LEO 卫星网络中一种简洁的星上分布式路由协议*

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A Light Weight On-Board Distributed Routing Protocol for LEO Satellite Networks

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Abstract: In LEO satellite networks with inter-satellite links, the highly dynamic topology and the limited on-board resources pose special challenges to routing protocol design. In this paper, a light weight on-board distributed routing protocol is proposed to cope with these challenges. For ODRP, the single layer LEO satellite constellation is considered as double-layer constellation. A satellite at special geographical position is selected as the plane speaker according to the dynamic characteristics of inter-satellite links and the distribution of traffic load carried by the network, consequently the idea of distributed hierarchical routing is realized. Experimental results show that ODRP has the adaptive abilities to deal with the dynamic topology of LEO satellite networks and guarantees the path's optimality, and especially can decrease the packet loss probability efficiently in case of high traffic load. Furthermore, results from the implementation complexity analysis demonstrate that the proposed protocol has lower onboard computational, storage and signaling requirements than other on-board routing schemes.

Key words: low earth orbit; satellite network; routing protocol; inter-satellite links (ISL)

摘 要: 在具有星际链路的低地球轨道(LEO)卫星网络中,高度动态的网络拓扑和受限的星上资源为其路由协议设计带来很大的挑战.提出了一种简洁的星上分布式路由协议 ODRP 来应对这种挑战.在 ODRP 协议中,单层 LEO 星座被作为双层星座处理.根据星际链路动态特性和流量分布情况,各轨道面内位于一定位置的卫星节点被选作为轨道面发言人,从而实现简洁的分布式分层路由.实验结果表明,ODRP 能够适应网络拓扑的动态变化,保证路由最

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优.尤其是在高负载情况下,能够有效降低分组丢失率.通过复杂性分析得知,与其他星上路由机制相比,ODRP 具有较低的通信开销、计算开销和存储开销.
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1 Introduction

Compared with traditional GEO (geostationary earth orbit) satellite systems, which are very suited for broadcast services, LEO (low earth orbit) satellites networks with ISLs (inter-satellite links) are the new generation of satellite networks in which Internet-based applications and services will be provided to users regardless of their degree of geographical mobility. LEO satellite networks will be an essential part of the Next Generation Internet and especially military communication networks, beyond their current user for TV broadcast, voice, and limited data communications[1,2].

For multi-hop LEO satellite networks, it is really a difficult issue to find feasible paths between a pair of satellites. The major challenge in the design of packet routing protocols is coping with both a time-varying topology and constraints on key system resources on-board[2,3]. When the special routing protocol is developed for satellite networks, these limitations must be considered.

Connection-oriented routing in LEO satellite networks has been research emphases in last decade. A dynamic routing concept for ATM-based satellite networks has been firstly introduced in Ref.[4]. After this, lots of other routing schemes developed for LEO satellite networks have also focused on connection-oriented scenarios[5−8]. The main problem with connection-oriented routing is that the initial connection may experience link handovers and/or connection handovers due to satellite movements. To maintain the initial path’s optimality, rerouting is necessary and will introduce large overhead. According to the initiative in the commercial and military world to push IP technology to satellite networks and consider the satellite networks as a part of terrestrial IP-based networks, people transferred their research emphases into connectionless-oriented routing in LEO satellite networks[9].

As the connectionless-oriented routing schemes have been devised, either a terrestrial-based or on-board implementation is possible, from the point of the location where the routing calculation is carried out. The idea behind terrestrial-based routing calculation method is to exploit the periodic and predictable nature of the constellation topology to the fullest extent. In this way, routing tables are computed in advance on the ground using proposed routing algorithms and then uploaded to satellites[10−13]. Because the proposed schemes are only using static and predictive information about the satellite constellation, the fault tolerance and adaptive capabilities are very weak compared with on-board way. Further, there is also a dependence on ground computing center, and so the satellite networks are less autonomic. While in on-board way, routing tables can be calculated on-board according to real-time network information. References [14−16] fall into this category. The routing protocol proposed in Ref.[14] employs a hybrid method that uses the geographic-based routing and the shortest path routing with limited scope. The MLSR[15] and SGRP[16] are two new proposals for multi-layered hierarchical satellite networks. Based on the delay reports sent by the lower satellites that are defined as higher satellite’s members, the higher satellite managers compute the minimum-delay paths for their lower satellite members.

