Mirror Routing for Satellite Networks With Cross-layer Optimization

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Abstract. Several strategies have been proposed for routing in the Low Earth Orbit (LEO) satellite networks. The multi-layered routing approaches are envisioned as promising because they use Middle Earth Orbit (MEO) satellite to extend the LEO satellite network's communication capabilities. The previously proposed multi-layered routing approaches, however, still assume that the satellites in the same layer share similar characteristics. This assumption is not true in the future satellite networks. This is because the satellites in the future will be heterogeneous with various computation, communication and power capacities that lead to more complicated route construction challenges. In order to solve this problem, we propose the usage of cross-layer designs that can collect information from the neighboring satellites and evaluate their capacity during route construction and maintenance phases. This paper first analyzes the advantages and disadvantages of different satellite routing approaches. Then a multi-layered routing scheme called Mirrored Routing with Cross-layer optimization (MRCL) is introduced. In order to reduce overhead caused by the routing scheme, a hop count limitation, instead of a strict grouping policy, is used to direct packets to the MEO layer. According to our simulations, the end-to-end delay can be reduced 15% when a proper hop count limitation is selected. The novel routing scheme also significantly reduces the packet loss and the routing overhead (in terms of bytes of routing information) compared to the routing without cross-layer optimization and hop limitation. We also simulate and careful investigate the performance of MRCL using various hop count limitation configuration.

1 Introduction

The future satellite applications require self-organized, dynamic network topology without predefined constellation. Such applications include: 1) deep-space exploration that need to relay data using other satellites; 2) LEO satellites control for satellites that do not have a direct link to ground stations. In order to support the above applications, researchers have proposed multiple-layer satellite routing structures that utilize the MEO and GEO satellites to extend the coverage of satellite telecommunication. These proposals ([1] etc.) use the geographic information of the satellites to calculate the routing information or establish formation. These approaches, however, assume that the quality of Inter Satellite Link (ISL) is simply a function of the distance between two satellites. They do not consider the communication and computation capacities of each satellite, and the interferences from the space such as the solar wind and those caused by the inter-satellite communication itself.

In order to develop a realistic multiple layer satellite routing architecture that fulfills the requirements of future applications, we take the advantages of cross-layer design. The cross-layer design optimizes the overall network performance by sacrificing the layer's independence [2]. A strict modularity and layer independence may lead to non-optimal performance in IP based next generation satellite networks. With the cross-layer approaches, the link quality information can be used during the routing discovery and maintenance phases to avoid establishing unstable ISLs among the satellites in the same layer as well as satellites in different layers. Furthermore, instead of organizing the satellites in a strict grouping fashion, we use hop count limitation to determine whether LEO layer or MEO layer routing is preferable. This significantly reduces the computation and communication overheads. By regarding the MEO satellites and ground stations as the backbone of the network architecture, the LEO satellite can select links to the ground station and the ISL to the MEO satellites. Consequently, the proposed routing scheme is named as Mirrored Routing with Cross Layer optimization for satellites (MRCL).

The main contributions of this paper are:

- Analysis of satellite routing approaches and their limitations;
- Novel Mirror Routing with Cross-layer optimization for satellite networks(MRCL);
- Careful simulation to validate the advantages of our routing scheme using ns-2.

This paper is organized as follows. The satellite routing proposals and their advantages and disadvantages are analyzed in section 2. The section 3 presents the Mirrored Routing with Cross Layer optimization. The simulation results are demonstrated in section 4. We finally conclude the discussion in section 5.

2 Traditional satellite routing approaches and their limitations

Centralized route construction is conducted by the "master nodes" in the network. The centralized routing may leads to static connection among the satellites if the routes are not recalculated frequently. Therefore, the centralized routing approaches such as the ones proposed in [3, 4] are not suitable for the ad hoc satellite networks.

The distributed satellite routing construction no longer depends on the "master nodes". Consequently, the distributed routing provides more feasibility, stability and adaptability to the network compared to the centralized one. The distributed satellite routing, however, does not take into account the geographic nature of the satellite networks. The inter-satellite links (ISL) between LEO satellites and the ISL between LEO and MEO satellites have very different propagation delays. They cannot be treated with the same routing policy.

