MINIMAL ENERGY ROUTING FOR

DEEP SPACE SATELLITE NETWORKS

By

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CHAPTER I

INTRODUCTION

Space-based networks are formed by satellites, one or more ground stations, and the corresponding collection of satellite-to-satellite and satellite–to-ground station links. Satellite networks provide a variety of services including sensor networking, data distribution networks, and all forms of broadband communications. Protocols for satellite networks must be designed to take into account the unique time varying characteristics of satellite systems [Modiano 04]. These characteristic are summarized below,

- Mobility – Satellites are always in a constant state of motion.
- Long propagation delays – Propagation delays for space communication links are variable and extremely long.
- Energy constraints – Solar energy is the only external source of energy. Rechargeable batteries are used whenever the solar cell go dark
- High Error Rates – Weather conditions (stellar interference) largely impact the channel conditions.

Broadcast satellite in geosynchronous orbit enjoy continuous sunshine for its solar cells except for brief periods of eclipse, may not require a sophisticated energy consumption strategy. Data communications satellite in medium or low earth orbit will experience prolonged periods of darkness. At the same time, if the satellite is providing packet data services, demand for such services will often be bursty, and the satellite must choose amongst users to be served. Cleary for such a situation, the need for an energy consumption strategy is obvious.

Energy management is a critical issue, as it translates directly into cost savings. Satellites with lower energy requirements require smaller energy sources (solar panels, reactors, rechargeable batteries), all of which translate into weight savings which generally in turn provide an economic benefit; smaller launch vehicle, or more maneuvering fuel could be carried, resulting in longer system life. It is important to consider link quality in route selection. Lossy links should be dropped in favor of high performance links. This selection should significantly affect the energy expanded by satellites transmitting packets. In this work we aim to develop a routing algorithm that minimizes the energy expanded by satellites by taking into account that links have errors. In this work the following assumptions are made about space-based networks,

- Satellite trajectories are assumed to be known (pre-calculated).
- Link Error Rates in the network are assumed to be known.
- Network topology is constant during a give period of time. Hence the routing algorithm is re-computed whenever a change in the topology occurs.

1.1 Thesis Outline

In chapter II, a brief background introduction to space based satellite networks is given along with their applications and characteristics. Previous work done in the area of space-based networks is discussed as a part of literature review in chapter III. The proposed routing algorithm is discussed in detail in chapter IV. Research objectives, scope and research methodology are described in chapter V. The simulation model, implementation details and results are presented in chapter VI. Chapter VII concludes the thesis and provides suggestions for future research.

CHAPTER II

BACKGROUND

Satellite technology has emerged tremendously since Arthur C. Clarke first invented it. Many emerging applications will incorporate multiple spacecraft that form communications networks necessary to achieve coverage, latency and throughput requirements [Clare 05]. Nowadays, many of the applications use satellite networks for data delivery. Worldwide communication using internet, telephone, television and radio are taken for granted, often using technology without even realizing presence of backbone satellites. The present day satellite networks enable people to transmit data from/to any part of the globe instantaneously.

2.1 A Brief Historical Review

Arthur C. Clark wrote the first well-known article "Extra-Terrestrial Relays" on communication satellites, which was published in Wireless World in 1945. In the article, Clark discussed the use of manned satellites in geostationary earth orbit to transmit television programs. Clark envisioned the possibility of covering the earth with a constellation of three geostationary satellites. Today, satellites used for telephones, television programs and computers to communicate around the world are in the geostationary orbit, as Clark envisioned. The world's first orbital spacecraft, Sputnik 1 from Soviet Union, was launched on October 4, 1957, which orbited the world for three months. However, the first communication satellite, Signal Communication by Orbital Relay (SCORE), was launched on December 18, 1958, which broadcasted a pre recorder Christmas message from President Eisenhower, orbited the earth for 12 days before the batteries failed. Syncom 3 was the first satellite ever used for televising parts of the Olympic Games at Tokyo, 1964. By then the early glimpses of globalization has been felt. On August 20, 1964, agreements were signed which created the International Telecommunications Satellite Organization (INTELSAT). First INTELSAT commercial service satellite, Early Bird, was launched by the end of 1965. Early Bird had a capacity of 150 telephone "half-circuits" and 80 hours of television service. With timeline many more satellites with advancements in technology are put in space making space based networks useful in many applications, like telephones, television and radio broadcasting, weather monitoring and forecasting, military surveillance and navigation and making globe a global village.

2.2 Elements of Satellite Networks

The two most important elements of the satellite networks are the satellites and the earth stations. Generally, data packets will be transmitted form earth stations to satellites and vice versa.

Satellites - A satellite is an object that orbits around another object like earth. Satellites carry equipments like antennas, cameras, radar and transponders. Satellite payload represents all equipment it needs to do its job. Communications satellites equipped with antennas and transponders receive the original signal from the transmitting earth station and re-transmit this signal to the receive stations on Earth. The omni directional antennas that were used in communication satellites were replaced by unidirectional, pointed antennas. Researches concluded unidirectional antennas pointing quite precisely towards the destination outperform omni directional antennas. These unidirectional antennas are steerable. Weather satellite has cameras included in its payload. Payload for satellites depends on the operation they perform. Inter-satellite links enable inter-satellite communication, while satellite-earth links are used for message exchange with earth stations. Satellites have processing capabilities and buffers to store information for transmission. Satellites also have rechargeable batteries to supply power when it goes out of Sun scope.

Earth Station – An Earth Station is located on the Earth's surface and is not mobile. Earth stations transmit or receive data using relay back bone of satellite networks. Earth stations like satellites have antennas, usually dish, and equipped with transmitters, decoders and receivers. In general, the earth stations have high power antennas which enable large coverage distance. Type and size of the antennas used varies with type of services provided. Earth stations are sink nodes, destinations, for a sensor satellite network. Application devices of the Earth stations transforms radio signals received into information and transfers to a computer or to a destined device, like a TV if it is a broadcast program. Similarly, this device will transform information to be transmitted into a signal that is suitable for transmission via the antenna, using modulation, amplification and other processing techniques.

2.3 Satellite Network Characteristics

Satellite network, composed of mobile satellites, fixed ground stations and communication links, have the following characteristics: long propagation delays, limited energy and time varying relatively high channel error rates.

Mobility - Satellites are mobile and their mobility can be pre-computed using Keplerian laws, as they rotate in their orbits. Geostationary satellites move relative to earth and are always stationary above a point on the earth. Satellite mobility balances the resource utilization among the satellites, avoiding any holes in the network.

Long Propagation Delay - Satellites communicate using inter-satellite links and uses satellite-ground links to communicate with earth stations. Satellites are usually far from one another and from ground resulting in long propagation delays. Propagation delay for deep-space communication links is variable and extremely long.

Energy Constraints - Solar energy being the only external source of energy, Satellite is equipped with solar panels to generate power used for satellite operations. Satellites also carry rechargeable batteries that can be used for power at times when it is out of the Sun view. High cost and the risk of radioactivity release in case of accidents, prevent from extensive usage in communication satellites.

High Channel Error Rates - Weather conditions largely impacts the channel conditions.

2.4 Types of Satellite networks [Nicole 97] [Jisc]

Satellite networking, using inter-satellite links, is essential to have continuous access to any part of the globe achieving global coverage and to carryout real time data transmission. A communication satellite is one used to receive and transmit data from and to any part of the globe, while sensor satellites like weather satellites are used to monitor and forecast weather conditions. Satellite sensor networks have sensors to sense the environment of our interest and transmit it to the ground stations. In general, space networks can be classified based on the operations they perform and here are the satellite network types.

2.4.1. Satellite based communication networks

Satellites that are used in communication networks are typically geostationary satellites, so that the broadcasting station will never lose contact with the receiver. Almost all of the communication sources television, radio, telephone and newspapers uses communication satellite network with ground stations for data transmission. A communication satellite receives a signal from uplink and amplifies before sending the signal on its downlink. Data transmission in communication networks is fast and reliable, achieving live coverage to/from any part of the globe. Communication satellites carry large volumes of data compared with terrestrial networks. Satcomes communication satellites are being used increasingly to handle long distance telephone calls, television programs, and other transmission around the world.

