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Inter-Orbital Cluster Formation and Routing in Satellite Sensor Network

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Abstract: Satellite plays an important role in earth observation, collecting the scientific information and providing multimedia services etc. Traditional satellites are costly to build, launch, design and operate. Thus to overcome these challenges of traditional single satellites, small satellites are used to which form a collaborative network to accomplish the mission. These small satellites are less expensive and reduced development time. The network of small satellites is called as Satellite sensor networks (SSNs) [29]. SSNs consist of large number of small, inexpensive, robust and low power satellites (nodes) working co-operatively. These SSNs are constrained by latency, limited sensor energy; but the real time applications such as above demands delay sensitive, reliable, limited sensor node size and energy efficient routing protocols in SSNs. It is also found that routing is one of major concern of satellite sensor networks. Hence, in this paper we propose cluster based routing protocol. The proposed scheme operates as follows. (1) Deployed satellites on various orbits form the clusters and elect the cluster head, (2) whenever the satellites are revolving around the orbit and come near the apogee, they transmit their data to other node in different orbit which is also called as orbit head node, (3) orbit head node intern transmit their data to cluster head, (4) cluster head filters the data to eliminate the redundant information and sends it to ground station using up/down link at perigee. The performance of the work is verified in terms of parameters such as network lifetime, energy consumption, average delay and cluster formation time.

Keywords: Satellite Sensor Networks, Cluster, Routing

1. Introduction

Implementing small satellites has been made easy by the newly invented technical advancements in MEMS technology. These small satellites have limited capabilities unlike huge satellites [27] [28]. One such constraint is small solar panel and reduced battery life restricts the satellites to its data directly to earth station (sink node). Thus data from small satellites is routed to the next node in the path to reach the destination using routing protocols to send its data to ground station. Each satellite has its own communication range to communicate with other satellites through wireless communication [1] [30]. Most of the communications Satellites are use d in applications such as earth monitoring and multimedia communications [14]. Each satellite contains a battery and solar panels which cannot be replaced. The energy stored in the battery is limited [25] [26] so the network life time of Satellite Sensor Network (SSN) is important. Further to reduce the launch cost, multiples at satellites are launched at a time.

SSN consist of small satellites called sensor nodes. SSN is a collection of small satellites with limited resources [12] [27]. Advancement in MEMS technology and manufacturing of light weight, small size and less expensive satellites has become important. SSN comprises of small satellites with computation, sensing capabilities and data transmission using is by wireless communication. Satellites are able to send their data each other or they send to the ground station called sink node.

In SSNs each satellite have an ability to sense the environment, the sensed data is aggregated at satellite called orbit head node (OHN) and aggregated data from the head is sent back to the sink node. Satellites are distributed over space with greater accuracy [2] [3]. Deployment of satellites in space is based on the some parameters like inclination angle, right assertion of ascending node, semi major axis and semi minor axis. Each of these deployed satellites has ability to gathered data and sends gathered data back to ground station (earth station) [13]. In Wireless Sensor Network (WSN), sensor nodes are used to aggregate the data and sends aggregated data to the ground by using wireless communication. Similarly in SSN each satellite has an ability to aggregate the data and send back to the ground station [4] [11]. In traditional satellite communication, each satellite has to send their data directly to the earth station so that energy consumption by the satellite is more.

The objective of this paper is to use concepts of terrestrial wireless sensor network to reduce the energy consumption of SNN. The second objective is to increase the network lifetime of SSN with collaborative and co-ordination of data using efficient routing. Some of the existing routing protocols are discussed

2. Related Works

HEJia-fu et. al [5] has discussed routing approaches based on satellite constellation features, minimum distance algorithm (MDA) and minimum hops algorithm (MHA). Traffic weighting based routing and k-shortest path based routing schemes are employed. MDA, which is based on the finding the distance between the source and destination satellite using Dijkastra algorithm and selects the path with less distance. MHA, which is based on the finding the minimum hops and selects the route with small number of hops.

Zhenfang li et. al [1] has proposed a (STAP) space-time versatile preparing approach consolidated with imaging calculation i.e., customary SAR imaging Algorithms which tackle issues, for example, array element errors, Doppler ambiguities and high inadequacy of the satellite cluster. The principle thought of this methodology is to use a STAP-based strategy to conquer the associating impact created because of lesser PRF and in this manner recover the unambiguous azimuth wide (full) range signals from the got echoes.

