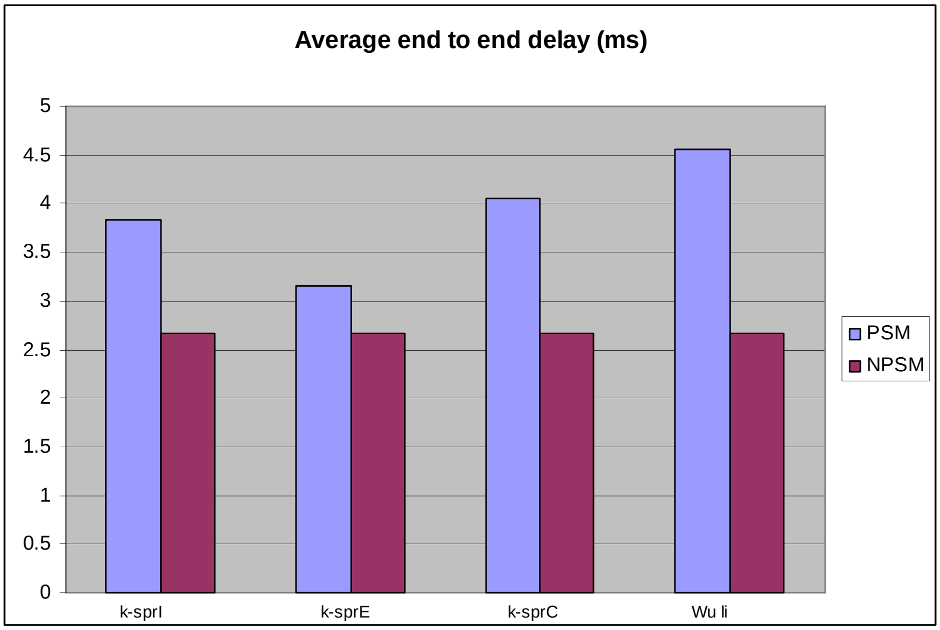


Figure 8: Average end to end delay (msec)

The figure below shows the 10 flows for case 1. .

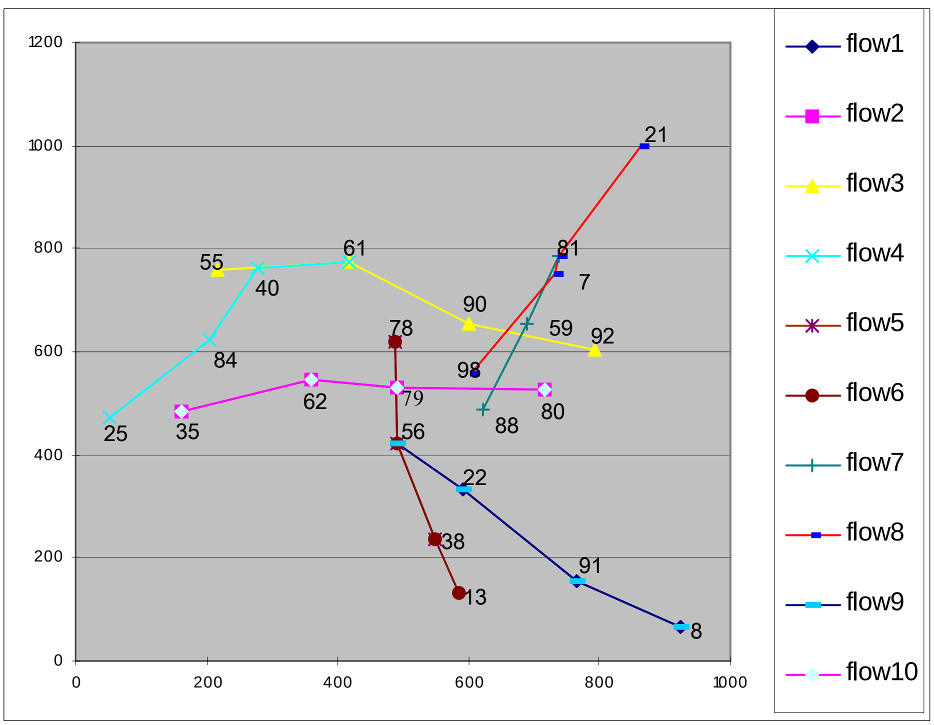


Figure 9: Representation of the ten flows (Case 1)

1st 10 flows (Numbers highlighted with yellow color are dominating nodes in corresponding algorithms)

KSPRI:
Flow 1: 8→91→22→56
Flow 2:35→62→79→80
Flow 3: 55→61→90→92
Flow 4: 61→40→84→25
Flow 5: 78→56→38
Flow 6: 13→38→56→78
Flow 7: 81→59→88
Flow 8: 21→81→7→98
Flow 9: 56→22→91→8
Flow 10: 80→79→62→35

KSPRE:
8→91→22→56
35→62→79→80
55→61→90→92
61→40→84→25
78→56→38
13→38→56→78
81→59→88
21→81→7→98
56→22→91→8
80→79→62→35

KSPRC:
8→91→22→56
35→62→79→80
55→61→90→92
61→40→84→25
78→56→38
13→38→56→78
81→59→88
21→81→7→98
56→22→91→8
80→79→62→35

Wu-Li:
8→91→22→56
35→62→79→80
55→61→90→92
61→40→84→25
78→56→38
13→38→56→78
81→59→88
21→81→7→98
56→22→91→8

80→79→62→35

In the following Figure 10, we have the results where we record the network lifetime (time when the first node fails in each of the algorithms) for case 1 with the node's initial energy being 3000mJ. In K-SPRC, the first node died earlier when compared to other algorithms since K-SPRC uses two floodings to find a K-SPRC dominating set based on the covering number.

Also the results show that more the dominating nodes exist in a network, higher the possibility it is to have dominating nodes lying on a path. A dominating node on the path consumes more energy than a non-dominating node on the path. Hence in other words, the more dominating nodes a network has, the faster the network (the first node) will die. And so the first node in K-SPRE failed earlier when compared to K-SPRI and Wu-Li.