2.4.2. Space based Sensor Networks

Satellites in the sensor network usually have one or more sensors onboard for sensing areas of interest. Remote sensing satellites of sensor networks study the surface of the Earth. Remote sensing satellites are spatially distributed for simultaneous sensing of multiple locations of earth. Space based sensor networks provides real-time observations by rapid dissemination of satellite sensed data like weather information, elevation measurement, air quality. The data provided by sensor web to the scientific models monitors and forecasts the implications. Some of the satellite sensor networks applications include environment monitoring, air traffic control, military sensing and video surveillance. Satellites forming sensor networks gathers data from ocean, desert, and polar areas of the Earth where conventional weather reports are unavailable or limited.

2.5 Space Network Applications [Jisc]

Satellites of different shapes and sizes are spread across the space forming connected network sharing the wireless media for data communication, serving demands of various communities. Satellite networks serve people with many services like predicting weather and broadcast storm warnings, relay radio and television programs, navigation, military engagements and worldwide internet. The communities using the space networks can be grouped into commercial, civil and military.

2.5.1 Commercial Applications

Space network used by the companies for providing profit oriented services is said to be in commercial use. Communication Satellite Corporation COMSAT, found in 1963, began the deployment and operation of communication satellites on a commercial basis. Typical services of commercial satellites include broadcast and point-to-point communications and position and navigation systems. Satellite broadcast communication is used in Satellite TV like DirecTV and Dish Network and a point to point communication is seen in in-flight internet services. Satellite network used for broadcasting plays an important role in forming "global village". Global Positioning System (GPS) is being used in variety of applications like military, navigation, surveying, and tracking and also for visually impaired. Satellite telephone service provides true global voice services by covering that landline and cellular do not.

2.5.2 Civil Applications

Space network is said to be used for Civilian applications, if it is used for non-military and non-intelligence government agencies. NASA, NOAA and FAA are some of the organizations in US, using space networks for civil services. NASA's main concern is the development of technologies to explore the space by carrying science missions on our solar system. NOAA is responsible for weather monitoring and forecasting. NOAA's operational environmental satellite system is composed of: geostationary operational environmental satellites (GOES) for short-range warning and "nowcasting," and polar-orbiting environmental satellites (POES) for longer term forecasting [NOAA]. A complete global monitoring system is achieved by having both kinds of satellites. Volcanic ash detection and ice monitoring and prediction is performed by these satellite Networks. Space based navigation for flights are serviced by FAA.

2.5.3 Military Applications

Armed forces, military agencies and intelligence agencies uses space network to gather information, communicate, navigate and execute operations. Space satellites are used by the intelligence agencies to monitor and study ongoing operations in restricted areas. Civilian based space applications like weather forecasting, navigation, communication and world wide internet are also used by armed forces. GPS developed by the military, is used for navigation almost everywhere on Earth, in remote areas, crowded cities, in an airplane, on water or in poles. GPS receiver can track the position using radio signals from satellites in sight.

2.6 Advantages of Space Networks over Terrestrial Networks

Satellite networks are advantageous over terrestrial networks, as they are less affected by congestion; their architecture is scalable and also has coverage at geographical locations where it is hard to have a terrestrial network. Satellite TV, like Direct TV, which is a satellite based application can serve any individual, irrespective of how far is he from the nearest cable TV junction with digital quality television programming. In a country like Japan these services will fit best as it is practically not feasible to lay cable through all its islands.

In the next section the previous work done in the area of space-based networks is presented, and differences between our work and that done in other papers are discussed.

CHAPTER III

LITERATURE REVIEW

To meet increasing demand for satellite networks by various applications, many researchers have worked on routing protocols that addresses satellite network problems. In this chapter, I discuss works done by some of the researchers that led me to my proposed work, discussed later in this paper.

[Clare 05]: Loren P. Clare, in his paper "Space based Multi-hop networking" presents "L2 mesh" routing protocol for space based multi-hop networks. Satellites in network are equipped with directional antennas due to large inter satellite distance and a single transceiver is used to minimize cost. Network is composed of the satellites and multiple ground stations to achieve connectivity. Traffic patterns assumed are sensor networks and relay communication network systems. Network potential topology is pre-computed, using Keplerian laws and the parametric elements associated with each satellite, is taken constant for the time interval. Each of the satellites has data loads, for transmission, associated with them. Link activation and routing algorithm is defined to activate the links, at each time slot, for each of the satellites to transfer/receive data. The algorithm, applied at constant time interval, finds tree structures rooted to the ground stations of the network. It builds trees using hop distance as the metric, by including the satellites that are one hop distance into the tree, starting from satellites which are one hop distance from the ground stations. The total network load is balanced among the branches by moving the subtrees among the branches. Once the tree structures rooted to the ground stations are load balanced, [Florens 02] scheduling algorithm is applied to find the schedule. [Florens 02] algorithm is known to be optimal in providing minimum schedule length for tree structure.

Here in the algorithm, links are assumed to have same data rate and the physical link characteristics of the satellite networks, which vary with time and weather, are not considered. As no link quality is considered in their routing protocol there may chances of ending up with routes leading to high data loss. Satellites though use abundant solar energy; energy management is a critical issue as they sometimes rely on their rechargeable batteries. Energy utilization is not considered in this approach. Our proposed approach is mainly based on this paper. We take their idea of flat structure and incorporate energy and bit error rate constraints in our routing algorithm.

[Chen 05] presents a routing protocol, Satellite Grouping and Routing Protocol (SGRP), for hierarchical LEO/MEO satellite IP networks. SGRP operates on a two-layer satellite network consisting Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites. LEO satellites are grouped according to the foot print snapshot of the MEO satellites. The LEO group members change as the MEO satellite moves. MEO satellite covering the LEO satellite group is taken as group manager. Link delay information is passed by the LEO satellites to their respective group managers. MEO satellites on receiving the link delay information, exchange with other MEO satellites and compute the routing tables for the LEO satellites. SGRP aims at finding minimum delay paths for LEO satellites by sharing the routing table information with all the higher level MEO satellites. Load on the satellite system is assumed to be moderate. MEO satellites role in protocol is mainly confined to routing table calculation and transmission of signaling and data control packets. The exchange of delay information and routing tables among the intra orbit and inter orbit may result in extra overhead for the protocol. In this algorithm packets are sent on minimum delay paths. Since the propagation delay is used as the routing metric, lossy links with lower propagation delays may be favored to links with higher propagation delays but lower transmission errors.

[Neely 03] considers power and server allocation in a satellite which transmits data to multiple ground stations over multiple downlink channels. Satellites have different queues to store data packets destined to different ground stations. Each of the output queues has a server assigned. Channel state is determined using concave rate-power curve. Server rate depends on the power allocated to a server and the channel capacity. Based on the number of packets available in the buffers corresponding to the different downlink channels, algorithm makes decisions of power allocation to the servers. The algorithm allocates more power to channels having buffers of more packets. We assume all the data packets are destined to any of the ground stations in our approach, whereas data packets are destined to different ground stations in ref [3.3].

[Fu 03] addresses the issue of optimal energy allocation and admission control for communication satellites. Method developed allocates energy to meet the demands for a satellite. Satellite may not be able to serve all the requests received due to the energy constraints. Data delivery decision is made based on amount of energy available onboard and anticipated future demands for energy. A reward is allotted for each unit of energy expended by a satellite. The reward assigned can be a function of any of, distance of satellite from user, overhead atmospheric conditions or payments made by users for services. The reward changes with time and will be know at the time of service. However, the available energy onboard can be known, as the rechargeable batteries capacity and the schedule of the solar energy generated is known. The approach is to serve the requests that maximize total revenue. A dynamic programming is developed for optimizing satellite energy allocation. Their approach, kind of serves priority services (highly rewarded) over others and not all the satellite demands are met.

So, most of the energy aware routing protocols typically select routes that minimize the total transmission power over the satellites of the path, but do not consider the retransmissions that may be needed. Essentially the effective total transmission energy is not considered. In the presence of transmission errors, two transmission strategies have been envisioned. They are

- Per-Hop recovery.
- No recovery (using reliable paths).

In Per-Hop recovery each satellite will retransmit missing packets or packets received in error, minimal energy routes are chosen. In the second strategy, since there are no retransmissions between satellites the objective now becomes to maximize the reliability of the path, i.e. we minimize the energy consumption for a given reliability. The more reliable a path is the less likely a transmission error will occur. However these routes may yield longer paths then those produced in the Per-Hop strategy.

The aim is to devise minimal energy paths in terms of their energy consumption. As stated previously the work presented in this paper is based on the work of [Clare 05]. We develop an energy aware routing protocol on their framework.