Hugo Cruz-Sanchez et. al [6] have talked about the Shortest Path Problem with Time Windows (SPPTW) is for satellite heavenly bodies. Keeping in mind the end goal to tackle the SPPTW, transport directing strategy is conveyed. Store and Forward satellites makes the overhauling of put away information at every circle. Portals (GW) are consolidating with store and forward satellites which serve as transfers where data can bounce from one satellite then onto the next keeping in mind the end goal to achieve destination quicker than sitting tight for a solitary satellite to fly over the destination.

Yurong Hu et. al [7] has explained static logical topology to solve routing problem. He proposed the static hop-by-hop routing approach which is logical topology dependent. This approach facilitates establishment of optimal shortest routes. In which there are M orbits, which are evenly spaced apart. The distribution of N satellites in an orbit involves angular separation.

Liang Jun et. al [8] has proposed a Snap-based Autonomous Routing Algorithm (SARA). To compute the routing table and partition of network topology, the scheme uses the inter-satellite link connection rules. When nodes failure occurs, GEO satellites perform recounting of routing table in autonomous mode. It partitions the network layer by connection ISL connection law.

Zhe Yuan et. al [9] have discussed hierarchical and distributed routing algorithm. To send short-distance traffics LEO satellites are used. MEO satellites are used to route the long distance information and it needed whole network topology information. The residual life time of inter satellite link is incorporated to compute the route weight. Double-Layered Satellite Network Routing Algorithm (DLRA) is proposed for LEO/MEO double layered satellite networks

3. Cluster Based Routing

In this section we describe the terminologies, network environment, mathematical models, proposed scheme, and algorithm and example scenario.

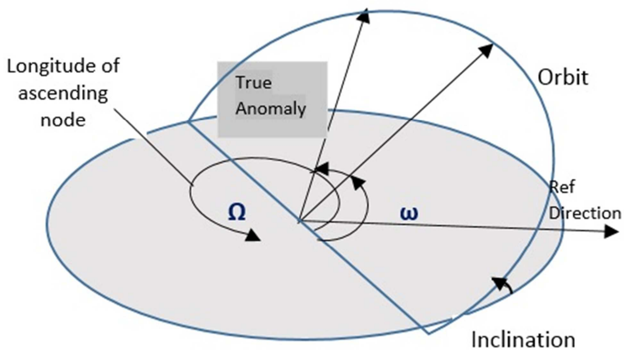

Figure 1. *Orbit Plane.*

3.1. Terminologies

Some of the terms used in proposed routing scheme are as follows.

1. Semi- Major Axis (a) (in km): The orbit size is defined using this element.
2. Eccentricity (e): The orbit shape is defined by eccentricity *(e)*.
3. Apogee: It is a point on the orbit, which is farthest from the earth.
4. Perigee: The point on the orbit of closest approach to earth
5. Prograde orbit: The motion of the satellite is in the same direction as earth rotates. The inclination of this orbit is from 0^0 to 90^0 as shown in figure 2.
6. Retrograde orbit: The satellite motion will be opposite to earth's rotation. This inclination is in between 90^0 and 180^0

shown in figure 2.

7. Inclination of Orbit (i): The inclination (i) defined with respect to the equatorial plane of the earth. It is a tilt of an orbital plane and is an angle measured in degrees shown in figure 1.
8. Right ascension of ascending node (RAAN) (ɵ): The angle which is measured at the equatorial plane and it is also counter-clockwise to that of the ascending node.