The basic shortcoming of those proposals is that they ignored the need for minimizing the scheme’s overhead and only focused on optimization of the calculated paths. However, when designing on-board routing protocols for satellite networks, one of the most important considerations is to minimize protocol overhead. The idea of light weight hierarchical on-board routing in single layer satellite networks was first introduced in Ref.[17]. However, the issue of loop avoidance has not been addressed. When handling of a satellite failure, if the secondary next hop is not chosen appropriately, there will be a risk of creating loops. In this paper, we extend the original work, and a new packet-oriented on-board routing protocol referred to as ODRP (On-board Distributed Routing Protocol) is derived, taking into account ISLs delay variations through a suitable hierarchical link state collecting scheme.

The remainder of the paper is organized as follows. The satellite network architecture used in the paper is provided in Section 2. In Section 3, the new ODRP routing protocol is described in detail. The performance evaluation of ODRP is presented in Section 4. The last section concludes the paper and figures out the future research directions.

2 Satellite Network Architecture

We consider a single layer Iridium-like[18] polar satellite constellation composed of N incline planes close to 90 degrees, each with M satellites uniformly distributed, for the needs of our study. As shown in Fig.1(reproduced from Ref.[4]), each satellite has four neighboring satellites: two in the same plane and two in the left and right planes, expect that the satellites along the counter-rotating seam only have three active ISLs, when the cross-seam ISLs are turned off due to link acquisition and special antenna steering requirement. The duplex links between satellites in the same plane are called intra-plane ISLs, and the duplex links between satellites in different planes are called inter-plane ISLs. The intra-plane ISLs are maintained at all times, and the propagation delay on them is always fixed. However, inter-plane ISLs are highly dependent on the antenna steering capabilities, and deactivated whenever one or both satellites are above a given latitude threshold (typically been set to 70 degrees, named polar region boundary[22]). The length of inter-plane ISLs is variable and so the propagation delay on them is changing all the time in company with the constellation movement. In Iridium-like constellations, all satellites are moving in the same circular direction within the same plane. Except for satellite or link failures, inter-plane ISL dynamics are periodic.

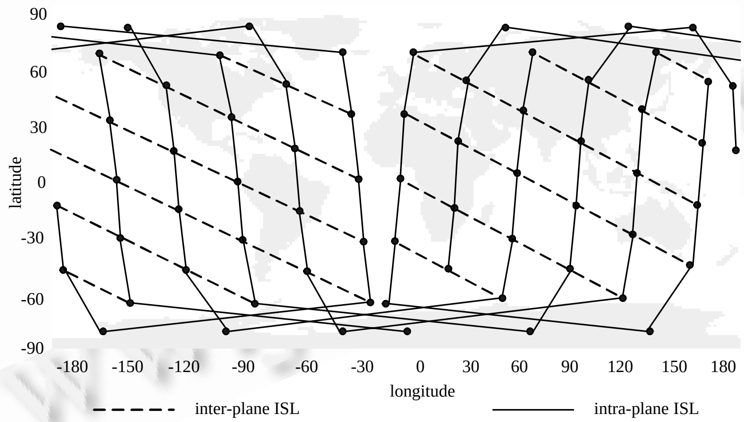

Fig.1 Iridium-Like constellation

The logical location of a satellite can be represented as $\langle P,S\rangle$, where P=0,1,…,N−1 is the plane number, and S=0,1,…,M−1 is the satellite number on plane P. We consider topology dynamics through the concept of dynamic virtual topology[9]. In this way, the network is modeled by a set of time-discrete snapshots of satellite positions within one system cycle T, which can be divided into n time intervals $\Delta t:[t_0=0,t_1],[t_1,t_2],...[t_{n-1},t_n=T]$. Over an time interval, the topology can be modeled as a constant graph G, i.e. link state changes take place only at discrete times t_0,t_1, ..., or t_n. The time interval is small enough to consider the costs of individual ISL as constant over this time interval. By this way, we do not need to be concerned with the satellite movements.