For the NON-PSM case, first node failure remained the same for k-SPRI, k-SPRE and Wu Li since all the nodes remained awake all the time and hence the first node drained out all its energy at the same time. This explains also why the first node failure in NON-PSM case is earlier when compared to its PSM counterpart (since nodes remain continuously awake).

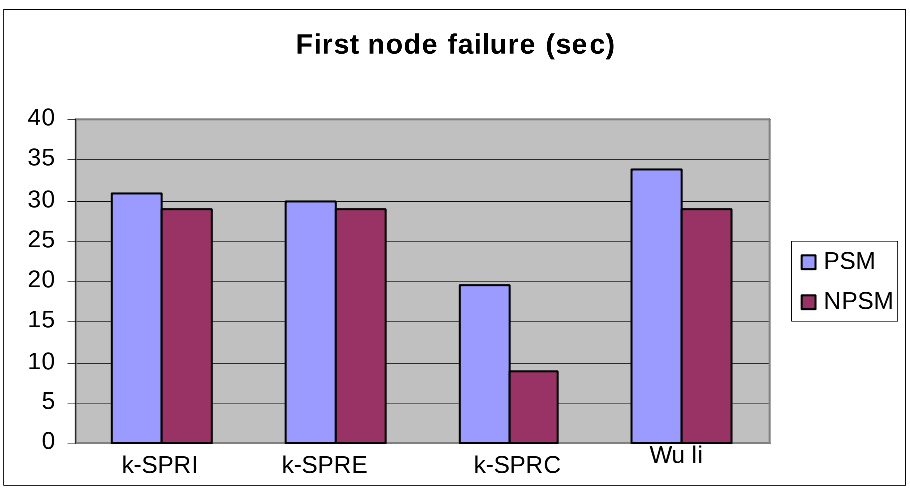


Figure 10: Network lifetime for node of initial energy of node of 3000mJ (First node failure in sec)

Results for 10 flows (Nodes with initial Energy of 6000mJ)

Below is the results collected for the first node failure for the same 10 flows discussed earlier but with initial energy of the node being 6000mJ. Clearly we can see it follows the same pattern of results for different algorithms collected earlier for node with initial energy of 3000mJ. As the initial energy of the nodes is increased, an expected increase in network lifetime is observed.

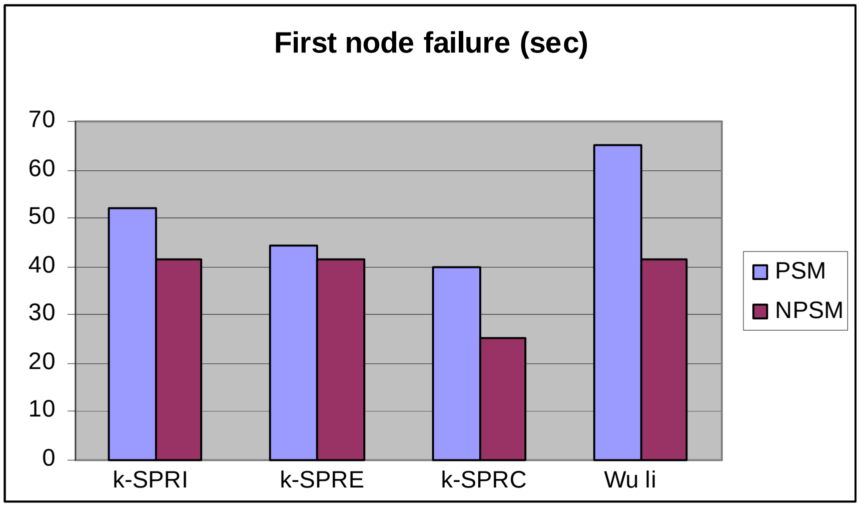
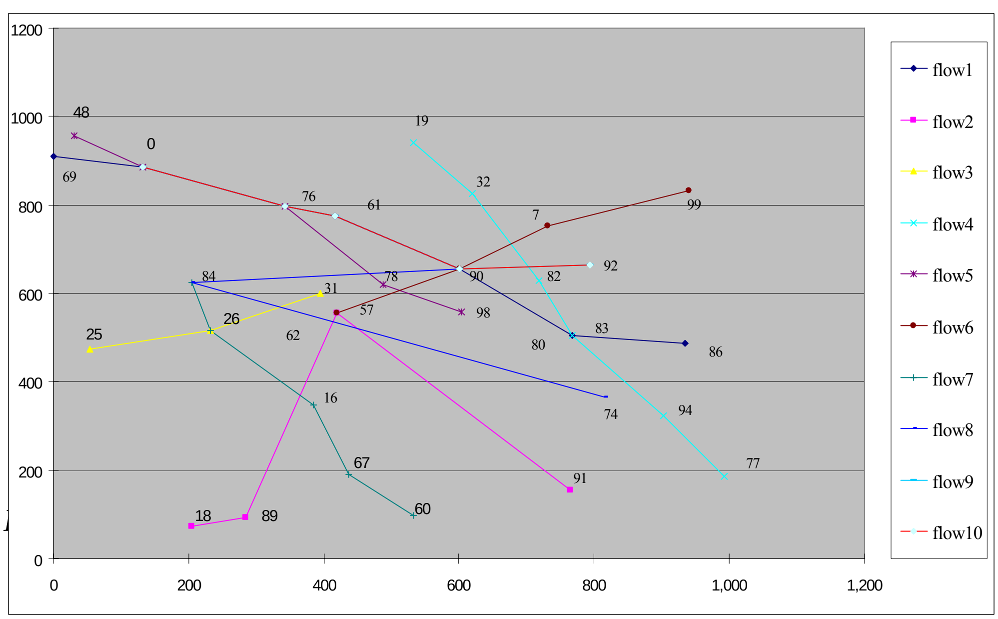


Figure 11: Network lifetime for node of initial energy of 6000mJ (First node failure in sec)

Case 2: Below is the second set of 10 flows.

