Routing Strategy for Satellite-Based Networks with a Hierarchical Space Grid Architecture

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Abstract
Routing algorithms and the hierarchical three-dimensional grid architecture of satellite-based networks (SN) are presented. The performance of the proposed architecture and the routing algorithms are analyzed. Simulation of the routing algorithm based on the extended OPNET platform is performed. It is shown in simulation that the proposed three-dimensional satellite-based network architecture outperforms other SN architectures, and the corresponding routing algorithms have superior performances in simplicity, expandability, robustness and high-speed convergence. The full protocols and the related algorithms of routing and switching for the satellite-based networks then can be proposed and verified on an OPNET platform.

1. Introduction
Satellite Network (SN) is a large-scale information service platform in which many types of information can be handled and distributed in time and reliably. Hence, the information provided by SN has the advantage of global coverage and inherent broadcast capability, and offer a solution of broadband access for end-users. At present, enormous amount of information can be obtained from many types of space-based systems, e.g. types of satellites. Routing information among the satellites becomes critical requirement for the overall performance of an SN. However, current solution to the satellite routing is still at infancy due to the high complexity in the space communication and harsh environment constraints.

In an SN, the shortest path can be chosen from the strategy of routing and switching between a source satellite node and the destination node for all kinds of services. The routing system rudimentarily needs to cope with the traffic jam, node failure, and other disrupting events in the satellite nodes. Presently, the routing technology of networks, particularly on the Internet, has significant progress and is widely adopted. The related technology of routing and switching has matured and moved toward higher speed and advanced intelligence. However, the Internet routing/switching technology cannot be directly applied to SN because SN has constantly changing network topology, large time delay due to large distances among satellites, and high communication error rate due to strong interference in the space environment. Therefore, many routing mechanisms have been studied and developed for the single layer LEO/MEO/GEO constellations and also the multi-layers integrated constellations. Compared to Geostationary Satellite Orbit (GEO), Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) have shorter round trip delay and lower transmission power requirements during communication. However, GEO has the advantage of synchronization between the earth and the satellite. Hence, a novel idea has been proposed here for simultaneously using LEO, MEO and GEO to construct a three-dimensional SN architecture. Such SN architecture can ensure that the three constellations compliment each other’s performance for connection-oriented services or connectionless-oriented traffics. A satellite-over-satellite (SOS) network architecture consisting of LEO and MEO is proposed in [1]. The Datagram Routing Algorithm in which the movement of satellite nodes is confirmed by the logical location propagates the packets over the minimum transmission delay path [2]. A link-state packet is flooded within the routing radius for a given satellite in [3]. The main shortcoming for such connectionless routing mechanism is that the metrics used to calculate the paths does not include the end-to-end propagation delay of a packet.

In this article a novel hierarchical architecture of 3D SN and the related routing algorithms with high efficiency are proposed and analyzed. The features of the 3D SN architecture and the routing algorithms are analyzed through computer simulation. From the simulation, the proposed solution shows an improved integrated performance such as the ability of supporting real-time service and the ability of supporting the conventional IP service.

2. Architecture
A reasonable and efficient architecture is the pivotal
technology in satellite-based networks. Presently, the major modes of SN architecture are the single satellite layer and multiple satellite layers. The single SN layer architecture is presently popular in the world, e.g., the “Iridium” system designed with single an LEO layer and the ICE system designed with a single MEO layer. There are some inevitable shortcomings in the single LEO layer solution or other single layer solutions such as frequent routing handover and multiple hops for longer distance communication. The multiple layer design can eliminate the shortcomings to a great extent because the multi-layer arrangement has high utilization of the space spectrum and flexible communication. Therefore, multi-layer design is the direction of satellite-based networks development. Some multi-layer solutions have been proposed [10]. Nevertheless, to get the best performance of an entire SN is still a challenging problem because of the conflict between the system architecture and the routing algorithm. A hierarchical three-dimensional grid architecture of satellite-based networks (Figure 1) is proposed. The characteristics of the proposed SN architecture such as time delay and stability are analyzed and compared with the other existing solutions. The 3D SN has the following structure.

Definition1: The core grid layer is formed by the satellites situated at MEO and GEO constellation, in which the functions of core routing and switching as well as the access are implemented.

Definition2: An intelligent access grid layer is formed by LEO satellites, in which the function of CAC (Connection Access Control) is implemented.

Definition3: An autonomous area indicated by area A or area B in Figure 1 is formed by a center satellite node and its adjacent nodes. A communication link must be available between any adjacent nodes.

3. Routing Strategy

The security and robustness of a network system is ensured when using the uniform routing algorithm for routing an entire path in the satellite-based network except for the drawback of high complexity in routing calculation. On the other hand, the security and robustness of the system will decrease significantly when partial routing algorithms are used within heterogeneous satellite layers in the hierarchical architecture satellite-based networks. Consequently, the basic notion of routing in hierarchical satellite-based networks is to combine simplified routing algorithms within the same satellite layer with lower cost routing algorithms between different satellite layers.