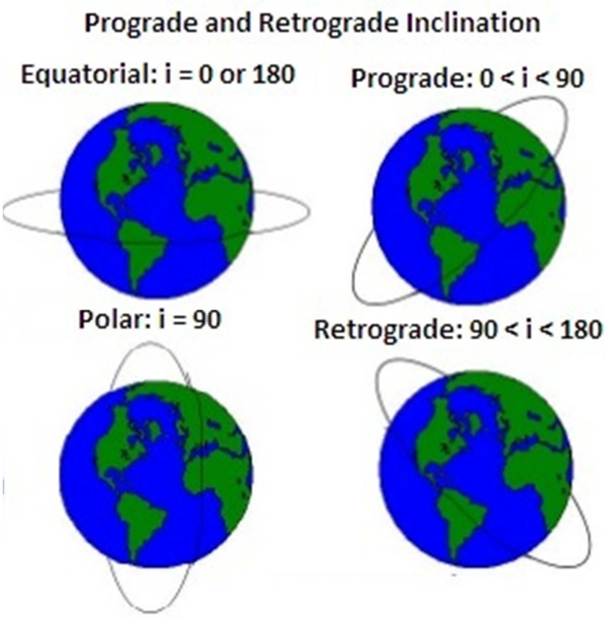

Figure 2. *Prograde and Retrograde orbit inclination.*

3.2. Network Environment

The satellite sensor network environment is shown in figure 3. The sink node location is prefixed. The satellites are deployed in the orbit based on the RAAN (in degrees) [17]. Based on the position of the satellites (i.e. when the satellites are within the predefined angle), the inter satellite link is established in the orbit and between the heads of each orbit. Whenever the satellites senses, they send data to orbit heads by establishing inter satellite links [18] [26] [30]. The cluster is created at the apogee, because the speeds of the satellites are low. And cluster head (CH) is selected based on the weight factor computation. Up/Down link (UDL) with the sink node is established, when the cluster head is nearer to ground station.

3.3. Mathematical Models

This section describes the mathematical models used to find out the position of a satellite such as UDL routing, ISL routing and inter orbit routing.

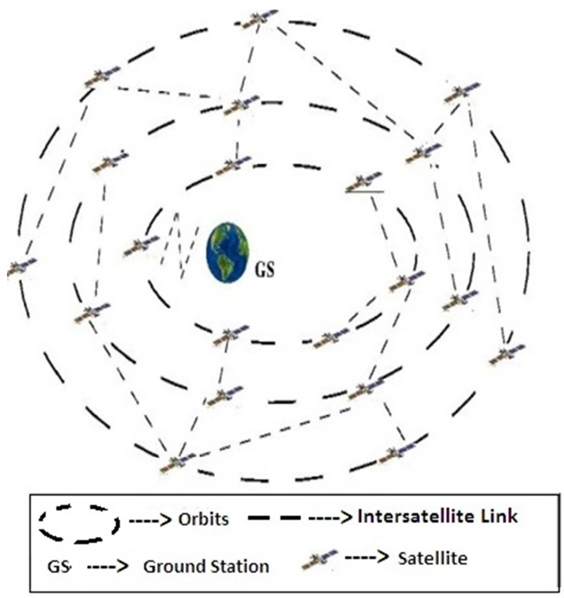

Figure 3. *Satellite Sensor Network Environment.*

Case(i): In this case, the satellite is nearer to earth station when it is at the perigee (i.e. RAAN = 0). Hence, UDL link to the earth station from the Cluster Head (CH) has to be established when the satellite is present at the perigee; the ±5° tolerance is accepted because the topology of the network is dynamic.

In this paper, we are considering 1500km as the altitude of the orbit and 7.12 km/s as its orbital velocity. The equatorial speed of earth is 0.464km/s.

From the above mentioned data's we can conclude that, the earth station is 15 times visible to the satellite for one complete rotation. Hence, 15 times we can establish a UDL link to the earth station from a satellite at different time intervals as given in equation 1.

Case(ii): In this case, we are describing the establishment of established when the satellites are at apogee. At the apogee, the motion of the satellite is slow, so we will get sufficient time to maintain an efficient ISL and exchange the information.

$$0 + T + 2T + 3T + \ldots\ldots\ldots\ldots\ldots + NT \tag{1}$$

Where, $0 \rightarrow$ satellite is at perigee

$T \rightarrow$ The time required for satellite to complete one rotation

$N = 15 \rightarrow$ Earth station is visible to statellite

Here, the approach is to find out the direction cosines of the satellites within an orbit, by using equation 2 and 3.

$$x = a \cos \theta \tag{2}$$

$$y = b \sin \theta \tag{3}$$

Where, x and y are the direction cosines of any point on an orbit, $a$and b are the radius on the x and y axes respectively and θ is the RAAN [19]. Once the position $(x_i, y_i)$of the satellites is found out, then next step is to find out the distance between the satellites using equation 4 i.e. distance formula.

$$d = \sqrt{(x2 - x1)^2 + (y2 - y1)^2} \quad (4)$$

The heads and the CH is selected based on the three parameters [20] namely available energy, speed of satellite and RAAN i.e. weight factor (wf) using equation 5.

$$wf = \frac{E * \theta}{S} \quad (5)$$

The routing table is maintained in all the satellites. Once we calculate the distance between the satellites the routing table will be updated by itself [21]. Based on the distance between the satellites the efficient ISL will be established for the exchange of the information or data. The ISL is established, if the distances between the satellites are within the predefined threshold value [22].

For example, the routing table of each satellite as given below in table 1. Consider the satellite S_1 as a head of an orbit and an orbit having 6 nodes. Same process is repeated for remaining orbits.