3 Proposed New Routing Protocol

With the idea of hierarchical routing, ODRP gathers the topology information within individual plane firstly, and then exchanges summary information in the whole constellation. The similar idea is also used in SGRP[16], i.e. MEO satellites exchange topology information reported by their lower layer member LEO satellites and calculate the routing tables for those LEO members. While in ODRP, the task of routing table calculation is performed by the so-called plane speaker, which is voted by other satellites in the same plane.

3.1 Definitions

Definition 1. Delay Functions(D): let $ISL_{A\to B}$ be a direct ISL from satellite *A* to *B*, the propagation delay function $D(ISL_{A\to B})$ is defined as follows:

$$D(ISL_{A\to B}) = D(ISL_{B\to A}) = \begin{cases} \frac{L}{C}, \exists ISL_{A\to B} \\ \infty, \text{otherwise} \end{cases} \quad (1)$$

where *L* is the length of ISL and *C* is the speed of light.

Definition 2. Link State Advertisement(LSA): route computations will use the propagation delay of a link as the cost metric. The *LSA* of satellite *A* is defined as follows:

$$LSA(A) = \{< S, D(ISL_{A\to S}) > | S \text{ is the directed neighbor of } A\} \quad (2)$$

Meanwhile, define the plane Summary LSA(*S-LSA*) as the set of all satellite's LSA on the same plane *I* as follows:

$$S - LSA(I) = \{LSA(S) \mid S \text{ is a satellite on plane } I\} \quad (3)$$

Definition 3. Failure-notification Advertisement (F-LSA): to handle satellite failures, define *F-LSA* of satellite *A* as follows:

$$F - LSA(A) = \{\langle S, D(ISL_{A\to S})\rangle \cup \langle F, \infty\rangle \mid S \text{ is the normal neighbor and } F \text{ is the failure neighbor of } A\} \quad (4)$$

Definition 4. Routing Information Base(RIB): the data structure that represents network topology and state. Each entry of RIB is defined as a triplet $\langle A, B, D(ISL_{A\to B})\rangle$, where *A* and *B* are two direct neighboring satellites.

Definition 5. Plane Speaker(PS) and Backup Plane Speaker(BPS): define a PS and a BPS for each plane to perform link state collection and routing table calculation, just like the designated router and backup designated router used in OSPF protocol. The PS and BPS selecting policy will be described in the next section in detail.

Definition 6. Routing table(RT): each entry of the routing table has a destination satellite field, a primary next-hop field, which is the second node on the optimal path, and a secondary next-hop, which is the second node on the suboptimal (or another optimal) path calculated by the PS or the BPS.

3.2 Link state update mechanism

We just characterize the state of a link by the propagation delay on ISL. However, we point out that the protocol can also be extended to use other routing cost metrics to support optimal routing calculation.

3.2.1 PS and BPS selecting

The basic selecting policy of PS and BPS is described as follows, Fig.2 illustrates the basic selecting policy:

$D_{south}(S)$ = spherical distance from satellite *S* to the southern polar region boundary.

S_left = a neighbor satellite on the left adjacent plane.

S_right = a neighbor satellite on the right adjacent plane.

$plane(I)$ = set of all the satellites on plane *I*.