The second 10 flows topology

In case 2, a different set of 10 flows is considered and throughput, average end to end delay and the time of the first node failure is recorded. Figure 12-14 gives the representation of the 10 flows in K-SPRX variants and Wu-li. It can be observed from Fig. 12-14 that if a destination node is within k+1 hops of the sending node, the path of flow remains the same for all the algorithms since local routing is used. The flow for different algorithms might change when the destination node is not within k+1 hops of the sending node since different algorithms generate different set of dominating nodes. Hence every algorithm might pick a different dominating node during global routing for forwarding the packet. For the ten flows considered here, the paths taken by the k-SPRI and k-SPRE are the same. Since Wu Li has lesser dominating nodes as a whole in the network, the path chosen by the Wu Li algorithm for a destination node not within k+1 hops of the sending node is the same or longer when compared to the k-SPRX variants. This can be observed in Fig. 14.



Again, numbers highlighted with yellow color are dominating nodes in corresponding algorithms

KSPRI:

Flow 1: 69→0→76→61→90→83→86

Flow 2:18→89→37→ 91

Flow 3: 25→26→31

Flow 4: 19→32→82→83→94→77

Flow 5: 48→0→76→78→98

Flow 6: 57→90→7→99

Flow 7: 60→67→16→26→84

Flow 8: 74→80→90→61

Flow 9: 80→79→62→26

Flow 10: 0→76→61→90→92

KSPRE:

69→0→76→61→90→83→86

18→89→37→ 91

25→26→31

19→32→82→83→94→77

48→0→76→78→98

57→90→7→99

60→67→16→26→84

74→80→90→61

80→79→62→26

0→76→61→90→92

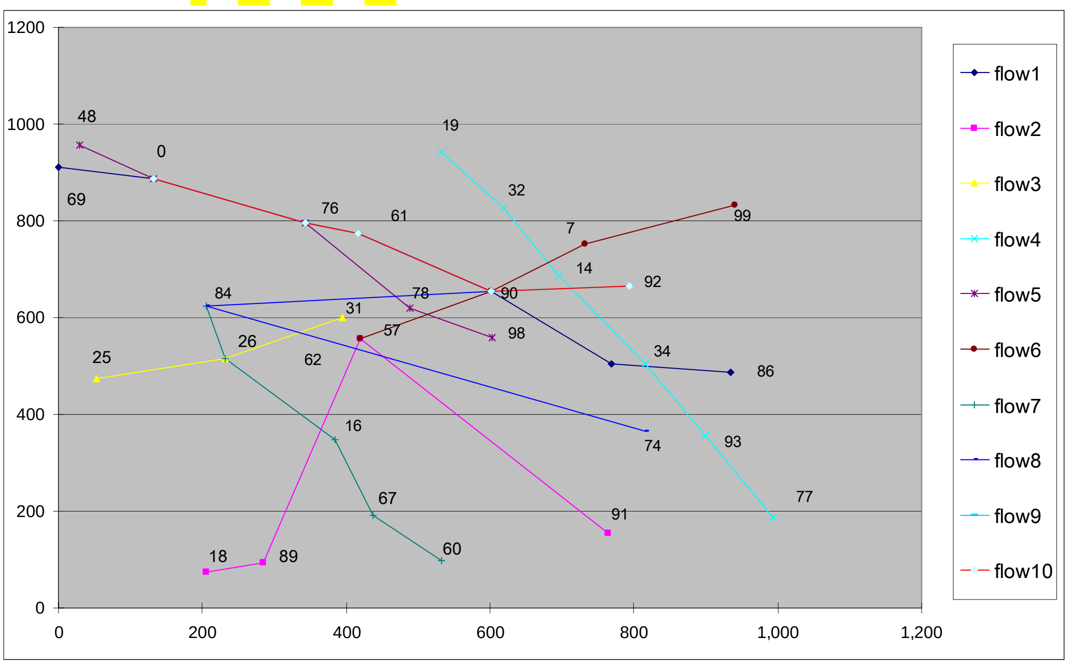


Figure 13: Representation of the KSPRC 10 flows (Case 2)

KSPRC:

69→0→76→61→90→34→86
18→89→37→ 91
25→26→31
19→32→14→34→93→77
48→0→76→78→98
57→90→7→99
60→67→16→26→84
74→80→90→61
80→79→62→26
0→76→61→90→92

Wu-Li
69→0→76→61→90→34→86
18→89→37→ 91
25→26→31
19→15→90→98→74→93→77
48→0→76→78→98
57→90→7→99
60→67→16→26→84
74→80→90→61
80→79→62→26
0→76→61→90→92