In the next sections we present our model for the spaced-based network, after which our routing algorithm is presented.

CHAPTER IV

RESEARCH STATEMENT AND METHODOLOGY

A space based satellite network is composed of satellites rotating in their own orbits, whose motion can be predicted using Keplerian laws along with the parametric elements associated with them, fixed ground stations and set of inter-satellite and satellite-ground station links. Satellite networks have advantage of wide range geographical coverage to its counterpart terrestrial networks. In satellite network all the satellites are connected through a wireless medium with predictable topology changes. Satellites being far from one another have long propagation delays. Space being the media for satellite communications, various distortion factors results in signal attenuation. Satellites rely on onboard limited energy batteries on times when they don't get solar energy and hence optimal energy utilization is critical. Routing protocols designed for Satellite networks should consider above stated satellite network characteristics like long propagation delays, predictable topology, communication link error rates and limited energy. In this paper, we propose a routing protocol aiming at optimal energy load balanced minimal schedule data routing. For a satellite network topology considered each potential link has link error rate. The routing algorithm initially discovers the paths for all the space satellites resulting in low cost, where cost defined as function of energy utilization. The energy load of a node defined takes into account the energy consumed of all the data packets including the retransmissions that occur due to bit error rates on the link. The algorithm then load balances the total energy. Slotted communication is used to accommodate the long propagation delays.

4.1 Research Objectives

The purpose of the thesis is to develop a routing algorithm for deep space satellite networks that considers link error rates and energy optimization. It is important to consider link bit error rates in route selection, as selection of high bit error rates significantly increases the energy spent to send packets. Secondly, the proposed approach will the compared with existing protocol for performance analysis. To achieve this, the following objectives are identified:

1. To develop a space based satellite network with varying data error links and varied data loads.
2. To develop a power optimized routing algorithm for the above satellite network.
3. To study the performance of the algorithm based in terms of energy ratios and schedule lengths.
4. To compare the proposed routing protocol with the existing routing protocols.

4.2 Scope of the Research

The purpose of this research is to develop a new routing protocol for deep space satellite network routing protocol. The protocol takes link bit error rates in route scheduling to optimize the energy consumed in the network. Simulator is developed in

C#.NET 2005. The network topologies for the simulator were developed using BRITE model, topology generator framework.

4.3 Research Methodology

In order to accomplish the objectives mentioned above, the effort is divided into the following stages,

Stage 1: The existing space based network protocols are studied and explored in detail to gain the understanding of their purpose, strengths and limitations.

Stage 2: Various metrics of wireless networks, MANETs and satellite networks are studied and analyzed in detail.

Stage 3: Based on the study from steps 1 and 2 a routing protocol for deep space network is developed.

Stage 4: Satellite network topologies for the simulation were generated using Boston University Representative Internet Topology Generator (BRITE).

Stage 5: The proposed algorithm is implemented in C#.NET.

Stage 6: The performance of the proposed algorithm for space networks is analyzed in terms of energy ratios and schedule lengths.

CHAPTER V

PROPOSED WORK

A space based satellite network is composed of satellites rotating in their own orbits, whose motion can be predicted using Keplerian laws along with the parametric elements associated with them, fixed ground stations and set of inter-satellite and satellite-ground station links. Today, fast, effective and reliable data delivery is largely dependent on the satellite networks. Satellite networks play a vital role in collection and dissemination of data packets, especially for geographical locations which lack in communication infrastructure. However, performance of the satellite networks depends on the quality of communication links used for routing the data packets. Weather can impact the quality of the communication links. Apart from the link quality, satellite network performance depends on the amount of energy consumed by the network satellites. As satellites are equipped with solar panels that gather energy from the sun to carry out operations and recharge their batteries, choosing routes should optimize the energy utilization. Protocols for satellite networks must be designed to take into account the unique characteristics of satellite systems: long propagation delays, limited energy and power, relatively high channel error rates, and time-varying channel conditions [Modiano 04]. Routing in space based networks aiming for high throughput and being energy efficient is always a challenge. Here we propose a routing solution for space based satellite networks, considering variable data loads along with their energy consumption, in achieving high throughput. Using the proposed algorithm, we find those routes having low bit error rates and energy optimized from the available links for routing. Implementing the algorithm yields trees routed to the ground stations covering all the space satellites. Modified Florens and McElience tree scheduling algorithm, which gives minimum schedule length for tree structure, is applied to the trees routed at each of the ground stations [Florens 02].

5.1 Satellite Network Model [Clare 05]

Satellite Network Model M is a set, which consists of sets of mobile satellites S, ground stations G, and inter-satellite links LSS and satellite ground links LSG. To generalize, we call Satellites S and ground stations G as nodes, and inter-satellite links LSS and satellite ground links LSG as links in rest of the paper. Here are the key issues and components of the satellite network model.

5.1.1 Mobile Satellites and fixed Ground stations

Satellites rotate according to the orbital kinematics and hence their motion can be pre-determined. Mobility of the satellites results in model load balancing. Resource utilization of satellites is balanced as the base stations, satellites close to the earth which consumes much of their resources for packet forwarding, keeps changing with time. On the other hand, ground stations are fixed and have much resource available compared with the satellites. All the satellites in the model are assumed to be working homogeneously. Similarly, ground stations are assumed to be homogeneous in nature.

5.1.2 Single Transceiver for satellites and ground stations (Half Duplex)

Cost of the network model is always a concern and to keep the cost low we use single transceiver for each of the satellites and ground stations. Though, we use a single transceiver we can make the network work in full duplex mode, i.e., receive and transmit data simultaneously, by operating as a regenerative repeater.

5.1.3 Directional Antennas

Satellites and ground stations are equipped with directional antennas that can be rapidly steered. Interference-free link with the neighbor node is achieved by managing, the accuracy at which the beam is pointed to its neighbor and the beam width. To operate in a full duplex mode we assume nodes using different beams, one for each transmitter and receiver to operate simultaneously.

5.1.4 Communication ranges to define the potential topology

Communication range 'r' is defined as the maximum distance within which two nodes can communicate. Communication range r varies for inter satellite communications and satellite ground communications, and is r_{ss} and r_{sg} respectively. It is reasonable to say that, $r_{sg} \geq r_{ss}$. The links formed between the nodes based on their communication ranges are considered as potential links, as they may not be having antennas pointing to each other.

5.1.5 Slotted Communication

Data in the network is transferred using fixed size packets and the time to transmit a data packet between neighboring nodes along with time guard band used to handle synchronization inaccuracies is defined as a time slot. Long propagation delays are a characteristic of satellite networks. Slotted communication will best suites the scheduling to address the propagation delays accumulated along then multi-hop communication path.

5.1.6 Communication Traffic Patterns

Generally, traffic flow from spacecrafts to ground stations is called as data collection and from ground stations to satellites as dissemination. Based on the data forwarding strategy used by the intermediate nodes, traffic patterns are further classified into four types. The proposed algorithm is implemented for “unicast collection”, where data packets are generated by the satellites and are destined to the ground stations. Whereas in “unicast dissemination” data packets are generated at ground stations and destined to the satellites. Other traffic patterns “aggregate collection” and “aggregate dissemination” differs from their counterparts in the way the data packets are forwarded. In aggregate traffic models packets combine with downstream packets to minimize the path load.

5.1.7. Routing metrics

As the model throughput and data delivery ratio in a wireless network are dependent on the error rate of the link, we implement link bit error rate as routing metric in space based networking. Each edge in the connected graph of nodes is assigned a cost, which is a function of link bit error rate, i.e., $C_{ij} = f\left(BER_{ij}\right)$. Satellites have limited battery capacity and hence their energy should be efficiently used. Energy consumed per satellite accounting for data transfer on link of cost C_{ij} is computed. Energy load L is used to find load balanced routes in the network. The routing algorithm proposed in the paper uses link bit error rate and the energy load for transmitting the data as its routing metrics.

5.2 Minimum energy path activation and scheduled routing algorithm

The potential topology of the network at each time is known, as the satellites motion is pre-computable. For the constant time C, at which the potential topology remains unchanged, proposed activation and scheduling algorithm is applied. Each link of the potential topology has cost associated with it, where cost being function of bit error rate. The algorithm is rerun when topology changes. For simplicity, algorithm is implemented for 'unicast collection' traffic pattern. It can be further extended for other traffic patterns. Network has D as the set of data load on the satellites in unicast collection at constant time C.

5.2.1 General solution approach

The working of satellite based network routing protocol proposed in this paper can be viewed in these simple steps.