$Life(ISL_A)$ = the time that ISL A will maintain.

$$Set(I)=\{S\,|\,S\in plane(I),\exists ISL_{S\leftrightarrow S\_left}\wedge(Life(\exists ISL_{S\leftrightarrow S\_left})>\eta),\exists ISL_{S\leftrightarrow S\_right}\wedge(Life(\exists ISL_{S\leftrightarrow S\_right})>\eta)\}\qquad(5)$$

$$S=PS(I)\quad \text{if}\quad D_{south}(S)=\arg\min_{A\in Set(I)}\{D_{south}(A)\}\qquad(6)$$

$$S`=BPS(I)\quad \text{if}\quad D_{south}(S)=\arg\min_{A\in\{Set(I)-PS(I)\}}\{D_{south}(A)\}\qquad(7)$$

For plane I, there are two satellites outside the southern polar region boundary, which have two inter-plane ISLs with the neighbors on the left and right plane. The one nearer to the boundary is selected to be Plane Speaker and captioned as PS(I), and the other is selected to be Backup Plane Speaker and captioned as BPS(I). If the distances to the boundary are equal at the selecting moment, then the one with lower sequence number is chosen to be PS. Obviously, within a length of time, PS(I) and BPS(I) are unique, and with time going, they will be replaced by their subsequent satellites. The value of parameter η in Eq.(5) is decided by the chosen calculation interval, which is typically one to three minutes for Iridium-like constellations[2].

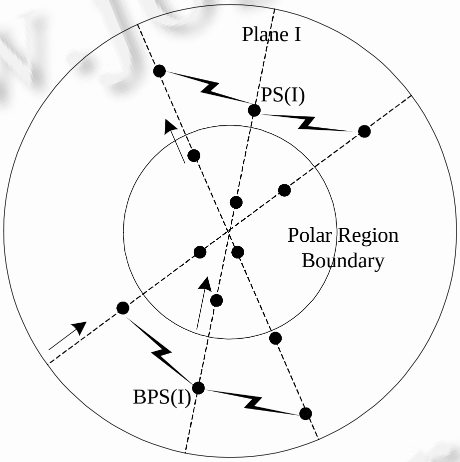

Fig.2 Polar view of satellites flying

There are two reasons to choose the satellites in southern hemisphere and nearest to the polar region boundary as PS and BPS. First, most of the population lives below the 50th latitude on the northern hemisphere, and so we can assume that most of the data traffic is exchanged within northern hemisphere[20]. The satellites above southern hemisphere will have little load compared with these above northern hemisphere, and letting them to compute routing tables for other satellites is reasonable and will allow other satellites to be absorbed in traffic forwarding. Second, wherever the PS is, the communication overhead for link state collecting within a plane is fixed. But, if the PS is at high latitude, the time for link state exchanging among different planes will be decreased, because the length of inter-plane ISL at high latitude is shorter than that of inter-plane ISL at low latitude, so the propagation delay is.

It is important to note that the PS and BPS can also be determined in advance, and there may be other policies, e.g. selecting PS and BPS for one plane according to the real time data traffic distribution.

3.2.2 S-LSA creating

Over one calculating interval, the S-LSA is created in each plane as follows, Fig.3 illustrates the S-LSA creating process for plane i.

Step 1. LSA Building: satellite $S_{i,j}$ measures the delay of its outgoing links on the discrete times t_k, then builds

LSA($S_{i,j}$) and sends it to one of its two directed neighbors in the same plane, i.e. $S_{i,j-1}$ or $S_{i,j+1}$, destined to the plane speaker PS(i). Whether $S_{i,j}$ sends LSA($S_{i,j}$) to $S_{i,j-1}$ or $S_{i,j+1}$ is decided by judging which one is nearer to the plane speaker PS(i) according to the satellite number's sequence in the plane.

Step 2. LSA Transferring: after receiving LSA($S_{i,j}$), $S_{i,j-1}$ or $S_{i,j+1}$ checks to see if it has been received before. If so, it is discarded. Otherwise, $S_{i,j-1}$ or $S_{i,j+1}$ will send LSA($S_{i,j}$) with its own LSA (or without, depending on whether it has been sent out already) to another directed neighbor, not $S_{i,j}$.

Step 3. S-LSA Creating: after a fixed period of time, PS(i) will collect all LSAs of other satellites in plane i. Then, with adding its own LSA, the summary LSA for plane i, S-LSA (i), is formed.