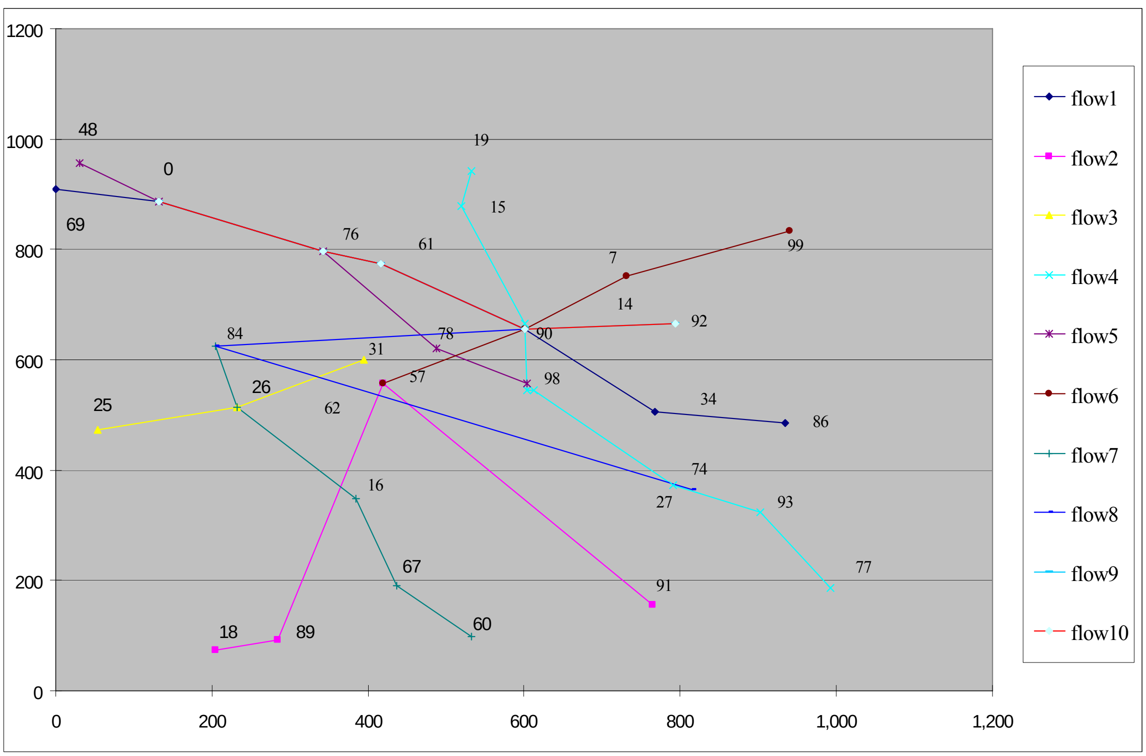


Figure 14: Representation of the Wu Li 10 flows (Case 2)

Below is the table showing the results for throughput and average end to end delay for the second case (different set of 10 flows) with initial energy of the node being 3000mJ. The average end to end delay is increased in case 2 compared to case 1 since there are longer paths in case 2 when compared to case 1 and more number of overlapping nodes in case 2 which introduces queuing delay and thereby increased average end to end delay. Also therefore the throughput decreases in case 2 when compared to case 1. It follows the same pattern for both average end to end delay and throughput between the four algorithms as in case 1 with k-SPRE having highest throughput and least end to end delay among all the algorithms.

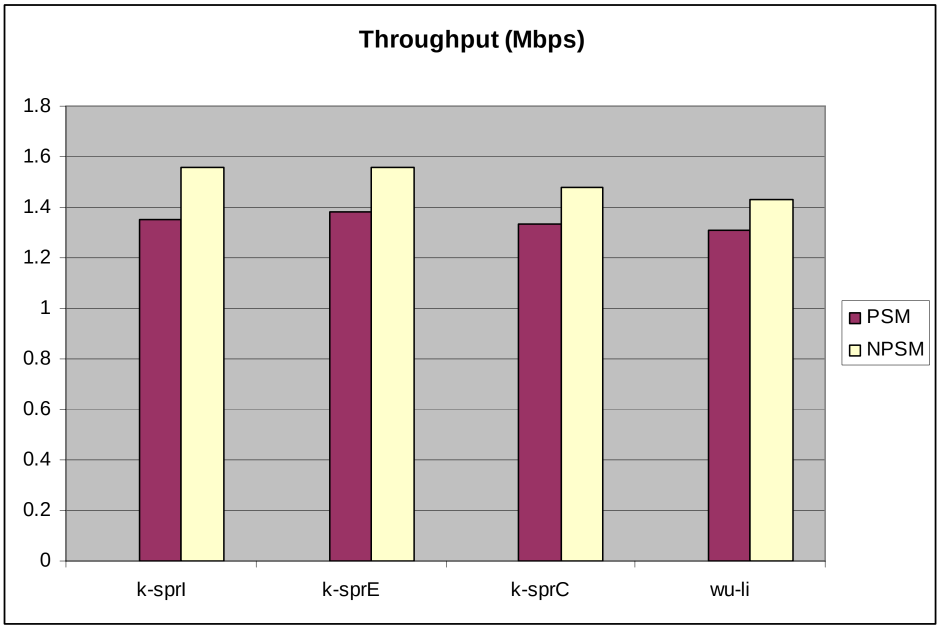


Figure 15: Throughput (Mbps)

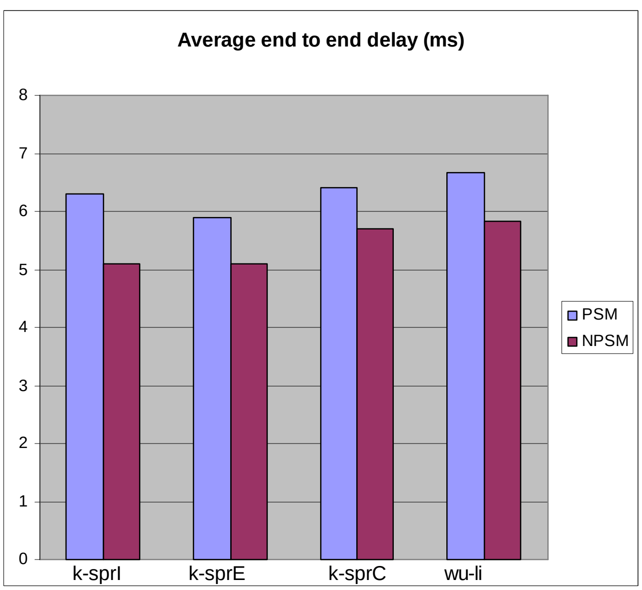


Figure 16: Average end to end delay (msec)

In case of first node failure, results are recorded for k-SPRI, k-SPRE, k-SPRC and Wu-Li. Again in k-SPRC, first node fails earlier compared to other algorithms because of two floodings used to form the k-SPRC dominating set based on the covering number. As observed in Figure 15, Wu- Li has the lowest throughput and the highest network lifetime in terms of the first node failure as can be observed in Figure 17.