1) Discover the shortest cost paths for each of the satellites to the branch root satellites using shortest path algorithm. This step is known as the link activation step. Here link cost is a function of link BER. Assign Parent child relations to satellites based on the paths found to each satellite.
2) Data and Energy loads are computed for the branches generated by the step above. Balancing the network traffic based on the energy utilization is done. Branch satellites are then connected to the ground stations.
3) [Florens 02] scheduling algorithm is modified to account for the re-transmissions due to link errors and then used on the trees to find a minimum schedule length.

5.2.2 Algorithm Implementation

Some of the notations used in algorithm,

S - Set of N satellites

G - Set of M ground stations

B – Set of Branch satellites which are at one hop distance from the ground

D – Data load set of N satellites at constant time C.

C_{ij} – Cost of the Edge between nodes i and j.

E – Set of SSL and SGL links at constant time C.

P(u) – Data load on node u

$P_{subtree}(u)$ – Data load on node u along with its descendents data load

L(u) – Energy load on node u to carry its own packets

$L_{subtree}(u)$ – Energy load on node u to carry all of its incoming packets along with its own packets.

Step 1: *Shortest Path Discovery and Link Activation*

Cost Metric Calculation:

Consider the connected graph of satellites S. A cost metric for each of the potential links in calculated and assigned. Minimum cost routes are then discovered using the required shortest path algorithm. In this step the satellite constellation is divided into branches. The number of branches will depend on the number of branch nodes. Each branch contains exactly one branch node. The cost metric defined depends on the strategy being employed. The two strategies proposed are per-hop recovery or no recovery.

a) Per-hop error recovery

Assume X_{ij} is the packet error rates on potential links from S_i to S_j respectively, we define the cost metric C_{ij} in per-hop error recovery as

$$C_{ij} \propto \left(\frac{1}{(1 - X_{ij})} \right)$$

Having the above cost metric also assures that data from a satellite is transmitted to the root satellites along the least energy expensive path.

b) No error recovery

Here the cost metric C_{ij} is defined as

$$C_{ij} \propto \log\left(\frac{1}{(1 - X_{ij})} \right)$$

By using this metric the route selected is a function of the reliability of the path. Paths with lower PER are aggregated. Having this cost could yield lengthier paths to those used by the Per Hop recovery strategy, hence more energy could be drained in this strategy. Taking this into account we try to put a limit on number of hops a given path may take. We fix a reliability threshold, and we find the minimum hop path that satisfies the reliability constraint.

Route Selection

Apply Dijkstra's shortest path algorithm on the graph at each of the branch nodes to find the minimum cost paths for each of the satellites to branch satellites. Satellites which are in the range of r_{sg} from the ground stations are considered to be the branch satellites B. Each of the (S – B) satellites store a vector Branchcost of size |B|, which is initialized to Φ. Branchcost vector of a satellite stores the cost of minimum path to each of the |B| branch satellites.

For each of the Branch Satellites b_i

Call Dijkstra's shortest path algorithm

For each of the |S - B| satellites s_j

Update the i^{th} value of Branchcost vector with the minimum path cost to b_i.

End for loop

End for loop

For each of the satellites with updated Branchcost vector, we choose the branch which has minimum cost shortest path based on the Branchcost vector and activate the links on the path. This step generates minimal energy cost branches by partitioning the satellites to one of the branches. For each of the branch satellites a unique id '*i'* is assigned. Satellites of all the branches, will store the information of its parent node in the branch, set of child nodes and the branch id. Parent of branch nodes and the children of the leaf nodes of all the branches B are set to NULL. At the end of this step, each of the satellites knows its branch, parent and children.

Step 2: *Data and Energy load calculation/assignment for satellites*

2.1 Data Load Assignment

For each of the satellites in the network, we have random data load P to transmit. For a constant time C, the load distribution of N satellites is a vector P of length N with P_i being the load of i^{th} satellite. So, P(u) is the data load or the number of packets satellite u intends to transfer to earth station. The data load of a sub tree $P_{subtree}(u)$ rooted at a node u is defined as, the sum of its data load P(u) and its descendents data load along with the retransmissions required.

$$P_{subtree}(u) = \frac{P(u) + \sum_{v \in descendents(u)} P(v)}{1 - C_{uv}}$$

Where C_{uv} being bit error rate on the downstream, defines the retransmissions needed. As we do not have links between the ground stations and the branch satellites, for this step we assume the bit error rate or C_{uv} to be zero for branch satellites to ground stations. $P_{subtree}$ is computed for all the satellites in this step.

2.2 Energy Load Assignment

For simplicity, we assume the energy needed to transfer a fixed size packet over an edge between the neighboring nodes to be one unit. Energy load of a sub tree $L_{subtree}(u)$ rooted at a node 'u' is defined as sum of the energy required transmitting its data load and energy load of all its descendents.

$$L_{subtree}(u) = P_{subtree}(u) + \sum_{v \in descendent\,s(u)} P(v)$$

$L_{subtree}$ is computed for all the satellites. At the end of step 2 we have data and energy loads of each of the satellites in the branches.

Step 3: *Energy load balancing for branches*

Branches B from the step 2 will have unbalanced energy loads associated with them i.e., some of them may get overloaded while some are under utilized. To maximize the system lifetime, the loads should be distributed to all satellites in the network. In this step we balance the total network load L among the B branches. First, we find the branches having the maximum and minimum loads. The maximum and minimum load branches are represented as b_{max} and b_{min} respectively. If the branch b_{max} has only one satellite then we proceed to step 4 else add the immediate children nodes of b_{max} to *Process* set sorted in descending order of their loads, which is initially set to Φ. *Processed* set is used to keep track of the nodes that are processed for load balancing. Initialize the *Processed* set to Φ. The pseudo-code for the algorithm is given below,

While Process set is not empty

For each of the satellites 'n' in the Process set do the following steps,

Case 1: If there is no link to any of the other branches then proceed with next satellite in Process set. Move the node n from Process set to Processed set.

Case 2: If there any links to other branches, choose the branch connected b_{conn} with minimum load and then check to see if Subtree Movement Criteria holds.

If Subtree Movement Criteria holds do

1. *Confirm the Subtree Move*
2. *Update the child parent relations in the branches b_{max} and b_{conn}.*
3. *Repeat step 3 with new b_{max}*

Else

Move the node n from Process set to Processed set

End if

End for loop

//Update the process set with children nodes of processed set nodes when Process //set has Φ nodes

For each of the nodes in the Processed set

Add the immediate children nodes to the Process set

End for loop

Set the Processed set to Φ.

End while loop

By visiting all the nodes of b_{max} branch with no node satisfying SMC, we exit the step 3 and proceed to step 4.

Subtree Movement Criteria (SMC)

We see that excess of energy load between the branches b_{max} and b_{conn}, before the subtree movement is strictly greater than the excess of load after the movement. Equality in the equation may result in oscillations in the SMC.

$$L(b_{\max}) - L(b_{conn}) > \left| L(b_{\max'}) - L(b_{conn'}) \right|$$

Here, $L(b_{max}`)$ is branch b_{max} energy load after subtree movement and

$L(b_{conn}`)$ is branch b_{conn} energy load after subtree movement.

Subtree Move - Computation of loads for branches after subtree movement

a. Data Load and energy load computation when satellite n is connected to b_{conn}

Data load of the satellite n considered for movement is computed taking link metric of the new link into account as follows.

$$P_{subtree}(n) = \frac{P_{subtree}(n_{old}) \times (1 - x_{old})}{1 - x_{new}}$$

Here $P_{subtree}(n_{old})$ is the data load of satellite n in b_{max} branch. x_{old} is the downlink metric of n in b_{max} branch and x_{new} is the downlink metric of n in b_{conn} branch.

Energy Load for subtree rooted at satellite n when connected to b_{conn} is computed using the equation,

$$L_{subtree}(n) = L_{subtree}(n) + P_{subtree}(n) - P_{subtree}(n_{old})$$

Let, current be the node n connected to the branch b_{conn} with new computed loads. Call step c to update the loads of b_{conn} along the downlinks of ‘n’ to root. Current node returned from c is the $b_{conn}`$ and we have $L(b_{conn'}) = L(current)$.

b. Data Load and energy load computation when satellite n is removed from b_{max}

As the subtree rooted at n is moved from b_{max} to b_{conn}, the link between n and the branch b_{max} is deactivated. To update the loads of b_{max} along the downlinks of n to root set the Parent(n) as current and call step c. Current node returned from step c is the b_{max}` and we have $L(b_{max'}) = L(current)$.

c. Update the nodes of the branch from current node towards the branch root

Load computation of the satellites along the downlinks from the current node to the branch root is performed in this step c.