The Multiple Layer Satellite Routing (MLSR) [1] solve the above problem by grouping the satellites to the LEO, MEO and GEO layers. In MLSR, each satellite collects its topology information and sends it to its manager in upper layer. Satellites in the top layer calculate the individual routing tables for all satellites separately and send the tables to the corresponding satellites, which causes high computation overheads. Furthermore, one of the assumptions of MLSR is that the MEO satellite constellation is arbitrary as long as it has a global coverage. This assumption cannot be taken for granted if we consider the fact that the MEO satellites may belong to different organizations just like the LEO satellites.

A dynamic routing algorithm named Double-Layered Satellite Network Routing Algorithm (DLRA) is proposed in [5] . In DLRA, double-layered satellite networks consisting of LEO and MEO satellites can make the convenience of those advantages of LEO and MEO satellites in short-distance and long-distance communications. The basic principle of DLRA is that traffic of short-distance communications is routed only through the LEO layer, and long-distance ones are accessed by the LEO layer and routed through the MEO layer. The shortage of DLRA is that the ISLs are considered to be stable and their quality is only related to the distance between two satellites.

The above multi-layered routing proposals, in general, use the geographic information to form subnetworks. This approach, however, strongly relies on the geographic information, and neglects the impact of other factors that affect the quality of communication links such as the satellite's communication and power capacity. Furthermore, these architectures assume the satellite network is homogeneous, and the satellites in the same layer share similar characteristics. In reality, the heterogeneous satellites have various power, computation and communication capacities. This leads to much more complex route selection problem then the homogeneous satellite networks. The multi-layered routing mechanism is also based on the assumption that the satellites are capable of recognizing the satellites in their own layer. This is only reliable if the satellite broadcast their own profiles when establishing routing table. Consequently, more overhead is introduced. Our proposal considers the satellite network scalable (multi-layer), and limits the information exchange within the same layer as much as possible.

3 Mirrored Routing with Cross-layer optimizations

We propose a Mirrored Routing with Cross-layer optimizations (MRCL) that uses link quality information, instead of geographic location information to predict and select routes. In a network where MEO satellites form global coverage, multiple routes exist from one source to one destination. These routes are ranked according to their predicted stability. Furthermore, in order to reduce the overhead in the resource-limited LEO satellites environment and reduce queue length in LEO satellites, hop count limitation in LEO layer is used to direct the packet from LEO layer to MEO layer. No strict grouping and voting for LEO/MEO up and down links are required.

3.1 Multi Layer Satellite Network

The satellite network is divided into two layers:

1) MEO layer: The MEO layer refers to the collection of all MEO satellites in the network. This layer is positioned at an altitude between the GEO and the LEO layers. The constellation of the MEO satellites can be arbitrary as long as global coverage is achieved at all times.

2) LEO layer: The LEO layer consists of all LEO satellites in the network. This layer has lower altitude than MEO layer. We assume that the LEO satellites form a Walker Star type constellation. They do not necessarily form a single connected network. The LEO satellites do not guarantee the global coverage. The LEO satellites, due to their shorter life time, are designed to be smaller than the MEO satellites. Consequently, they have less power and communication capacity than MEO satellites.

The coverage of the MEO satellite network is better than that of the LEO satellite networks because of MEO satellites' higher orbits. The GSLs of MEO satellites is more stable (last longer) than the GSLs of LEO satellites because MEO satellites' higher orbits. Therefore, we can assume the ground stations and the MEO satellites form the backbone of the satellite network. In this backbone the links are stable but with various quality. For instance, the GSL of MEO satellites may suffer bit error rate (BER) ranging from 0.1% to 10%. This is similar to Internet that have congestion, which also has package loss due to buffer overflow in routers.

3.2 Assumptions for the Satellite Network

There are many assumptions for the satellite network design and its various activities including constellation, access policy and network architecture, etc. In this paper, discussions and results are conducted and obtained based on the following basic assumptions:

1) The MEO satellites and the ground stations (GS) can provide continuously and seamlessly coverage for its immediate lower satellite layer. This means the MEO satellites and ground stations are in constant stable state to provide access and routing functionalities to LEO satellites. The communication between the GS and MEO satellites are continuous. Consequently, the GS and MEO satellites form a "mirrored" backbone of the network, while the LEO satellites are between this mirrored backbone. This is illustrated in figure 1.