***Table 1.** An example for routing table of each satellite.*

S_1(Head)	Distances between the satellites
S_1S_2	D_1
S_1S_3	D_2
S_1S_4	D_3
S_1S_5	D_4
S_1S6	D_5

Case (iii): Inter Orbit Routing

The inter orbit routing is made between the heads of the orbits. Again the ISL is established between the heads [23], when they are present at the apogee i.e. $\theta_{min} < \theta < \theta_{max}$ $ie\ (170^0 \leq \theta \leq 190^0)$

Proposed Scheme

1. The proposed scheme of SSN is shown in figure 4.
2. The nodes (i.e. satellites) are deployed around the orbits based on the RAAN (θ) which is counter clockwise from the perigee of an orbit.
3. The proposed scheme is for the LEO satellites (i.e. with an altitude of 160km to 2000km), the orbits are considered an elliptical $(0 < e < 1)$
4. The satellites in an orbit are dynamic, so the topology of a network is also dynamic.
5. Here the approach is to find out the efficient routing algorithm so that the energy consumption by the node should decrease; hence the life time of the space sensor network should increase [24].
6. The inter satellite communication link is to be established when the distance between the satellites is within the predefined threshold value and also they are at an angle between $\theta_{min} < \theta < \theta_{max}$ $ie\ (170 \leq \theta \leq 190)\ at\ apogee$
7. The distance between the satellites is to be found using the distance formula, by finding the direction cosines (DCS) of satellites [25].
8. The heads are selected for each of the orbits based on the available energy (E), angle (ɵ), and speed (S).
9. Then the cluster head (CH) is selected such that the node should be nearer to the earth (i.e. ground) station.
10. The communication link to the earth station is to be established whenever the CH is between $\theta_{min} < \theta < \theta_{max1}$ $ie\ (355^0 \leq \theta \leq 5^0)\ at\ perigee$
11. By doing this energy consumption will be reduced by the satellite for transmitting the information or data to the earth station.
12. The routing table in each of the heads is maintained and it is continuously updated because the topology of the network is dynamic, and also the heads and CH changes as the life time of the network increases.

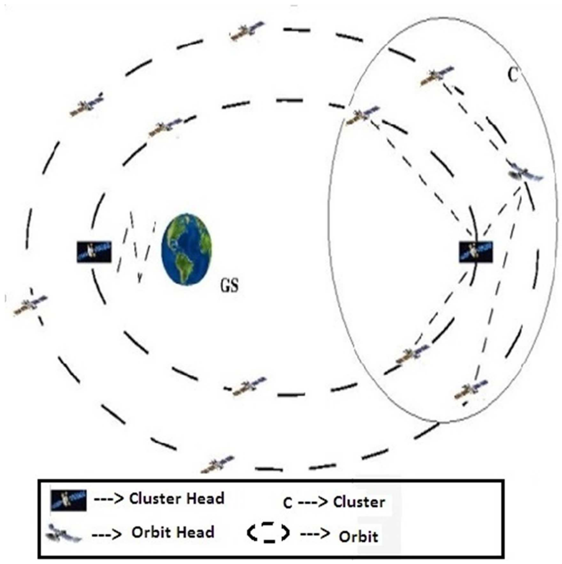

***Figure 4.** Satellite sensor network proposed scheme.*

3.4. Algorithm 1 for Intra Orbital Routing in Satellites

Nomenclature: ɵ= Right Assertion of Ascending Node (RAAN) $\theta_{min} = 170^0, \theta_{min} = 190^0$, ISL= Inter Satellite Routing, C= Cluster.

Consider an orbit with an altitude of 1500km from earth equatorial plane.

1. If satellites are between
2. $\theta_{min} < \theta < \theta_{max}$
3. Then create a C and establish an ISL between the satellites
4. Else
5. No ISL between the satellites
6. End

3.5. Algorithm 2 for Inter Orbital Routing in Satellites

Nomenclature: ɵ= Right Assertion of Ascending Node (RAAN), $\theta_{min} = 170^0, \theta_{min} = 190^0$, ISL= Inter Satellite Routing, H= Orbit head.

1. Begin
2. If H's are between $\theta_{min} < \theta < \theta_{max}$
3. Then establish an ISL between the H's
4. Else
5. No ISL between the H's
6. End

3.6. Algorithm 3 for Satellites to Ground Station Routing in Satellites (UDL Routing)

Nomenclature: ($\theta = $ RAAN) , $\theta_{min1} = 355^0$, $\theta_{max1} = 5^0$ ISL= Inter Satellite Routing, CH= Cluster head, UDL= up/down link.