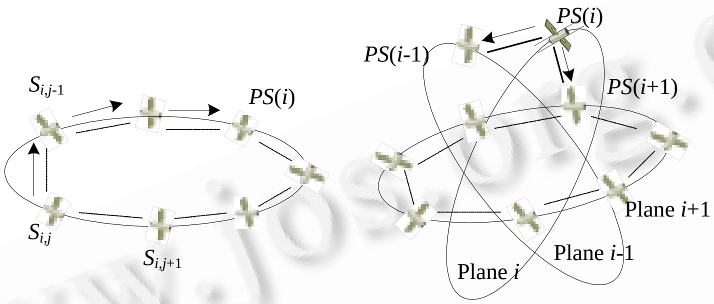

Fig.3 S-LSA creating and RIB building on PS

3.2.3 Building RIB on PS

The summary LSA of each plane is always formed synchronously, unless some deviant things have happened, such as link congestion and node failure. PS(i) will send S-LSA(i) to its neighbor plane's PS, and wait for receiving all other plane's S-LSA to creating RIB of the whole network. The RIB building process on PS(i) is completed in the following steps, as illustrated in Fig.3.

Step 1. S-LSA exchanging: PS(i) sends S-LSA(i) to its two neighbor satellites destined to the plane speaker PS(i−1) and PS(i+1) respectively through its two outgoing inter-plane ISLs. The neighbor satellites may or may not be the plane speakers. All plane's S-LSA are sent in a parallel way, i.e. each PS start to send it's S-LSA from the time t_k. On a satellite $S_{k,j}$ in plane k (k=i−1 or i+1) receiving S-LSA(i), $S_{k,j}$ checks to see if S-LSA(i) has been received before. If so, it is discarded.

Step 2. S-LSA processing: $S_{k,j}$ has the knowledge of which satellite is the PS of plane k (may be itself). If $S_{k,j}$ is not the PS, it will just forward S-LSA(i) to its another adjacent plane's neighbor satellite, which is different from the incoming one, through inter-plane ISL, and transfer S-LSA(i) to its own plane speaker PS(k) through intra-plane ISL. If $S_{k,j}$ is the plane speaker of plane k, it will store S-LSA(i) and forward S-LSA(i) to another adjacent plane's neighbor satellite, which is different from the incoming one through inter-plane ISL .

Step 3. RIB building: After a fixed period of time, each PS will collect all other plane's S-LSAs. Then, it will construct a topology graph for the whole network and the RIB is built.

3.3 Routing table calculation and distribution

After building RIB, the PSs answer for calculating routing table for each satellite in the same plane using the extended Dijkstra's shortest path algorithm and the network state information stored in RIB. Let N^i be the set of neighbors of satellite i and S_j^i be the successor set of satellite i for each destination j. According to the loop-free invariant(LFI) conditions presented in Ref.[21], $S_j^i=\{k\in N^i \mid D_j^k<D_j^i\}$ will be the next hop set of the multiple loop-free paths from i to j. Then, the routing table calculation can be done as follows with satisfying the LFI conditions ($Nh_{i,j}^1$ denotes the primary next-hop on the path from i to j):

```
for each  i ∈ N  do
   Run Dijkstra's shortest path algorithm on G_k ;
   /*get  Nh^1_{i,j}  for i to all the other node j*/
   for each node j ∈ N ∧ j ≠ i do
      for each node h ∈ N^i  do
            if D^h_j < D^i_j  then  S^i_j ← h  endif;
            /* other next hops which satisfy LFI conditions */
      end;
      select the node g with minimum delay from S^i_j ;
      RT^i ← (j, Nh^1_{i,j}, g) ;
   end;
end;
```

The PSs will compute two loop-free paths for all the satellites pairs in the network. One is optimal (primary one) and another is suboptimal (secondary one, may be optimal too) according to total path propagation delay. PS arranges the paths into destination and two next-hops pairs in the same entry. This will make the protocol have the capability to handle congestion and node failure by forwarding the packet to the secondary next-hop. The PSs distribute the result of routing tables to the satellites that are in the same plane with it.