While Parent of current node not NULL

$$P_{subtree}(current) = \frac{P(current) + \sum_{v \in descendents(current)} P(v)}{1 - C_{currentv}}$$

$$L_{subtree}(current) = P_{subtree}(current) + \sum_{v \in descendents(current)} P(v)$$

$$current = Parent(current)$$

End while

Current node at the end of the step will be the branch node.

Step 4: *Connecting load balanced branches to Ground stations*

In this step the B branches are linked to the G ground stations, by finding the best of all the possible assignments. Each of the branches has set $BG(b_i)$ of ground stations to which they can be connected. All the possible combinations of branch ground node connectivity are considered as a set of *Assignment.* Assignment is a set of BA vectors. An assignment vector BA has ground station g as i^{th} value assigned to branch i from the set

BG(b_i). For each of the BA vectors in *Assignment* Load cost is computed.

Finding load cost for an assignment

For each vector BA of Assignment set

For each ground station gi in vector BA

$$Load(gi) = \sum_{gi \in BA} \frac{L(bi)}{1-x}$$

End for

$$Load\cos t(BA) = \max(Load(G))$$

End for

Finally, the Assignment vector BA with minimum cost is activated.

Assignment considered $A = \min(Assignment)$

Step 5: *Finding the schedule*

Florens and McEliece tree scheduling algorithm, which is know to be optimal in proving minimum schedule length for tree structure routing, is modified to account the network link BERs in our approach. The modified [Florens 02] algorithm is applied outbound from the ground stations to the satellites in a unicast dissemination pattern to find the schedule. The schedule for the unicast collection is obtained by reversing the schedule found from unicast dissemination. Schedule length is found following these simple steps,

- Schedule load for a satellite is defined as the actual data load transmitted, counting path BERs, for successful data delivery. First, the schedule loads for each of the satellites is calculated as given below,

$$\mathrm{SL(u)} = Ceil\left[\left(\sum_{x \in Path} \frac{1}{1-x}\right) * \left(P(u)\right)\right]$$

- Satellites of branches rooted to a groundstation are pushed onto Queue in order of decreasing hop distances. ScheduleLoad data packets are then scheduled using [Florens 02] and a schedule for each of the ground stations is determined.
- Maximum schedule length of the ground stations is the Network minimum schedule length.

In the next sections we present our simulation model implementation for the proposed link error aware routing algorithm for deep space satellite network. The simulator design issues and results are discussed in next section.

CHAPTER VI

SIMULATION MODEL

The proposed minimal energy deep space satellite network routing algorithm is implemented in C#.NET 2005. Object Oriented Design (OOD) concepts were used in the design of the simulator. Satellite network models for the simulation were developed using Boston University Representative Internet Topology Generator (BRITE). BRITE, implemented in java and c++, is a topology generator framework. BRITE supports multiple generation models including flat router topology which is used for generating various topologies that were used in our simulations. The flexibility of BRITE allows us to add link quality metrics needed to carry out our simulations. BRITE model, being interoperable and extensible, is used for our simulations as a topology generator. A graphical user interface (GUI), to show the network topology connectivity at various stages of algorithm implementation, is developed in C#.NET. The Interface developed allows viewing the properties of any of the topology objects.

6.1 Objective

The objective of this simulation is to implement the link packet error rate (PER) aware routing algorithm for deep space satellite networks proposed and compare with [Clare 05]. The comparison is done with respect to the network energy distribution and the schedule length. Simulations are carried out with varying network topology densities and varying network PERs.

6.2 The Traffic and Mobility Models

There are two types of nodes in the network, “satellites” to send the data packets and “ground stations” to receive the packets. The traffic model implemented in the simulator is unicast data collection, where the source traffic generated by the satellites is collected by the destination ground stations, shown if Figure 6.1.

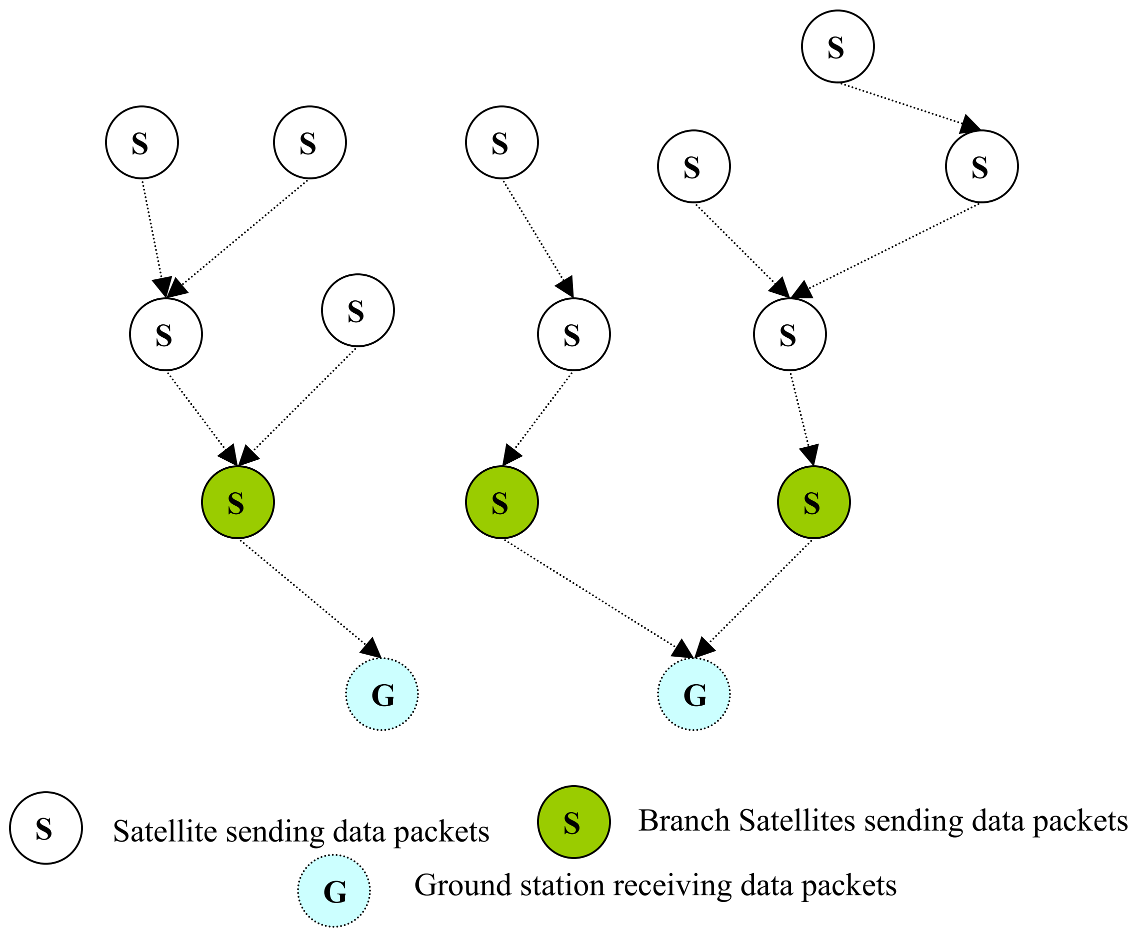

Figure 6.1. “Unicast collection” Network model.

We implement the routing algorithm and used throughout the duration when the potential topology C is constant. So, when the topology changes the algorithm is rerun. The potential topology used is developed using BRITE model. The topologies with 10, 20, 30, 40 and 50 satellites were used in the simulations. The degree of each of the satellites in the network is chosen to be four. Data load, which is the number of data packets a satellite sends to the ground station, is assigned for the network satellites using uniform random distribution (1 to 10 packets). The packet size is assumed to be constant in the network. The packet error rates of $5*10^{-6}$, $1*10^{-6}$, $5*10^{-5}$, $1*10^{-5}$, $5*10^{-4}$ and $1*10^{-4}$ are used for edges of the satellites.

Identical network topology, traffic scenarios, data loads and error rates are used for both the proposed approach and [Clare 05] to gather fair results. The performance of the algorithm is compared in terms of energy ratios and minimum schedule lengths. Energy ratio is defined as the ratio of maximum to minimum energies of the load balanced branches, while minimum schedule length is the minimum time taken for all the data to get delivered successfully to the destination. The energy ratio metric defines how well the energy load is balanced in the network.