2) Satellites in LEO layer are organized into the polar constellation.

3) We only consider the space segment of the LEO/MEO satellite constellation and their connectivity to the ground stations, while the ground users ter-

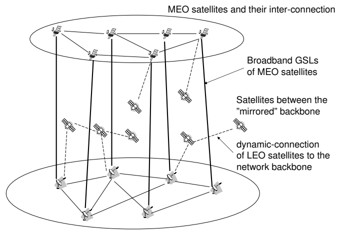

Fig. 1. LEO satellites in the mirrored network backbone

minals are beyond of discussion in the paper. Consequently, we do not discuss terminal handover issue in this paper.

4) All satellites in the network are capable of on-board processing and routing.

5) The ISLs can be always maintained between the LEO and MEO satellite layers. The ISLs in LEO layer (if any) should turn off when any of its connected LEO satellites enters the polar area. ISLs in MEO layer are functioning all the time.

In such a network, the MEO satellites and ground stations do not need to keep and maintain the network topology of the LEO satellites. Instead of forming a strict hierarchy, the mirrored routing structure only guarantee the network backbone that consists of the ground stations and MEO satellites. This is because of the following reasons:

- The number of LEO satellites is unpredictable. In the future, more and more small and micro LEO satellites are projected to be launched by many organizations such as industry and research groups, as well as universities. It is unrealistic to maintain their information.
- The LEO satellites have shorter life time due to their design and mission purposes. Therefore, the LEO satellites are much more dynamic than the MEO stationary satellites. The network topology is also fast changing.
- The LEO satellites have extreme various power and communication capacities. Consequently, even when the LEO satellite is at a predefined position that can be detected by the network backbone, it is still unclear if the connection can be established.
- The LEO satellites are not designed to be operational during the whole mission. For instance, they may shutdown to reserve power. This type of self controlled behavior has great impact on network topology. Such behaviors, however, cannot be predicted by ground stations or MEO satellites that, we assume, are always operational.

3.3 Cross-layer Information

We propose an architecture that uses cross-layer information to optimize the performance of the routing protocol and reduces the overhead caused by the routing. An integrated MAC/PHY layer that provides more accurate and adequate information to other cross-layer optimizations [6] is used to provide such low level information that reflect the real-time wireless link situation. The proposed MRCL then use this information at both the LEO and MEO satellite layers.

The cross-layer designs have potential risk when interact with each other due to reasons such as shared information and adaptation loops [7]. In order to prevent such problems, we use the infrastructure for cross-layer design interaction proposed in [6] to ensure that the optimizations are loop-free, and behave correctly according to their designs.

In the integrated Mac/PHY layer of the above proposal, share communication channels are established among the data link control layer (DLC), MAC layer and physical layer. Therefore information such as BER and SNR is available to upper layers. In order to simplify the information to upper layers, we define a normalized variable called Ranking of Link (R_l) to rank wireless link quality of all ISLs in terms of BER and SNR, and collision possibility $P_{collision}$ of outgoing packages from this node. Higher R_l value indicates more network congestion or package loss.

R_l is calculated using two probability functions:
1) *error probability* P_e as a function of BER and SNR, and
2) *collision possibility* P_c of outgoing packets from this node.
A higher R_s value indicates more network congestion or package loss (1).

$$R_l = f(P_e, P_c), R_l \in (0, 1] \tag{1}$$

The error related to noise and collision are equally important indications of link quality. Therefore the R_l is calculated as the weighted sum of probability of error P_e and collision P_c (2). For simplification, we use (3) in our simulation.

$$R_l = W_e \times P_e + W_c \times P_c \tag{2}$$

$$W_e = W_c = 0.5 \tag{3}$$

A more careful selection of the two parameters may improve the accuracy of R_l. But as stated earlier, this accuracy does not influence the performance of the proposed mechanisms. In order to rank multiple available routes according to the link quality, we add a variable $S \in (0, 1]$ in the routing cache/table to indicate the stability of the route as shown in the algorithm below. The value of S equals to 1 when the route is most stable. The value of S decreases when the route becomes less stable. S is updated 50 times during the time when the satellite travels between the two polar regions. The value of S is calculated according to R_l and the availability of the route. If the satellite passes the polar region and starts moving in another direction, S is reset to 1 and the calculation starts over. The calculation of S is shown in the routing construction at LEO and MEO layers.