1. Begin
2. The cluster head is selected based on the three parameters as described in the mathematical model section.
3. If CH is between $\theta_{min1} \leq \theta \leq \theta_{max1}$
4. Then establish UDL between CH and ground station
5. Else
6. No UDL between CH and ground station
7. End

4. Simulation

C programming language is used to test the performance of proposed scheme. The proposed work is compared with the existing routing schemes in SSNs. This section presents the performance parameters, simulation procedure and simulation model.

4.1. Simulation Model

Network model: We have considered the network with orbits for SSN. A network consists of satellites, which are distributed over the orbit in space. In this work, 100 satellites are considered for the simulation.

Channel model: The TCP/IP protocol is used for media access. Packets transmission is considered at discrete time intervals. During the receiving intervals, the receiver will receive the packet from the sending node. In this, channel is assumed to be free from error.

Propagation model: The free space propagation model is assumed for the proposed work. Each satellite transmission range in SSN is R. For every satellite at a given time, it is assumed that the transmission energy per data is E joules.

Table 2. *Simulation Inputs.*

Parameters	Value
Number of satellites	<120
Satellite node communication range	100to200km
Initial energy of sensor node	100kjoules
Cluster head time constant	50to60mseconds
Local satellite time constant	10-15mseconds
Orbit head time constant	15-20mseconds
Weight factor	wt=E*ɵ/S
RAAN	0-360^0
Eccentricity	0<e<1
Inclination	<90^0

4.2. Simulation Procedure

To analyze the proposed work, we have considered the some of the parameters is given in table 2. Simulation steps are as follows.

1. Network initialization.
2. Routing scheme is applied.
3. Performance parameters of routing scheme are computed.

4.3. Performance Parameters

For the analysis of the proposed work following performance parameters are evaluated.

1. Network lifetime: It is the aggregate number of rounds taken by the satellite to die in the SSNs.
2. Weight factor: It is defined as the ratio of available energy in the satellite and RAAN to the speed of the satellite.
3. Energy consumption for routing: It is aggregated sum of energy consumed for information transmission, route setup and route discovery.
4. Data Delivery Ratio (DDR): The ratio of data sent to the data received.
5. Latency: time required to transmit data from source to destination satellite.

5. Results

This section shows simulation results. The results are compared with the existing routing schemes in SSNs.

5.1. Energy Consumption

Figure 5 presents the energy consumption Vs. Satellite rotation time; we observe that as the time increases, energy consumption also increases. The satellite transmits information to the ground station and it takes about 100 minutes to complete one rotation around the earth. When the CH is nearer to ground station, it transmits information to ground station. We observe from figure 6 that as the number of satellites increases, there is an increase in the energy consumption by the satellites. The amount of data increases as the number of satellite increases in the network, so the overall energy consumption in the network will also increase. rotation of the orbit, either it clockwise or anticlockwise. It takes almost same delay when it establishes an ISL with same orbit satellite, which is shown in figure 7.