6.3 Simulation Implementation

BRITE model is used to generate topologies having 10, 20, 30, 40 and 50 satellites with average degree for each of the satellite being four. Assumptions made in the implementation are, topology has fixed ground stations "G1" and "G2" and the topology has three proximal satellites (branch satellites). It is also assumed that each of the proximal satellites have potential links to all of the ground stations. Simulator is developed to implement the proposed approach and also [Clare 05]. The simulator implemented in C#.NET loads the initial BRITE topology and the following steps are performed in algorithm run,

- Each of the satellites is assigned a data load and each of the edges is assigned bit error probability (uniform random distribution). This topology is used in both the approaches to have same data loads and error rates, to gather fair results.

- Link activation is implemented to active the links of the potential topologies using each of the approaches.
- Data loads and energy loads are computed independently in both the approaches.
- Load balancing is implemented and the ratio of maximum energy to minimum energy of the branches is determined for each of the topologies.
- Branch satellites are then connected to the ground stations.
- Minimum schedule length is determined for both the topologies and the resulting values are collected for comparison.

6.4 Design of Simulator

Object Oriented Design (OOD) concepts were used in the design of the simulator. The C#.Net simulator is built on set of classes and functions performing designated tasks. A data structure for the network topology is developed in C# and used in the routing algorithmic implementation simulator, which is also developed in C#.NET. The data structure is composed of nodes and edges, along with graph traversal, connectivity and editable operations. The basic node structure containing different data members to keep track of the node's behavior is given below.

```
public class Node
{
Private:
      string key;/* Node Unique ID */
      int _xdist;/* Node's X coordinate */
      int _ydist;/* Node's Y coordinate */
      float _dataLoad;/* Node Data Load */
      AdjacencyList neighbors;/* List of Node's neighboring Nodes */
      Node _Parent;/* Node's Parent Node */
```

```
        NodeList _Children;/* Node’s Children NodeList */
        string _BranchKey;/* Node’s Branch Key */
        int _hopCount;/* Node’s hop distance from the Ground station */
        float _branchDataLoad;/* Node’s subtree Data Load */
        float _branchEnergyLoad;/* Node’s subtree Energy Load */
        float _ActiveLinkCost;/* Node’s active link cost */
        string _groundStation;/*GroundStation to which Node is connected
        int _ScheduleLoad;/*Node’s Scheduling Load*/
        float _berToGround;//Link error rate for branch node to
        groundstations
}
```

Node structure

The classes used in the simulator and their purpose are given below.

- Class SpaceWebGUI is simulator’s main class. In this class the network topology is loaded into the data structure. This class interacts with all other classes to run the algorithms and outputs the desired simulation results.
- Class ParentChildMap – The parent children relationship for all the satellites are set in this class, based on the activated links.
- Class Assignments – The subtree data and energy loads are calculated for each of the nodes in the link activated topology.
- Class LoadBalancing – This class takes the branches rooted to the branch nodes and performs recursive energy load balancing. It returns load balanced branches.
- Class Scheduling – For each tree rooted at a ground station, tree scheduling algorithm is applied in this class. Class returns minimum schedule length for the link activated network topology.

At any point of simulation time the network topology and the satellite properties, like data and energy loads, can be viewed using the interface “TopologyViewer”.

6.5 Simulation Input Parameters

The input variables that are required for the simulation are given below.

Topology Generation Inputs

BRITE model used for the topology generation requires the following inputs.

Number of Nodes: The number of satellites present in the network for the simulation. Numbers of nodes used in the simulation are 10, 20, 30, 40 and 50.

Average Network Degree: The average number of edges for each of the satellites in the network in network degree. The average network degree used for the simulations is four.

Simulation Inputs

Branch Satellites: The network satellites which are at one hop distance or directly connected to ground stations are branch satellites. Number of branch satellites used in the simulations is three.

Ground Stations: In "unicast collection" traffic model ground stations are the destinations for the data packets routed from the satellites. Number of ground stations used in the simulations is two.

Data Loads: For each of the satellites in the network, the data packets P transmitting to the ground stations is assigned. Data loads ranging from 1 to 10 packets were used in the simulation.

Link Packet error probability: Link error rates of the network which defines the rate at which data packets are dropped or lost in the network. For the simulations error rates ranging from $5*10^{-6}$ to $1*10^{-4}$ were used.

6.6 Simulation Results

Two different scenarios of simulations are performed to compare the algorithm performance in terms of energy ratios and minimum schedule lengths.

Scenario 1:

In scenario 1 energy ratio and minimum schedule lengths of both the approaches, using different node topologies, are compared. The simulation was carried out using 10, 20, 30, 40 and 50 nodes with the following network conditions.

- The average packet error probability for the potential topology links is chosen as $5*10^{-6}$.
- The data load of the satellites is chosen between 1 to 10 packets.
- The network has two ground stations and three branch nodes.

For each of the simulation runs the energy ratio and minimum schedule length, for each of the algorithms are plotted and the graphs are shown as Figure 6.2 and Figure 6.3 respectively.

Energy Ratio vs. Number of Satellites in topology

The energy ratio graph clearly shows that using our algorithm results in better energy load balanced network for all the topologies. It is also seen that with the increase in the network density, proposed algorithm gives better energy load balanced branches with the energy ratio closing to one.

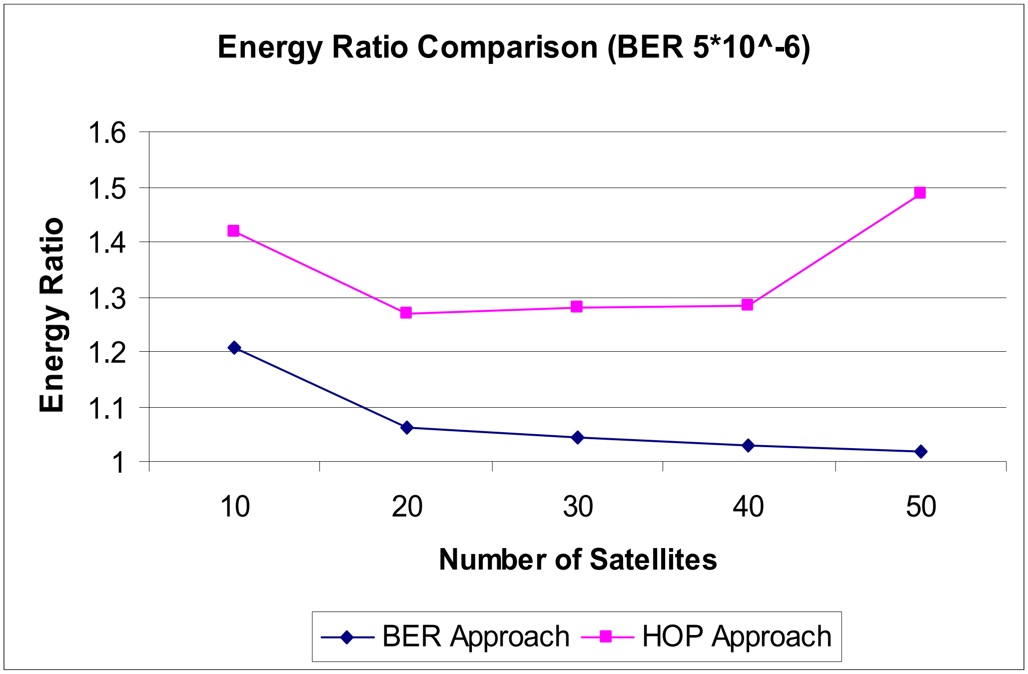

Figure 6.2. Energy Ratio vs. Number of Satellites in topology.

Minimum Schedule length vs. Number of Satellites in topology

The minimum schedule length which defines the minimum possible schedule time for a given link activated topology is analyzed in both our approach and [Clare 05], with varying node count in topologies. The number of retransmissions required for successful data transmissions are lesser in our approach, as we consider the link packet drop probabilities in selecting the routes. This guarantees that the minimum schedule length in our approach is at least the minimum schedule length in [Clare 05]. However, with the increase in network density our approach yields lesser schedule length than [Clare 05].