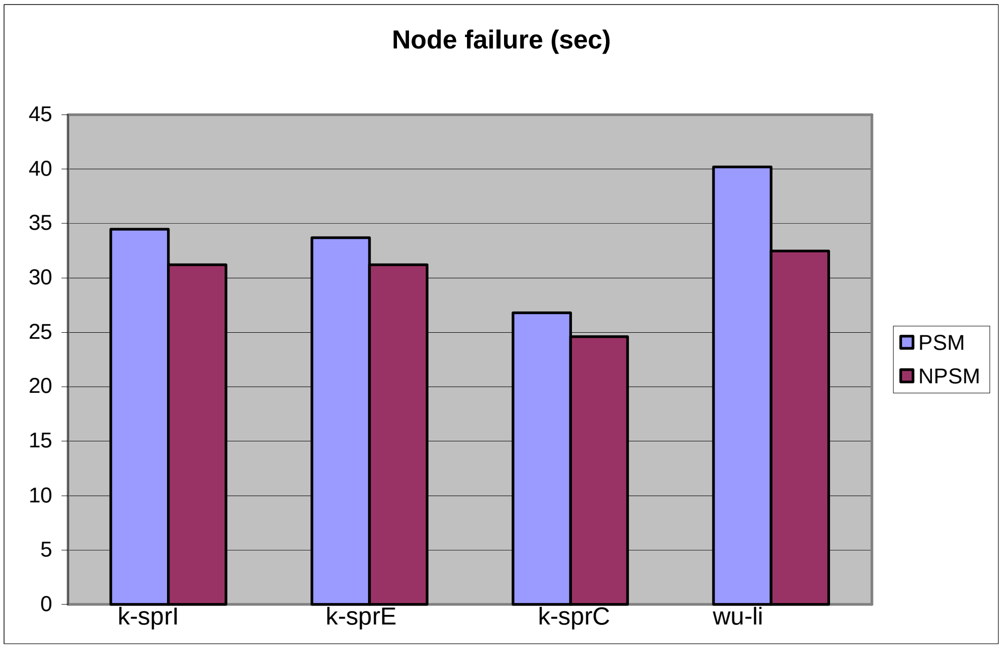


Figure 17: Network Life time (First node failure in seconds)

4 Dynamic Dominating Set Generation Algorithm for Routing in Ad hoc Networks

4.1 Motivation:

In the k-SPRE algorithm, we have seen that initially every node finds dominating nodes within d-hops based on the residual energy level. This dominating node set needs to be recomputed periodically. This approach definitely would increase the energy consumption because the number of active dominating nodes in k-SPRE dominating set is bigger in size as shown in Figure 6 and also re-computation consumes energy. Also this would mean greater number of state switches which would again consume energy.

So in the proposed approach (Dynamic Dominating Set Generation algorithm), dominating nodes are dynamically created only based on demand and these dominating nodes are selected based on combination of residual energy levels & geographical forwarding (closer proximity to the destination node). This results in a smaller dominating set and higher energy nodes being selected as dominating nodes which helps in increasing the network lifetime. Also Geographical forwarding selects nodes from the d-hop neighbors which are closer to the destination node as dominating nodes. This reduces energy consumption since energy consumed by any node during transmission is proportional to the distance transmitted.

However, if several routing paths have a common host, then that common host would drain out its energy eventually after it has transmitted/received packets for a longer period of time. Thus to avoid the nodes from getting exhausted of battery power, it is very important that the role of routing is distributed in the network. To overcome this issue, in the proposed approach the dominating nodes are made energy optimizing nodes. They automatically go to sleep state when their battery level falls below the pre-determined threshold value and a new dominating node is selected if needed. This threshold value is computed every time a node is selected as a dominating node.

Benefits of this on demand dominating node selection approach:

- Fewer active dominating nodes
- Nodes selected on the fly based on demand
- Nodes sent to sleep mode after low energy levels
- Reuse existing tree/dominating nodes for destination with closer proximity
- Minimum re-computation of dominating nodes only based on demand triggered by the source node
- Role of routing distributed in the network.

In the area of Mobile Ad hoc networks, two prominent on demand routing protocols namely Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) are used. While the approach (DDSG algorithm) presented above makes use of the on demand concept too, the on demand selection of nodes however is limited to only dominating node. Hence DDSG algorithm makes use of both pro-active and reactive based approaches. Table 4 given below gives more comparisons about the three algorithms namely AODV, DSR and DDSG.

	AODV (Ad-hoc on-demand distance vector)	DSR (Dynamic Source Routing)	Proposed Approach
Category	Reactive	Reactive	Based on both reactive & proactive approaches
	No routing table maintained at the set-up phase	No routing table maintained at the set-up phase	Local routing table maintained for dhop nodes
Route discovery	Broadcasts RREQ until intermediate node having path to the destination node or destination node replies with RREP back to source	Broadcasts RREQ until intermediate node having path to the destination node or destination node replies with RREP back to source	1) Selects list of dominating nodes closer to destination node using geographical forwarding. 2) Sends Energy REQ packet as unicast packet to the selected list of nodes to get their current energy levels. 3) Energy REP containing their current energy level sent as unicast packet back to the source node. 4) Source node selects highest energy node as dominating node & uses local routing table to send data packet to dominating node.
Routing mechanism	Complete path from the source node to the destination node determined with the RREQ & RREP packet.	Complete path from the source node to the destination node determined with the RREQ & RREP packet.	Dominating node determined with Energy REQ & Energy REP packet.
	Complete routing path created on demand	Complete routing path created on demand	Dominating nodes created on demand

Table 4: Protocol Comparison Chart

4.2 Algorithmic Design:

Initially, all nodes but the source node operate in power saving mode. Every node finds its d-hop neighbors and thereby knows the geographical location (x, y) of its d-hop neighbors. Also every node maintains local routing table to its d-hop neighbors. Dijkstra's algorithm is used to compute the local routing table. Once the local routing table is formed, following are the steps involved in selecting a dominating node:

Initially, *dominating nodes* list is empty for all the nodes in the network. *Dominating status* is false for all the network nodes. Local routing table is used for a packet to be sent to a destination node within d hops from a sending node. However, if a packet is to be forwarded to a destination node not within d hops, DDSG algorithm described below is used.

4.2.1 Dynamic Dominating Set Generation Algorithm (DDSG)

When a packet has to be forwarded by a source node it selects "L" nodes among the D-hop nodes that are closer to the destination using geographical forwarding approach. This selected list of nodes is stored in *potential dominating nodes* list.

Among the *potential dominating nodes* list
Two cases to be considered:

1. If a dominating node already exists in the *potential dominating nodes* list, it will be selected for routing
2. If not,
    a. Then the node sends energy queries to every node in the *potential dominating nodes* list.
    b. Upon receiving energy queries the potential nodes respond back with their current energy level in energy reply packets.
    c. Upon receipt of the energy reply packets from all the potential dominating nodes, the sending node determines the highest energy node and declares it as a dominating node. It updates its *dominating nodes* list by appending the newly selected dominating node. It notifies the selected dominating node about its status by sending a dominating notification packet to it.
    d. Upon receiving dominating notification packet, the node sets its *Dominating status* to true. It broadcasts that it is a dominating node (dominating node status notification) to all its d hop neighbor nodes.
    e. Upon receiving the broadcast packet all the d hop neighbor nodes also update their *dominating nodes* list.