3.4 Congestion and satellite failure handling

The routing decisions made above are only based on the propagation delay information in the modeled constant topology without considering traffic load information at all. As in other proposals[11,13,16], to avoid congestion in the constellation, in ODRP, each satellite is continuously monitoring its output buffers of their adjacent links. If the next hop of a packet is associated with an overloaded output buffer, i.e., if the output buffer has more than ξ packets, it is interpreted as a congestion occurrence. The main idea behind the congestion avoidance phase is to send the packets to their secondary next-hop, if the link to the primary next-hop is congested.

In case of a satellite failure, the paths that go through failing satellite can no longer be used. Above steps must be changed such that the neighboring satellites deflect the packets that pass through the failed satellite instead of dropping them. In ODRP, the rerouting caused by satellite failure can be done in the following several situations:

1) If the failure satellite $S_{i,j}$ is not a plane speaker, its immediate neighbors are the first to sense this occurrence. The neighbors whose routing table entry's next-hop is $S_{i,j}$ will just forward the packets to the secondary next-hop.

2) If the failure satellite $S_{i,j}$ is a plane speaker, the backup plane speaker must be informed and take over the task of PS in next time interval. Further, the neighbors whose routing table entry's next-hop is $S_{i,j}$ will forward the packets to the secondary next-hop too.

3) If there are more than one satellite fails in one plane, e.g. plane I, immediate path recalculation is needed. The policy is to let the plane speaker of right plane, captioned as PS(I+1), replace PS(I) to take over the task of PS(I). All satellites in plane I will send their LSA to PS(I+1) through inter-plane ISLs. The directed neighbors of the failing satellites in plane I+1 set all link delays associated with the failing satellites to infinity and send a F-LSA to PS(I+1). Upon receiving F-LSA, PS(I+1) does two things: update the S-LSA of plane I and send the updated S-LSA(I) to other plane's PSs. In this case, all PSs in the constellation will be triggered to do path recalculation. The resulted new routing tables will be distributed back to all other satellites in plane I through inter-plane ISLs.

4 Performance Evaluation

4.1 Implementation complexity

The implementation complexity is mainly comprised of onboard computational, storage and signaling requirements. We analytically compare these factors with other on-board routing schemes, i.e. fully distributed approach that calculates the shortest paths using Bellman's algorithm, MLSR[15] and SGRP[16].

4.1.1 Time and space complexity

Table 1 presents the time and space complexity comparison of the four routing schemes. For ODRP, the PSs calculate the routing table using the extended Dijkstra's algorithm whose time complexity is $O(n^2)$, where n stands for the number of satellites in the network. Whereas, other non-PS satellites will just use the resulted routing table to forward packets, the time complexity of routing calculation for other satellites is $O(1)$. Therefore, the time complexity of ODRP is only $O(n^2)$ for PSs. In fully distributed approaches, each satellite in the network is responsible for calculating routing table for itself. The time complexity is $O(n^2)$ for every node in the network. In SGRP, the so-called MEO group managers collect the link delay information from their LEO members, and compute the minimum-delay path for them. The time complexity is also $O(n^2)$ for every MEO satellite. The situation is similar for MLSR, expect with introducing some GEO satellites. Although the maximal time complexities are equal for the four schemes, ODRP distributes the computation burden to several plane speakers, thus balances the power consumption among all the LEO satellites, without using more additional MEO/GEO satellites.