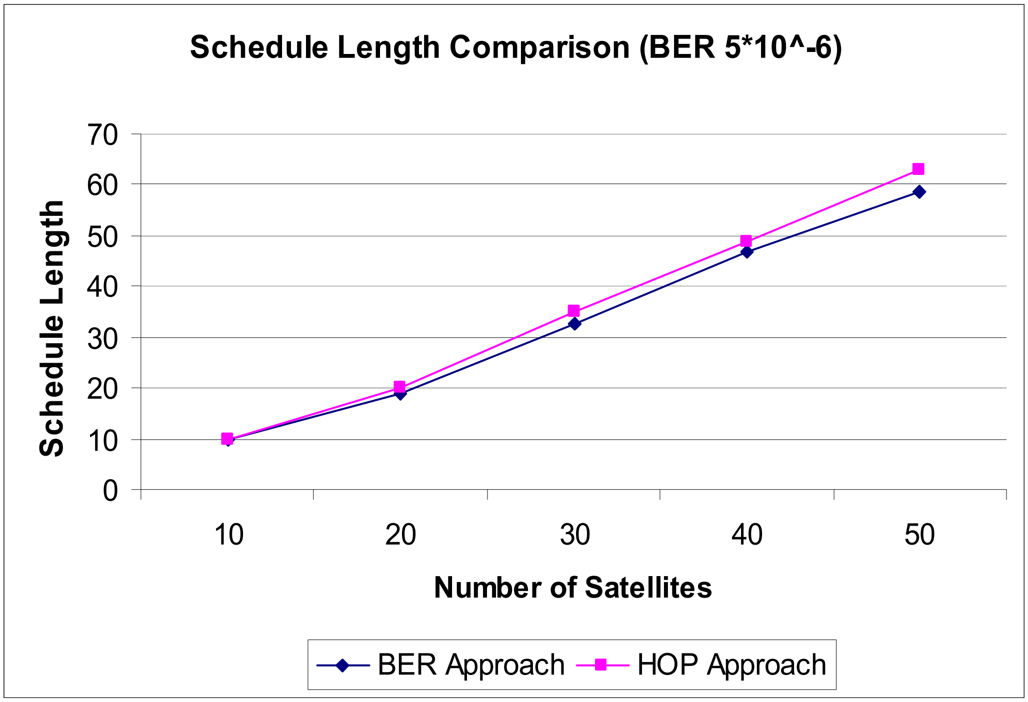

Figure 6.3. Minimum Schedule Length vs. Number of Satellites in topology.

Scenario 2:

In scenario 2 energy ratio and minimum schedule lengths of both the approaches, for topologies having different packet loss probabilities, are compared. The simulation was carried out using $5*10^{-6}$, $1*10^{-6}$, $5*10^{-5}$, $1*10^{-5}$, $5*10^{-4}$ and $1*10^{-4}$ packet error rates with the following network conditions.

- The network with 30 satellites is chosen.
- The data load of the satellites is chosen between 1 to 10 packets.
- The network has two ground stations and three branch nodes.

For each of the simulation runs in scenario 2 the energy ratio and minimum schedule length, of both the algorithms are plotted and the graphs are shown as Figure 6.4 and Figure 6.5 respectively.

Energy Ratio vs. Bit Error Rates (BER)

The energy ratio comparison graph (Figure 6.4) suggests that, using our approach clearly comes up with well energy load balanced link activated topology compared to [Clare 05]. It is also observed from the simulations that for a topology with the increase in the packet loss probability, proposed algorithm gives better energy load balanced branches with the energy ratio closing to one. On the other hand, increase in link BER results in increasing energy ratio for [Clare 05] for a topology.

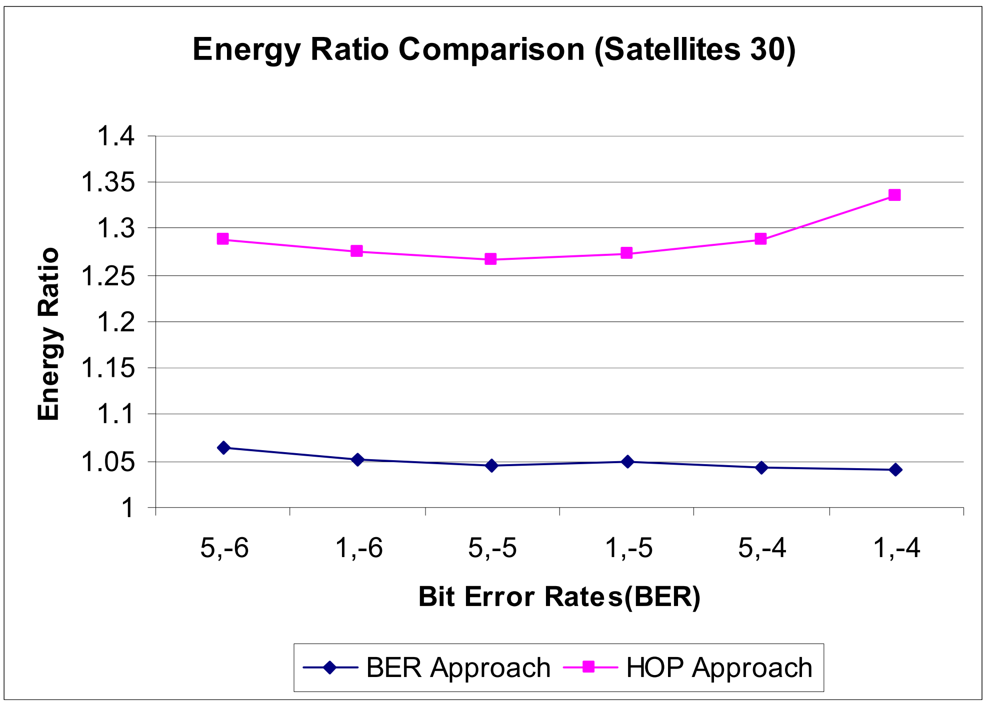

Figure 6.4. Energy Ratio vs. Bit Error Rates.

Minimum Schedule length vs. Network Bit Error Rates

The minimum schedule length is studied in both our approach and [Clare 05], with varying network packet error probabilities, shown in Figure 6.5. Simulations observed conclude our approach having lesser schedule lengths than [Clare 05] in any of the error probability networks. However, it is also observed that with increase in error rates the schedule length for both the approaches increases.

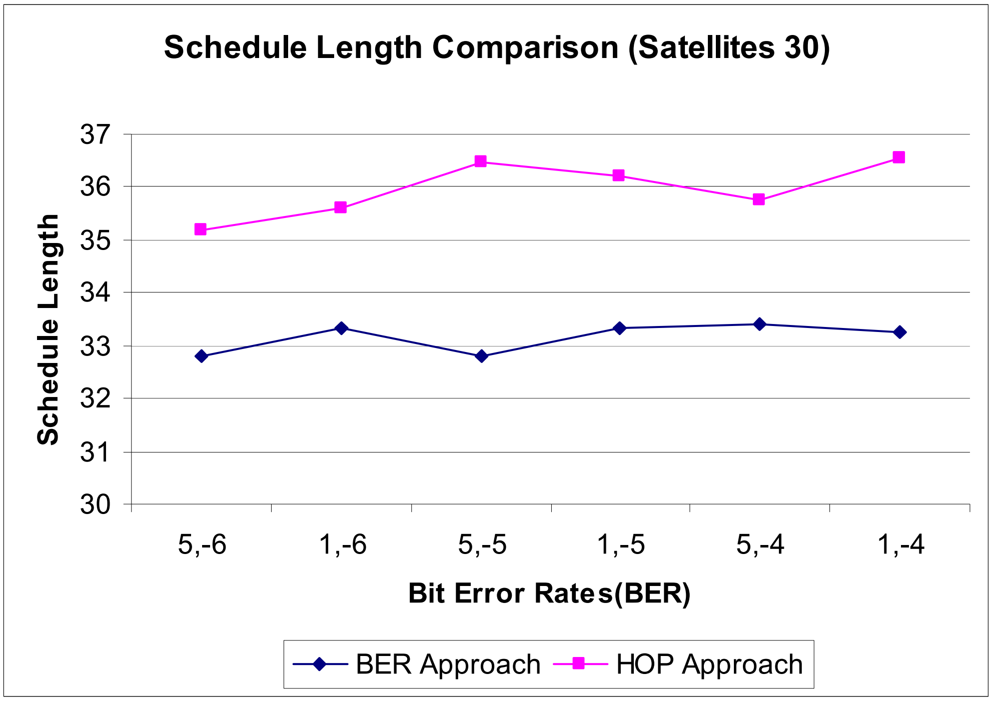

Figure 6.5. Minimum Schedule Length vs. Bit Error Rates.