Once a dominating node is selected, the packet is forwarded to the dominating node using local routing table information. Upon reaching the dominating node, if the destination node is not within d-hops the above steps will be repeated. If the packet reaches a dominating node which is within d hops from the destination node, then local routing table is used to forward the packet to the destination node.

The selected dominating node continues to be powered on until the current energy level of the node falls below the pre-set threshold value. Thereafter it goes to sleep mode to conserve energy.

4.2.2 Threshold value

1. Once a dominating node's current energy level falls below the threshold energy level the dominating node sets its *Dominating status* to false.
2. It informs its d hop neighbor nodes by broadcasting that it is no more a dominating node and that it is now a non-dominating node (non-dominating node status notification).

3. Upon receiving the broadcast packet all its d hop neighbor nodes remove the dominating node from their *dominating nodes* list.

4.2.2.1 Setting the threshold value

Let "**p**" be the percentage of the node's current energy level until which the node continues to be a dominating node after which the node is switched from active state to sleep state.

Initially $e_t = p. e_i$

where e_i = initial battery level.

e_t - Threshold battery level

Every time a node is switched from sleep mode to active state, the node computes a new threshold battery level.

Current threshold battery level is computed as $e_t = p. e_c$

where e_c - Current battery level of the node

e_t – Current threshold battery level

Benefits of re-setting threshold values

- Eliminates continuous usage of same node by changing the threshold values
- Helps in distributing the role of routing equally among all the nodes in the network
- Prevents in draining out of energy of node and hence helps in increasing the network lifetime subsequently

4.3 Performance Evaluation Plan

The performance of the DDSG algorithm is evaluated using simulation results. As in the previous algorithm simulations of k-SPRX and Wu Li, Dijkstra's algorithm is used to implement the local routing [9] and Geographical forwarding to implement the global routing. Network life time, average end to end delay and throughput is recorded for various values of percentage p and the results are compared.

4.3.1 Simulation Settings

The simulation parameters for the DDSG algorithm remain the same as used for the previous algorithm's simulation. Simulation results for network lifetime, throughput and average end to end delay is recorded for various values of "p" in the DDSG algorithm where "p" is used to set the threshold value for energy. The value of p is varied from p = 0.3 to p =0.8. The value of L chosen for this simulation is 3.

4.3.2 Simulation Results

Case 1: For this set of results the value of p=0. This implies that the threshold energy setting is not applied in this case. Simulation is run and performance parameters are obtained at the time of the first node failure. The set of 10 flows considered for this case is shown below.

23→40→57→56→38→60→85
18→89→37→ 91
3→72→86
19→32→14→34→72→77
48→0→76→78→98
72→68→2→99
60→67→16→26→84
79→54→58→72
77→72→83→88
0→76→61→90→92

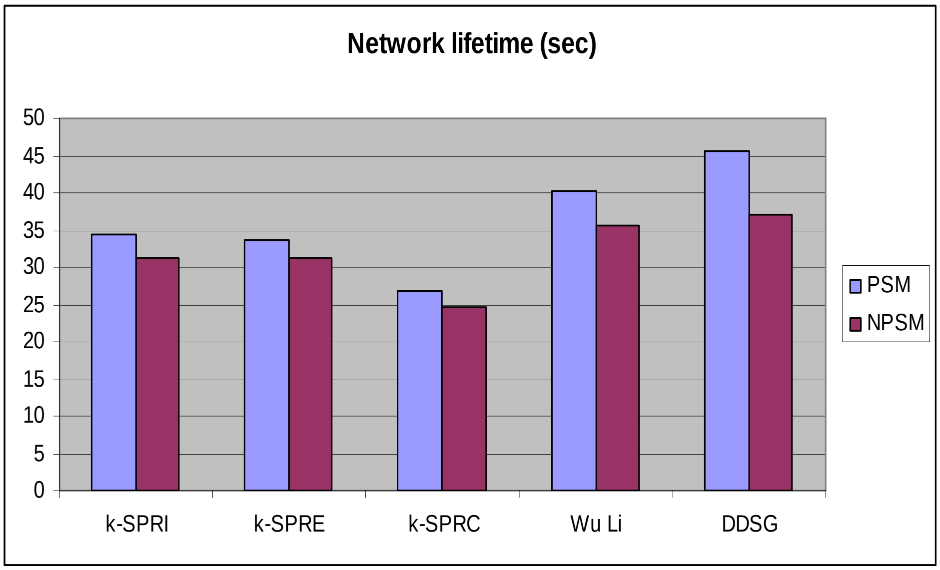


Figure 18: Network Life time (First node failure in seconds)

Figure 18 gives the network lifetime in terms of the first node failure. It can be seen from the graph that network life time increases in case of DDSG algorithm when compared to other k-SPRX and Wu Li algorithm. This is due to the fact that in case of DDSG algorithm, highest energy node among the selected list of nodes is picked as a dominating node. Also the number of dominating nodes affect the network lifetime. Since this approach selects dominating nodes based on demand, it results in selecting fewer dominating nodes. Thus majority of the nodes follow power saving mode and thereby the network nodes conserve more energy. Thus, this on demand approach adds another layer of energy efficiency over the 802.11 Power Saving Mode and helps increase the network life time.