3.4 High level Routing policy

The packets in the mirrored satellite network are processed and forwarded individually in every satellite on their paths. The routing decisions are stored in routing caches/tables onboard the satellites. These tables must be updated to reflect the changes in the network topology and in the traffic load carried by the network. The following issues were considered when designing the MRCL.

- Computational Complexity: The satellite network of both LEO and MEO satellites consists of a large number of nodes. The periodic routing table calculations are performed in the satellite network and require high processing power in a power limited environment especially for LEO satellites. To cope with this problem, we develop the LEO layer routing based on Dynamic Source Routing (DSR) for the following reasons: (i)DSR is on-demand routing that does not use periodic messages to update the routing information. Consequently, it consumes less bandwidth and energy than table-driven (proactive) routing protocols. According to [8], DSR has the smaller overhead than other protocols when pause time is 0s. (ii) DSR records the complete route from source to destination. Therefore, all the intermediate links are known to the source. The source can optimize the route using the links' information. (iii) The intermediate nodes also utilize the route cache information efficiently to reduce the control overhead. (iv) DSR does not maintain a routing table and consequently needs less memory space. A simple ID instead of full IP address can be used in such networks. Both the limited hop-count and the simple ID reduce the overhead in packets. Thus, the main disadvantage of the DSR is avoided.
- Communication Overhead: In order to reflect the current condition of the satellite network to the routing decisions, the up-to-date link delays must be used while calculating the routing tables. The collection of the delay measurements puts additional communication load on the satellite network. In our proposal, LEO satellites reactively construct the routing table to save the computation and communication resources onboard. The MEO satellites with much higher capacity perform proactive routing table construction.
- Delay and hop count assumption: The measured link delays used in MRCL include the propagation and processing delays. Although the propagation delay is a major part of the link delays, the processing and queuing delays can become larger than the propagation delay on the congested links. Furthermore, the LEO satellites have much less computation and communication capacities than the MEO satellites due to their smaller size and shorter lifetime. Therefore, we assume that after the packet is relayed among the LEO satellites for N hops, the total end-to-end delay is longer than relaying with MEO links because of the processing delay and retransmission on the LEO satellites. The N is defined as hop count limitation in LEO layer. When

multiple LEO and MEO layer routes are available, the route with MEO satellites should be selected if hop count of the LEO route exceeds N, even if the propagation delay of the LEO routing is smaller.

3.5 Routing table calculation in LEO satellites

There are the following cases concerning the relative quality of the ISL between two LEO satellites and their ISL to MEO satellites and ground stations.

- The ISL between the LEO satellites is good enough in terms of BER and stability.
- The ISL between the LEO satellites is good in terms of BER but is going to vanished due to fast changing relative position of the two satellites.
- The ISL between the LEO satellites is not good enough to establish direct communication. Route can be found using either GSL or ISL to MEO satellites.
- The connection between two LEO satellites cannot be established. This means at least one of the LEO satellites is not connected to the backbone.

At the LEO layer, the satellites try to use the MEO satellites to route if the the destination is not accessible in N hops. If a bigger N is selected, the LEO satellites prefer to use ISL at the LEO layer. We use the hop count limitation instead of constructing complete LEO satellite groups like MLSR. This is because the topology at the LEO layer changes very quickly so that the grouping maintenance consumes a lot of resources. If there is no packets being delivered, the computation is useless. We prefer more reactive fashion to determine whether to use MEO layer route or not, instead of proactive calculation like grouping in MLSR. In reality, if we consider the coverage difference between the LEO and MEO satellites and the delay caused by packet relay, we can find out that the N is a small number. This is because the delay caused by the queues of the LEO satellites is much longer than the propagation delay between MEO satellite and LEO satellite or GS if hop count N is too big. The following algorithm is used at the LEO layer to calculate the routing table:

Algorithm to calculate stability variable S and route construction in LEO

```
FOR (each found route i )
    S_{i} = S_{i} / (1 + sum of all the R_{l}
                     of LEO ISLs on the route)
ENDFOR

IF (route is only found in LEO layer)
    use the route in LEO layer with the highest S
ELSEIF (route is found in LEO layer and MEO layer)
    IF (hop count > $N$)
        use the MEO layer route with the highest S
    ELSE
        use the LEO layer route with the highest S
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    ENDIF
ELSEIF (route is found only in MEO layer)
    use MEO layer route with the highest S
ENDIF
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3.6 Routing table calculation in MEO satellites

In the route discovery phase, the ISLs between LEO satellites and ISLs between LEO and MEO satellites are both ranked according to the R_l algorithm. The difference is that the LEO ISLs calculation is performed every time when route discovery is required. The ranking of ISLs between the MEO satellites are only calculated periodically because the relative positions among MEO satellites change much slower than those among LEO satellites. We assume that in the routing discovery phase, the route involves least ISL between two LEO satellites should be selected if the link quality ranking is the same. This is because the ISLs between LEO satellites are much less stable than ISLs between MEO satellites due to the rapid movements of LEO satellites. The following algorithm is used at the MEO layer to construct routing table according to the stability variable.

Algorithm to calculate stability variable S and route construction in MEO