Table 1 Time and space complexity comparison of the four routing schemes

Protocol	Computation complexity		Space complexity	
	Normal nodes	Special nodes	Normal nodes	Special nodes
Fully distributed	$O(n^2)$	No	$O(M^2\times N^2)$	No
ODRP	$O(1)$	Plane speakers $O(n^2)$	$O(M\times N)$	Plane speakers $O(M^2\times N^2)$
SGRP	LEO satellites $O(1)$	MEO satellites $O(n^2)$	LEO satellites $O(M\times N\times L)$	MEO satellites $O(M^2\times N^2\times L^2)$
MLSR	LEO satellites $O(1)$	MEO satellites $O(n^2)$ GEO satellites $O(n^2)$	LEO satellites $O(M\times N\times L\times G)$	MEO satellites $O(M^2\times N^2\times L^2\times G^2)$

For ODRP , a size of $O(M\times N)$ is needed for every satellite to store the routing table, where N is the number of planes and M is the number of satellites in a plane. An additional size of $O(M^2\times N^2)$ is needed for plane speakers to store RIB. While in fully distributed approaches, each satellite needs at least a connectivity matrix, which is of size $O(M^2\times N^2)$, and a routing table of size $O(M\times N)$. On the other hand, for SGRP, all the satellites need a routing table of size $O(M\times N\times L)$, where L is the total number of MEO satellites, and furthermore all the MEO satellites need a connectivity matrix, which is of size $O(M^2\times N^2\times L^2)$, to store delay reports. In MLSR, all the satellites need a routing table of size $O(M\times N\times L\times G)$, where G is the number of GEO satellites, and the MEO/GEO satellites need additional space for connectivity matrix of size $O(M^2\times N^2\times L^2\times G^2)$. Therefore, in our new protocol, the non-PS satellites have much less space complexity than the other schemes, and the PS satellites also have less space complexity than MEO/GEO satellites in SGRP and MLSR.

4.1.2 Communication overhead

The total communication overhead can be expressed in terms of transmission units, which is an entry either in the link state advertisement or in a routing table. Figure 4 presents the evolution of the communication overhead within a system cycle for values of the advertisement period equal to 60, 120, 180 and 240 seconds. Definitely, the communication overhead of all four schemes is impacted by the advertisement period.

Among the four schemes, ODRP has the least amount of communication overhead, which is computed according to the geometric aspects of the constellation and the protocol processes. This is mainly because that ODRP uses plane speaker to collect LSAs within a plane and only exchange summary LSA(S-LSA) with other plane's plane speakers. However, in fully distributed(FD) approach, the link state information is broadcasted among all the satellites, and then boosts up its signaling traffic greatly. Although SGRP and MLSR abstracts its LEO groups to nodes and aggregates the links adjacent to the LEO groups into the summary links, the information must be exchanged among all higher layer satellites (the MEO constellation is chosen as ICO network[22] in both schemes, and there are three GEO satellites in MLSR) just like the fully distributed scheme does.

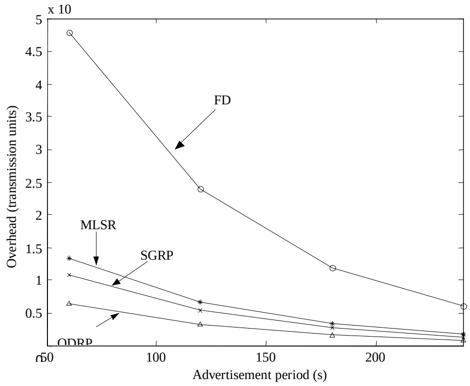

Fig.4 Communication overhead comparison for four schemes

4.2 Path optimality

The path optimality has been evaluated in terms of average packet delay and packet loss probability, important from the end user point of view. Minimum hop method and central routing table calculation method are used to evaluate the end-to-end propagation delay performance of ODRP. SGRP and MLSR are also suitable for comparison but not included because they use a customized network simulator that is not available for the public use.

4.2.1 Simulation environment and parameters

The UCB/LBNL/VINT network simulator (ns2.26) is used as the basic simulation platform. The network model used in the simulation is the Iridium-like polar constellation introduced in Section 2. In all simulations, the link capacity for ISLs and UDLs are chosen as 100 Mb/s. The buffer space of each outgoing of link is set to be 3MB and the average packets length is set to be 1000 bytes. The handoff policy between ground terminal and satellites is chosen to be asynchronous handoff, i.e. the terminal checks whether the serving satellites has dropped below its elevation mask every ten seconds. For inter-plane ISL handover, we set the polar boundary be 70 degrees. The parameters measured are delay and packet loss probability. In all experiments, the duration of simulations is 1500s, and the advertisement period is set to 100s.