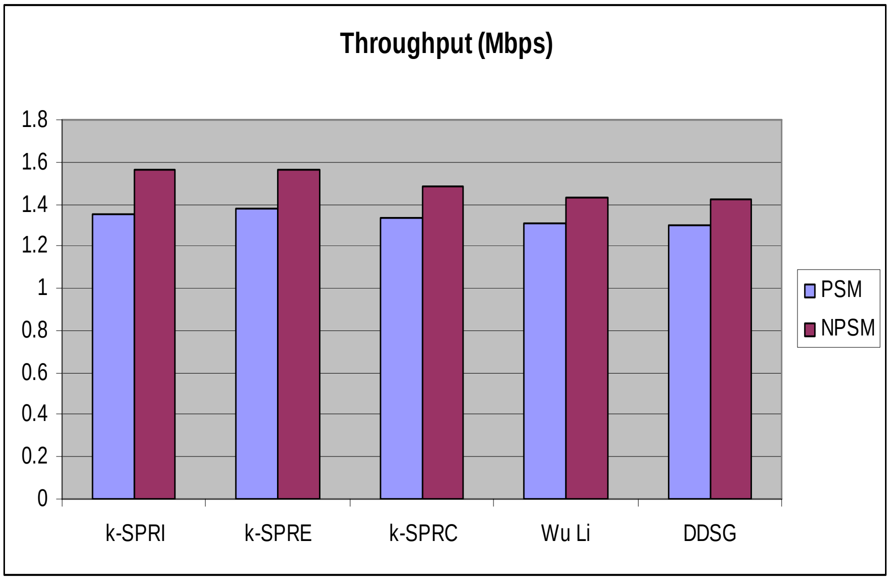


Figure 19: Throughput (Mbps)

Results for throughput indicate that the performance of DDSG is comparable to Wu Li. Since the dominating nodes are formed on demand, it results in fewer dominating nodes in the network and on the path. Non-dominating nodes on the path follow PSM. Nodes following PSM mode send ATIM packet before sending the actual data packet. These nodes introduce ATIM delay. Since there are more number of non-dominating nodes on the path in case of DDSG algorithm there is more ATIM delay encountered and hence throughput for DDSG algorithm falls slightly below compared to other k-SPRX protocols.

Based on the same reasoning for throughput results as mentioned above, average end to end delay as shown below (Figure 20) increases in case of DDSG algorithm in comparison with k-SPRX and Wu Li algorithm. In addition to the ATIM delay introduced in DDSG algorithm, average end to end delay increases due to the initial dominating node selection process.

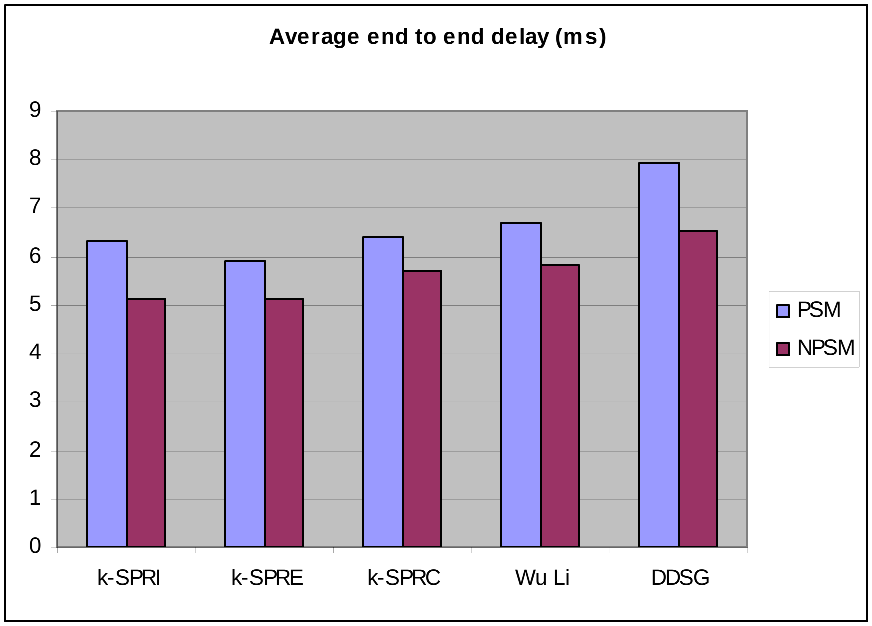


Figure 20: Average end to end delay (ms)

Case 2: Results for varying values of percentage p.

Simulation results are collected for varying values of p. Since threshold value setting is applied in this case, once a dominating node's energy falls below a pre-set threshold energy value new dominating node is selected for routing. Below are the various paths chosen during this simulation case.

23→40→57→56→38→60→85
23→40→62→4→67→60→85
23→40→57→56→71→60→85
18→89→37→ 91
3→72→86
19→32→14→34→72→77
19→32→14→34→74→77
19→32→14→34→86→77
48→0→76→78→98
72→68→2→99
60→67→16→26→84
79→54→58→72
77→72→83→88
0→76→61→90→92

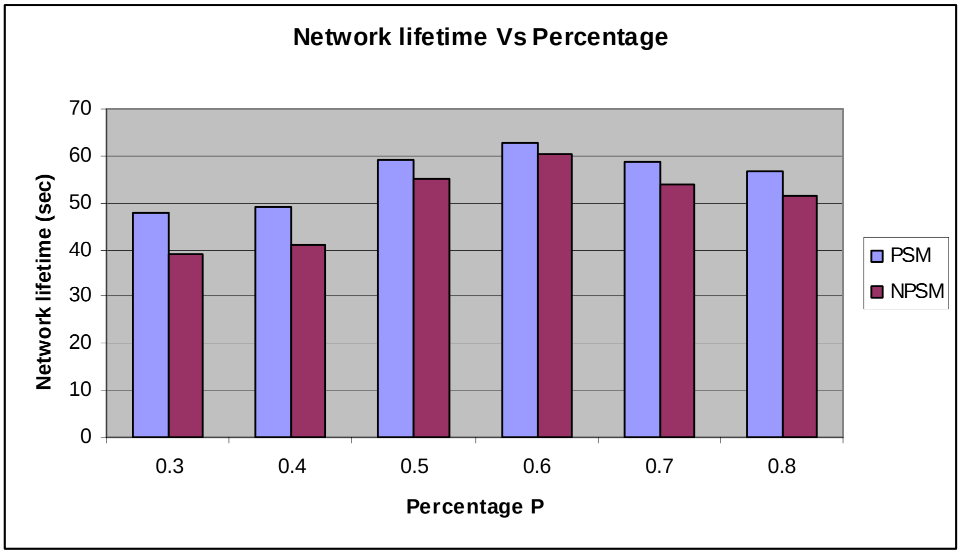


Figure 21: Network lifetime vs. Percentage

As seen from Figure 21 above, optimal network lifetime is obtained at p = 0.6. For the values of p above p = 0.6 (i.e. say p = 0.8) network lifetime reduces since there is more energy dissipation due to the additional broadcasts involved in the dominating node and non-dominating node status notifications. For p values below p = 0.6, dominating node is active for longer time and is continuously involved in transmitting/receiving of packets and thus drains out energy sooner. Thus due to the same node being used as dominating node for relatively longer period of time there is a decrease observed in the network lifetime for lower values of p.