```
FOR (each observation time)
    IF (if route is available)
        S = S / (1 + sum of all the
                 R_{l} of MEO ISLs on the route)
    ELSE (route is broken)
        S = S/2
    ENDIF
    IF (ISL is between LEO satellites)
        select the link with highest S
    ELSE (ISL is between LEO and MEO/GEO satellites)
        select the route with least LEO ISLs
        IF (more than one route are selected)
         select the route with highest S
        ENDIF
    ENDIF
ENDIF
ENDFOR
```

The route construction is reactive on the LEO layer, and proactive on the MEO layer. This approach reduces the unnecessary overhead caused by fast change topology of LEO satellites, and still benefits from the much reliable MEO satellite routes.

4 Validation and Results

In order to validate our cross-layer optimizations, we implement the Mirrored routing with cross-layer optimizations in the Network Simulator 2 (ns-2) version

2.28 [9]. Our simulation is based on the ns-2 satellite package provided by [10]. In order to validate our cross-layer optimizations, the following improvements are made to the satellite package:

- The energy model is introduced to simulate the satellite's behavior without the energy source (in the shadow of the earth);
- 802.11 MAC like collision is introduced to evaluate the probability of collision;
- The success receipt of package is calculated using probability of error, which is a function of distance;
- The satellite package and the DSR package in ns-2 are modified in order to replace the centralized routing with MRCL.

We use the following configuration for our study:

1) LEO satellites: 10 to 50 LEO satellites on random polar orbits (altitude 500-800km) within 5 degrees deviation with random start elevation degree (based on longitude 4.0 E); GSL from 500kbps to 2Mbps for each LEO satellite; ISL from 1Mbps to 2Mbps for LEO satellites; both symmetric links.

2) MEO satellites: 10 MEO satellite nodes as Intermediate Circular Orbit (ICO) [11], two orthogonal planes at an altitude of 10,390 kilometers, 5 satellites per orbit; 2 intra-orbit ISLs, 2 inter-orbit ISLs, global coverage; GSL and ISL are both set to 100Mbps to simulate unlimited capacity.

3) Three Ground stations: A (in Delft 51.9792 N, 4.375 E); B (New York 40.30N, 73.24W); C (Beijing 39.92N, 116.46E). Data Sources: 10 CBR on UDP simulates the realtime data from GS A to B and from GS B to C. 20 FTP on TCP simulates non-realtime data from satellites to GS; duration: 1 day (86400s).

We use the centralized routing calculation to simulate the routing based on location information without CL optimization. The LEO satellites choose the closest GS or MEO satellite to establish communication link if necessary. Then we compare the result with the proposed MRCL.

Figure 2 demonstrates the end-to-end packet delay with different hop limitation. The MRCL always has less delay than shortest path first based routing without CL optimization (WO CL). When there are few LEO satellites (15 satellites), which means few ISL in the LEO layer, the impact of hop count limitation is neglectful. When the number of LEO satellites increases (20-35 satellites), more hop in the LEO layer ($N = 3$) provides better performance. This is because the LEO satellites form several isolated groups. Consequently, delay is decreased by allowing more hops inside the group. When the number of LEO satellites continues to increase (more than 40), the LEO satellites start to form bigger groups and eventually one big network that includes all LEO satellites. In this case, the payload significantly increases because more routes are available among the LEO satellites. The queue delay dominates the delay in the LEO layer. Therefore, by encouraging the LEO satellites to use MEO satellites ($N = 1$), the delay is reduced. Also, for the same reason we predict that the performance of even bigger N would be closer to shortest path first scenario.

Figure 3 shows the throughput comparison. The performance of $N = 3$ is almost equivalent to that of the shortest path first, which means most of the

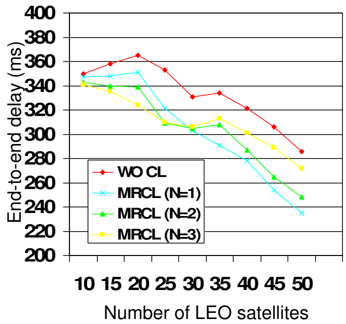

Fig. 2. end-to-end delay with different hop limitation N

packets are already dropped within the first three hops. By using more MEO satellites that have much higher bandwidth and better link stability ($N = 1$), the packet loss is significantly reduced. The reason why the performances are more or less the same when few LEO satellites are in the network (10 to 20)is that the LEO satellites are isolated and there are few routes available within the LEO layer. Consequently the packets are forwarded by the MEO satellites no matter the value of N.

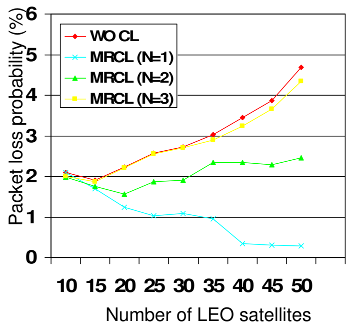

Fig. 3. packet loss probability with different hop limitation N

Figure 4 shows the packet overhead in term of bytes in packets introduced by the MRCL. There are three kinds of packet overheads introduced by the MRCL: overhead caused by cross-layer optimization, overhead caused by the routing table construction and overhead in packets to carry route information (because of DSR like routing in LEO layer). The results show that our proposal always has less packet overhead than centralized shortest path first. When the hop count limitation N increases, the packet is allowed to stay in the LEO layer for longer time. This means the packet header must contains the complete route information longer just like DSR. Therefore, the packet overhead is also higher. Although we cannot compare the packet overhead between our proposal and the MLSR due to lack of information, it is clear that the MLSR is proactive while MRCL is reactive on the LEO layer. The packet overhead of proactive routing is generally much higher than reactive routing because of periodical broadcasting of routing information and route maintenance even there is no traffic in the network.

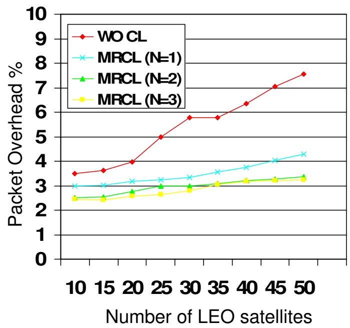

Fig. 4. packet overhead with different hop limitation N

5 Conclusion and future work

The MRCL provided a simple solution for dynamic interconnection of LEO satellites by using both ground station and MEO satellites as the network backbone. Compared with MLSR, the proposed MRCL introduced less overhead because no calculation of grouping or summary links is required. The MRCL also considered the real link quality by using the cross-layer information from MAC/PHY layers instead of the geographic information. The MRCL significantly reduced packet loss when a proper hop limitation was selected. Furthermore, the MRCL employed reactive routing at the LEO layer and proactive routing at the MEO layer, which reduced the overhead caused by fast changing topology at LEO layer and benefited from the stable routes on the MEO layer. Consequently, in a more realistic scenario as shown by the simulation results, the overhead was reduced because no useless routing request is sent out during the discover phase. In the future, we will continue designing satellite routing protocols using CL optimizations. We will focus on satellite architecture without any constellation at all to establish a real ad hoc networking for future satellite applications.

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