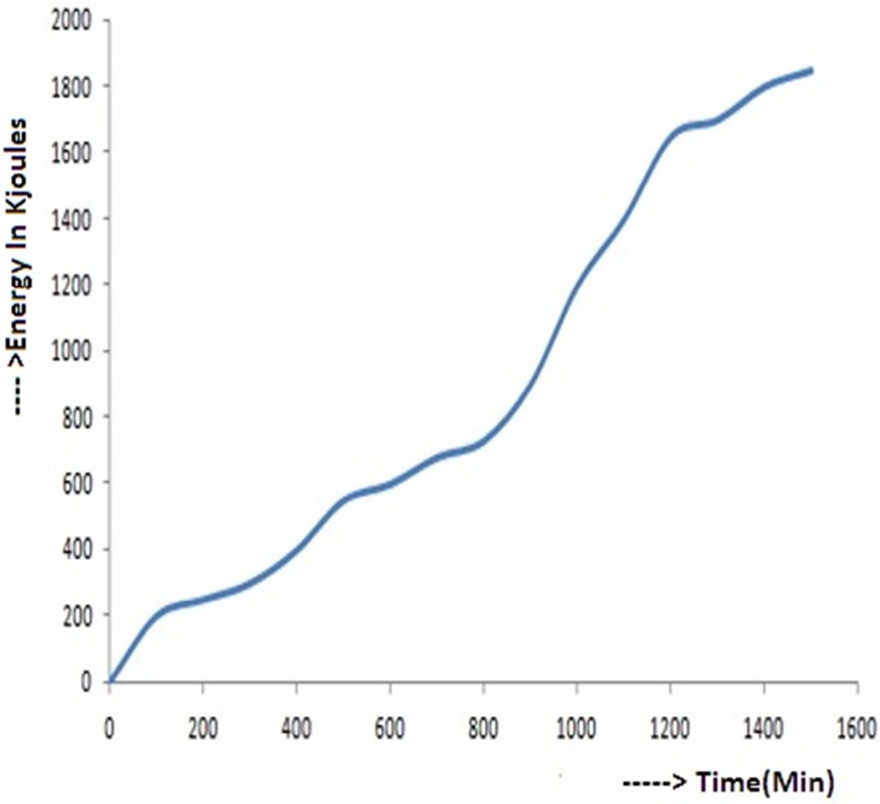

Figure 5. *Energy consumptions Vs Time.*

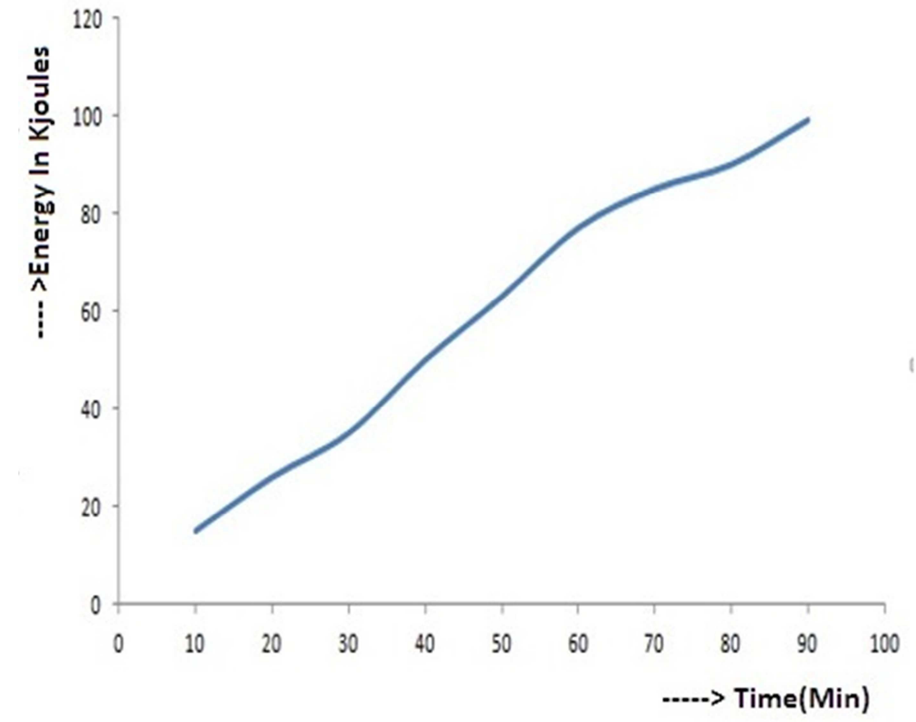

Figure 6. *Energy consumption vs Number of satellites.*

5.2. Average Delay

Let us consider the satellite in an orbit, when the satellite establishes an ISL with other orbit satellite, it may take less average delay or more average delay depending on the number of satellites.