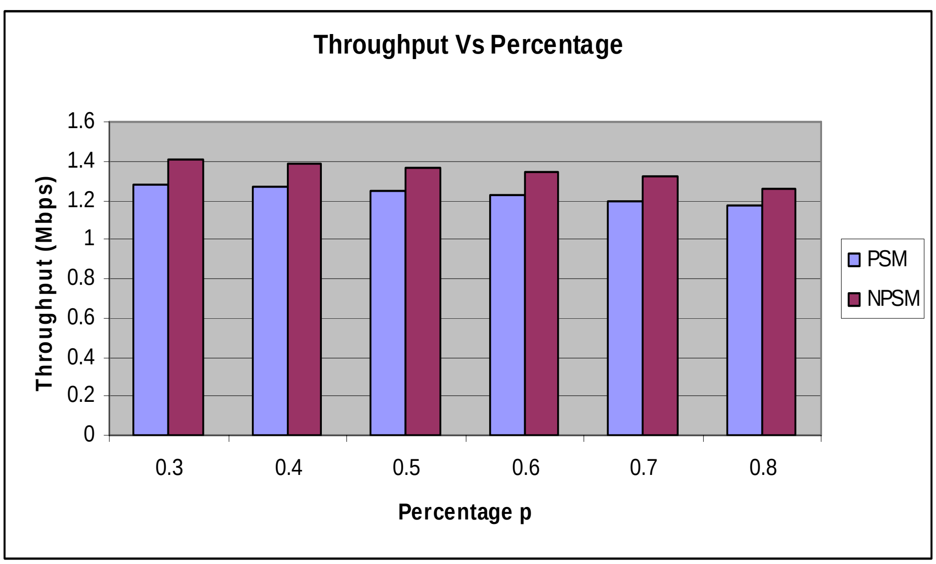


Figure 22: Throughput vs. Percentage

Figure 22 indicates that throughput at p=0.6 is comparable to p = 0.3. Throughput is higher in p=0.3 (p < 0.6), since there is lesser number of times a new dominating node is selected and hence there are lesser number of energy queries, energy responses being sent out. For the same reason throughput is lower in p=0.8, since there are more number of energy queries and energy responses (i.e. more number of new dominating node selections).

Based on this same reasoning, average end to end delay increases for larger values of p as shown in the Figure 23 below. At p = 0.6, there is a slight increase in end to end delay when compared to the result for p = 0.3.

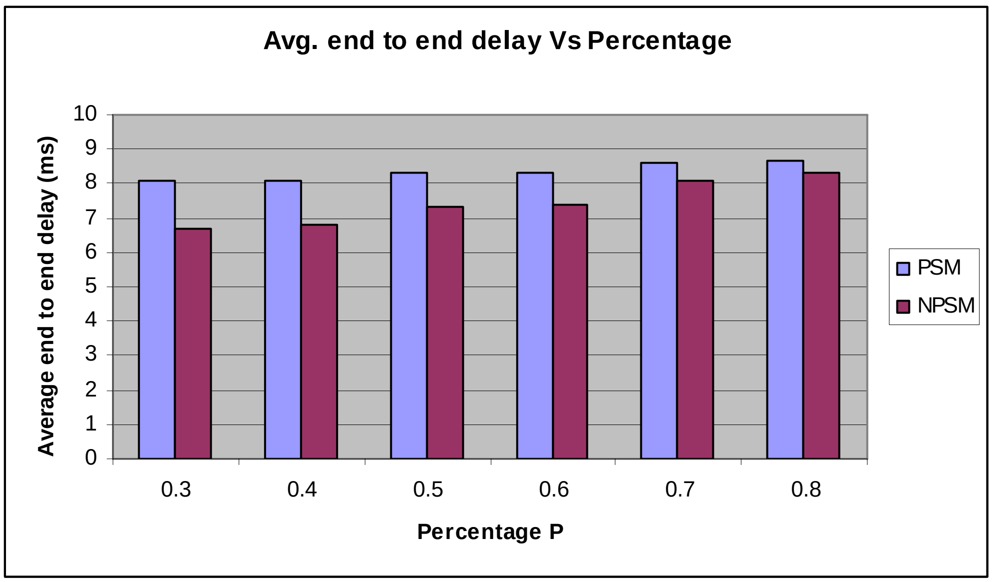


Figure 23: Average end to end delay vs. Percentage

5 Conclusions

In this report, I have started with a brief introduction to mobile ad-hoc networks and discussed some of the issues involved in MANET routing. Later I introduced a few of the existing virtual backbone approaches of forming dominating set for energy efficient routing in mobile ad hoc networks. Wu-Li algorithm and K-SPRI are discussed in particular. I have also mentioned about the other variants of K-SPRX i.e. K-SPRC and K-SPRE in brief. The simulation results show their performance measures in terms of throughput, average end to end delay and network life time (time of the first node failure). Based on my previous CS 297 study and the simulation results, I discuss DDSG algorithm an energy efficient approach to decrease the energy consumption and thereby optimize the network lifetime. This approach is based on selecting dominating nodes on the fly. The algorithm also helps achieve distributed role of routing in the network and eventual increase in network lifetime by incorporating the threshold energy setting. Simulation results show increase in network lifetime with comparable results for throughput and small penalty on average end to end delay in comparison to the k-SPRX and Wu Li algorithms. Also DDSG algorithm requires no initial set up phase for forming a dominating set and thus minimizes the computational overhead.

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