The source-destination pair is selected randomly, and the source node is configured to send a packet to the destination node every 2 ms, and one-way delay is measured. To compare the delay and packet loss probability performance under different link loads, we increase the ISL utilization gradually by adjusting the background traffic carried by all ISLs.

4.2.2 Simulation results

Here, we simply give some representative results due to the limited paper length. Figure 5 shows the one-way delay performance for the three routing schemes under different average link loads. It can be seen that the total average delay of minimum hop routing is longer than the other two schemes under all volume of link loads. The reason is that for minimum hop routing the two routes with the same number of hops can have very different one-way delays, so the total average delay may become longer. When average link load is lower than 85%, the delay performance of ODRP and Bellman's shortest algorithm are similar. However, as average link load increases, the delay of the path calculated by Bellman's algorithm becomes longer than that of ODRP. This is because when average link load increases, ISLs with higher traffic density are tending to be congested, and the queuing time becomes longer. For ODRP, as it leads suboptimal paths to avoid possible congestion, although the queuing time is not dominating, these routes also experience tiny increasing delay.

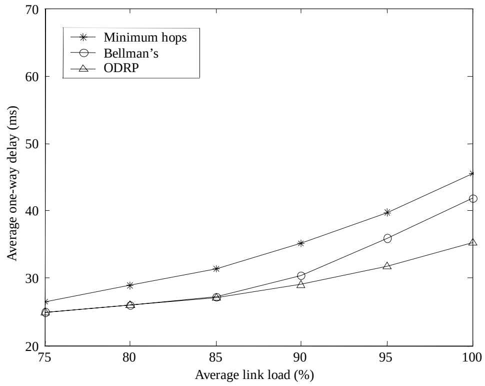

Fig.5 Delay performance comparison

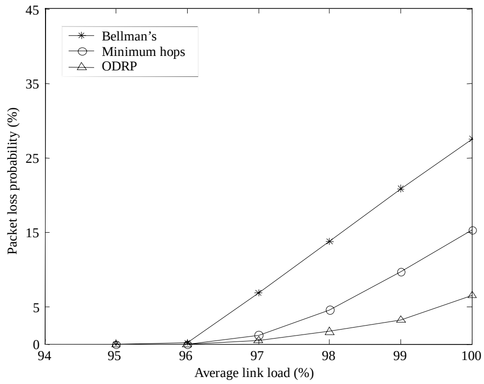

Fig.6 Packet loss probability performance comparison

In Fig.6, the packet loss probability of the three routing schemes is depicted. With this set of experiments, we demonstrate the packet loss probability performance gain obtained by using our new protocol. The packet loss probabilities of the three schemes are much lower when average link load is below 96%. After this, along with the average link load increases, Bellman's algorithm provides much worse loss possibilities due to buffer overflows, and its packet loss probability increases linearly until up to 27.6%. For minimum hops routing, the situation is better, because there may exit more than one paths with the same number of hops. The loss probability of ODRP also starts increasing but slowly as the average link load reaches 97%. The reason is that in ODRP every satellite is continuously monitoring the out buffers of their adjacent links. If the next hop is associated with an overloaded output buffer, the packets will be forwarded to their secondary next-hop, and so will not be dropped.

5 Conclusions

In this paper, we have introduced an on-board distributed routing protocol (ODRP) for LEO satellite networks. The new protocol uses a hierarchical routing approach to provide optimal paths with low implementation complexity and communication overhead. In case of link congestions and satellite failures, the protocol is also capable of routing the packets to the secondary next-hop on the suboptimal or another optimal paths. The protocol has been proved to be efficient by theoretical analysis and experimental results. More analysis and simulations are needed to evaluate the performance of ODRP in the future work, for example, how the traffic distribution impacts the average end-to-end delay and loss probabilities, and how to evaluate the effect of satellite and ISL failures on the performance of ODRP.

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