Network Average Path Cost vs. Number of Satellites in topology

The network average path cost before and after the load balancing in our proposed approach is compared, shown in Figure 6.6. Simulations observed conclude that the average link cost is compromised to achieve the network load balancing. It can be observed from the results that the average link cost increases after load balancing. The link costs before and after the load balancing is shown as Before LB and After LB respectively.

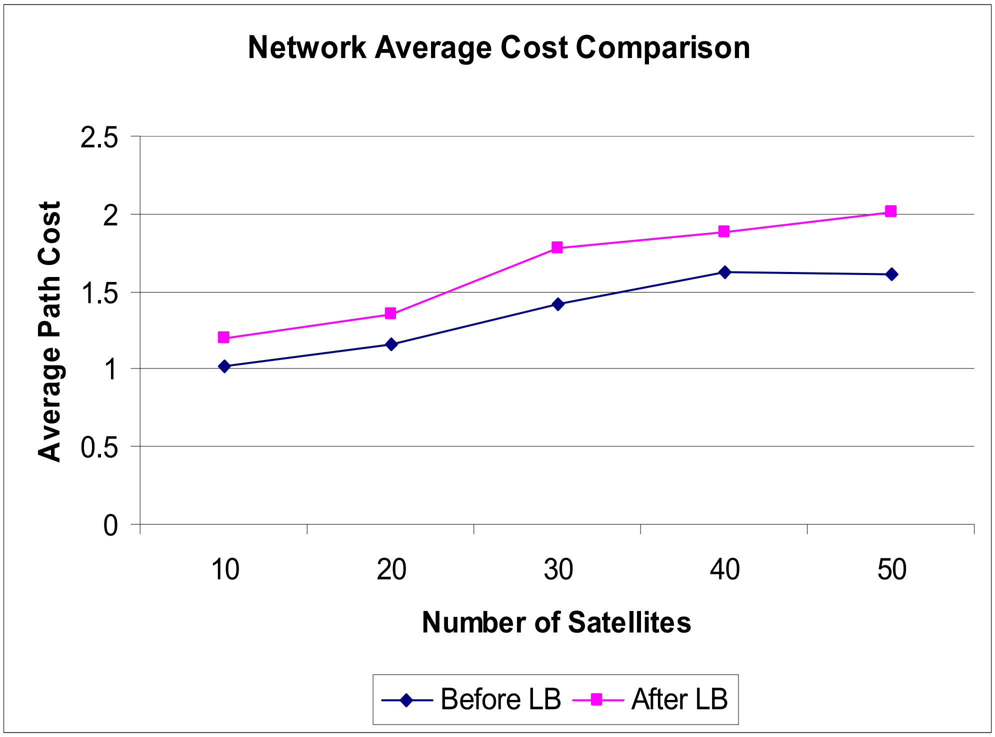

Figure 6.6. Network Average Path Cost vs. Number of Satellites in topology.

CHAPTER VII

CONCLUSION AND FUTURE WORK

This chapter includes the summary of the work done and also gives an insight into the future related to this area.

7.1 Summary:

Most of the energy aware routing protocols typically select routes that minimize the total transmission power over the satellites of the path, but do not consider the retransmissions that may be needed. Essentially the effective total transmission energy is not considered. It is important to consider link quality in route selection. Lossy links should be dropped in favor of high performance links. This selection should significantly affect the energy expanded by satellites transmitting packets. The primary objective of this work is developing a routing approach to achieve minimal energy utilization and network energy load balanced data routing. The work presented in this paper is based on the work of [Clare 05], developing an energy aware routing protocol on their framework. The simulations were carried out using the proposed algorithm and results were compared with [Clare 05]. Performance of the proposed algorithm is analyzed. The simulations conducted on this protocol once again suggest the importance of considering link error rates on route selection. The simulations also confirm the minimization of energy utilization and reduce in network schedule length when compared with protocol not considering link error rates.

7.2 Future Work:

The proposed approach can be implemented for no recovery situation, by using the no recovery cost metric defined in this paper and compare with the one proposed. The link cost function addressing both reliability and energy utilization could be developed for better implementation. Scheduling algorithm with varied timeslots could be developed to best get the schedule lengths in link error aware networks.

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APPENDICES

APPENDIX A

GLOSSARY

BER	Bit Error Rate
BRITE	Boston University Representative Internet Topology Generator
COMSAT	Communication Satellite Corporation
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
INTELSAT	International Telecommunications Satellite Organization
LB	Load Balancing
LEO	Low Earth Orbit
LSG	Satellite Ground Links
LSS	Inter-Satellite Links
MANET	Mobile Adhoc Networks
MEO	Medium Earth Orbit
PER	Packet Error Rate
POES	Polar-Orbiting Environmental Satellites
SCORE	Signal Communication by Orbital Relay
SGRP	Satellite Grouping and Routing Protocol
SMC	Subtree Movement Criteria

APPENDIX B

RESULT TABLES

The results gathered from the simulation are given below,

1. Energy Ratio vs. Number of Satellites in topology

Nodes	Energy Ratio	
	BER Approach	HOP Approach
10	1.205	1.419
20	1.062	1.269
30	1.043	1.279
40	1.027	1.283
50	1.019	1.487

Table B.1. Energy Ratio vs. Number of Satellites in topology.

2. Schedule Length vs. Number of Satellites in topology.

Nodes	Schedule Length	
	BER Approach	HOP Approach
10	9.80	10.00
20	19.06	19.93
30	13.46	35.00
40	46.73	48.86
50	58.73	62.93

Table B.2. Schedule Length vs. Number of Satellites in topology.

3. Energy Ratio vs. Network Bit Error Rates

Bit Error Rates (x)*10^y	Energy Ratio	
	BER Approach	HOP Approach
5,-6	1.064	1.288
1,6	1.051	1.275
5,-5	1.045	1.267
1,-5	1.049	1.272
5,-4	1.043	1.288
1,-4	1.039	1.335

Table B.3 Energy Ratio vs. Network Bit Error Rates.

4. Schedule Length vs. Network Bit Error Rates

Bit Error Rates (x)*10^y	Schedule Length	
	BER Approach	HOP Approach
5,-6	32.8	35.2
1,6	33.3	35.6
5,-5	32.8	36.5
1,-5	33.3	36.2
5,-4	33.4	35.7
1,-4	33.3	36.5

Table B.4 Schedule Length vs. Network Bit Error Rates.

5. Network Average Path Cost vs. Number of Satellites in topology

Nodes	Before LB	After LB
10	1.02	1.192
20	1.16	1.35
30	1.42	1.78
40	1.63	1.89
50	1.61	2.01

Table B.5 Network Average Path Cost vs. Number of Satellites in topology

VITA

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Name: Vamsi Krishna Maram Reddy Date of Degree: July, 2006.

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Title of Study: Minimal Energy Routing for Deep Space Satellite Networks

Pages in Study: 52 Candidate for the Degree of Master of Science

Major Field: Computer Science

Scope and Method of Study:

The purpose of this research is to find out a packet routing algorithm for link error rate aware satellite networks, achieving minimal network energy utilization. The existing energy aware routing protocols typically select routes that minimize the total transmission power over the satellites of the path, but do not consider the retransmissions that may be needed. A new protocol considering the link error rates in route selections for satellite networks is required. In our approach of data routing, the effective total transmissions and the energy required for these transmissions is considered. Energy load balancing is performed on the network to see that none of the satellites are overloaded or under utilized. Simulations are performed and the algorithm performance is analyzed in terms of energy load balance and schedule lengths.

Findings and Conclusion:

The simulator developed in C#.NET was designed and programmed to simulate and analyze the proposed link error rate aware routing protocol performance. Satellite network models for the simulation were developed using BRITE, a topology generator framework. Simulations were performed by varying network densities and link error rates to compare the algorithm performance in terms of energy ratios and minimum schedule lengths. The simulation results of energy ratios clearly suggest that the proposed algorithm yields better energy load balanced networks for all the topologies, irrespective of their densities and link error rates. The results also suggest that the schedule lengths were less using the proposed algorithm. Also, with the increase in node densities and link error rates, it is found from the simulations that the proposed algorithm performs well in energy load balancing and schedule lengths.

ADVISER'S APPROVAL: Dr. Venkatesh Sarangan______________________