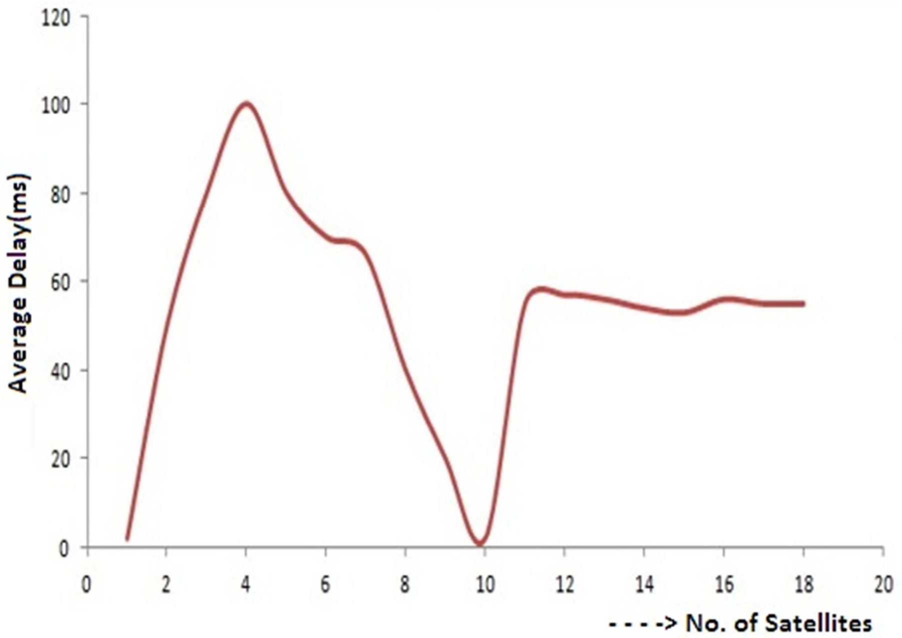

Figure 7. *Average delay vs Satellite Number.*

5.3. Network Lifetime

For increase in communication range, the number of connected satellites and the coverage area increases. As coverage area increases, the CH finds more number of neighboring satellites in the cluster. Thus there is an increase in network lifetime with increase in communication range and number of satellites as shown in figure 8. In the cluster, the CH will keep on changing based on the weight factor. Hence, the satellite with higher weight factor in the cluster will become a CH and remaining satellites will act as normal nodes.

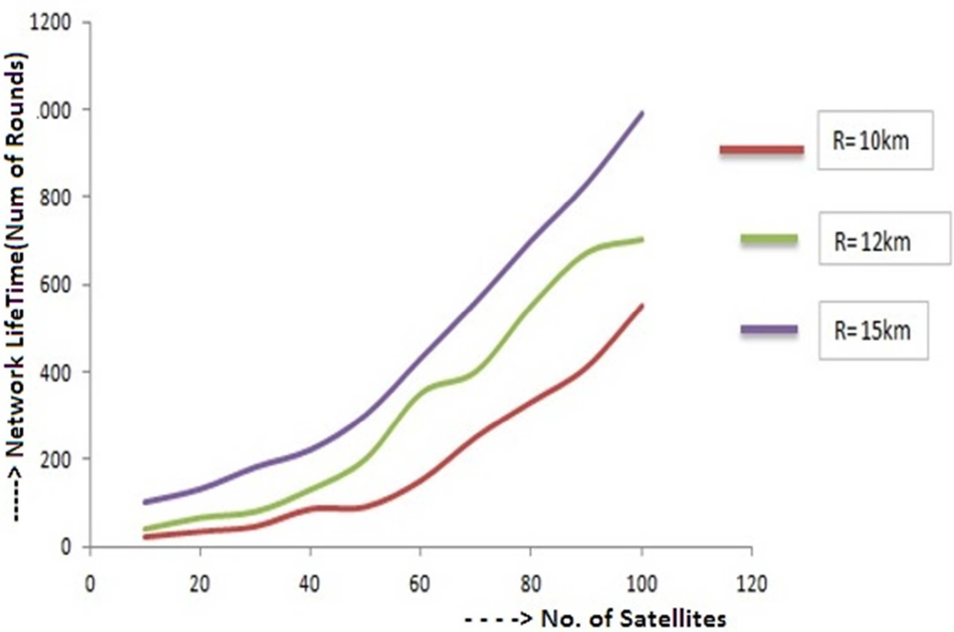

Figure 8. *Network lifetime vs Number of satellites.*

5.4. Cluster Formation and Cluster Selection Time

From figure 9 we concluded that with increasing satellite numbers at the apogee, the cluster formation time also increases and for increase in communication range there is an increasing cluster formation time. If the communication range of the satellite is increased, than more number of satellites will exist in the cluster.

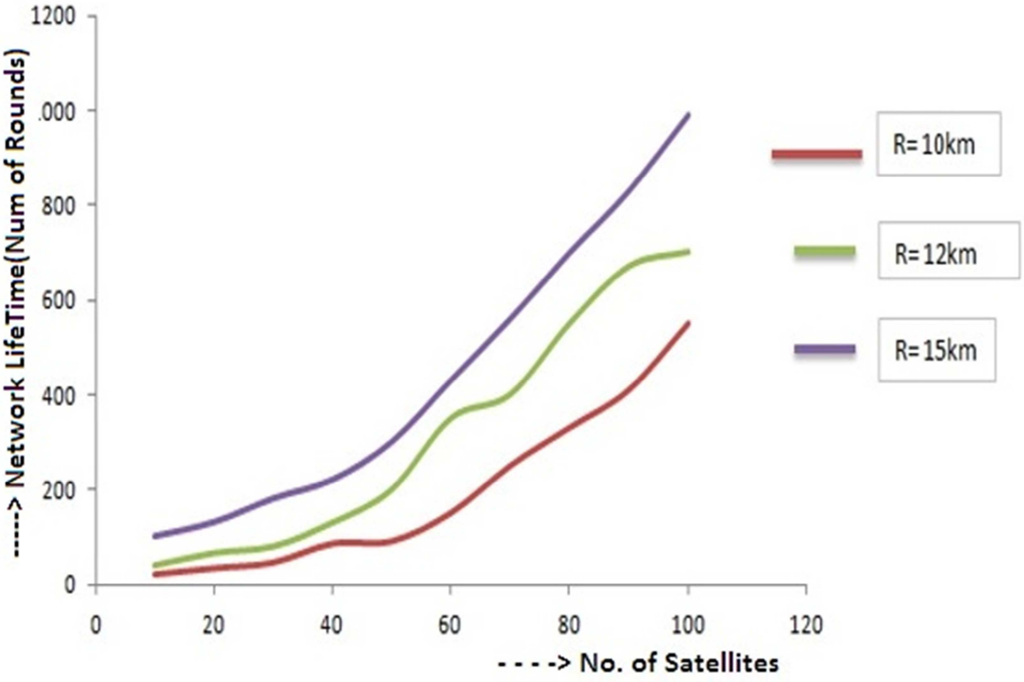

Figure 9. *Cluster formation time vs Number of satellites.*

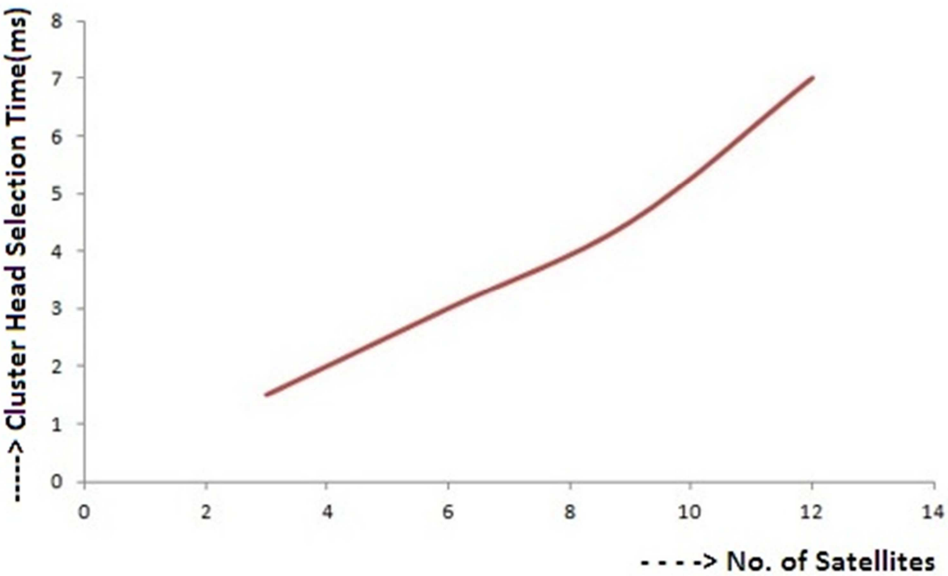

Figure 10. *Cluster heads election time vs Number of satellites.*

Figure 10 shows that cluster head selection time increases for increase in number of satellites. If there is increase in number of satellites in the cluster then calculating weight factor of each satellite consumes more time. Hence, it automatically takes more time to select the head.

6. Conclusion and Future Work

New challenge/issues arises as the satellite networks move towards less expensive, Nano-Pico and Femto satellites missions in LEO. The cluster based routing protocol proposed in this paper for connecting satellites with use of ISL in the cluster shows the improvement over the current protocols. The current improvements are efficient utilization of available energy in the satellites and increased network lifetime. Considering the performance parameters, the proposed work performance is tested in terms of network lifetime, energy consumption, cluster formation time, average delay and cluster head selection time.

The SSNs applications have fruitful scope in recent years. SSNs applications facilitate the layman job easy. The technological challenges have to be addressed in order to bring these applications in reality. This section presents the future work to proposed schemes.

For the proposed work we can minimize the latency by employing any of the routing protocol. For the proposed routing scheme, we consider the location based cluster for better performance of routing scheme. We also consider the multiple heads to improve the routing performance.

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