3.1 Simplified Routing within Single Satellite Layer

Routing within the access grid layer: There are several communication links among LEO satellites according to the architecture and the relative stability of communication links. Adjacent LEO satellites within the same orbit and adjacent satellites in different orbits form a neighborhood relation by their communication links. Hence, all satellites in LEO constellation can construct a steady 3D grid based on the adjacent links at any time. In the 3D grid, every satellite acts as one node on the grid. Naturally many autonomous routing areas can be formed among adjacent nodes (Figure 2). Routing within an access grid layer can be simply processed only in every autonomous routing area. In other words, for a concise routing, the routing can only be implemented when the source-destination nodes are located within the same autonomous routing area. There are three adjacent autonomous areas in Figure 2.

Figure 2. Adjacent autonomous areas

Routing within the core layer: The number of satellites in the core layer (10 satellites or so) is usually less than that in the LEO layer. There exist also several steady communication links between the satellites in the core layer. The links also represent the adjacent relation of the satellites in the layer. Hence, a steady space grid can be formed based on the adjacent relation in the core layer and can be treated as an independent routing area. We define this as a core grid layer of routing switches for the satellite-based network. Furthermore, the layer cannot only undertake the function of the routing switch of the core layer but also the CAC of the access layer for the requirement of satellites.
3.2 Optimal Routing between Different Satellite Layers

Routing between intelligent access grid layer and core grid layer: We utilize the rule of the satellite orbits to build a relative position database of satellites among different layers for routing implementation between the intelligent access grid layer and the core grid layer. In the meantime, the priority algorithm of coverage time with weighted elevation angle is chosen because it is necessary to take the coverage time and the satellite elevation into consideration simultaneously for the routing implementation. This implementation is described as follows.

The satellite elevation relative to a calling can vary frequently in mobile communication through LEO satellites. There is a close relation between the elevation and the characteristics of the communication channel. A big attenuation can be produced as the microwave goes through clouds, fog, rain and snow in a round trip transmission across the atmosphere, the attenuation is relative to the elevation of a calling. Moreover, the vertical part of transmitted signals may be obstructed during signal transmission, which has more significant impact as the elevation becomes lower. A target function can be calculated using two weighted variables of the coverage time and the satellite elevation in the solution of a priority algorithm of coverage time with weighted elevation angle. The function can act as the arbitrator of service satellites for multi-satellites access. The target function can be represented by:

\[ P_s = \alpha_s * \frac{T_{s1}}{T_{s2}} - \beta_s * \frac{\theta_{s1}}{\theta_{s2}} \]  

where \( \alpha_s \) is the weighted coefficient of the coverage time, \( \beta_s \) is the weighted coefficient of satellite elevation, \( T_{s1} \) is the coverage time according to satellite current position, \( T_{s2} \) is the maximal coverage time of a satellite in the system. Here, the coverage time is the time that core nodes can cover access nodes. \( \theta_{s1} \) is the satellite elevation (access nodes versus core nodes), and \( \theta_{s2} \) is the minimal design elevation for the system as:

\[ \beta_s = \beta_1 + \beta_2 + \beta_3 \]  

where \( \beta_1, \beta_2, \) and \( \beta_3 \) are the weighted coefficients of satellite elevation corresponding to the attenuation of the atmosphere, rain and obstruction respectively. In view of the situation of different layers, \( \beta_1 = 0 \) and \( \beta_2 = 0 \) because \( \beta_1 \) and \( \beta_2 \) represent the coefficients between the access layer and the MEO layer, and between MEO layer and GEO layer respectively. Hence, \( \beta_s = \beta_3 \).

For actual implementation, we use the following method to obtain the routing result for different layers in order to avoid heavy computation: First, send the position information of core layer nodes to an access node periodically and then based on the information and the priority algorithm of coverage time with weighted elevation angle, the target function \( (P_s) \) of every core layer node related to the access node is calculated in the access node. The maximum value of \( P_s \) is as the routing result of current period for the access node.

Routing between users and intelligent access grid layer: Considering routing between users and the access grid layer, we utilize the rule of satellite orbits first to divide the globe into several areas and then distribute an ID for each area. When a satellite arrives at the area, the area’s ID also acts as the identification of the satellite. Therefore, there may be several satellites able to service a user within the same area when the user requests for service. Then, the access satellite nodes can decide whether to provide service for the user according to the priority algorithm of coverage time with weighted elevation angle and the handshake signaling between the adjacent access nodes. In the solution of the priority algorithm of coverage time with weighted elevation angle, the weighted values of the coverage time and the satellite elevation are different from the case of routing implementation between different layers. The target function can be expressed as

\[ P_c = \alpha_c * \frac{T_{c1}}{T_{c2}} - \beta_c * \frac{\theta_{c1}}{\theta_{c2}} \]  

where \( \alpha_c \) is the weighted coefficient of coverage time, \( \beta_c \) is the weighted coefficient of satellite elevation, \( T_{c1} \) is the coverage time according with satellite current position, \( T_{c2} \) is the maximum coverage time of a satellite in the system. Here, the coverage time is the time that access nodes can cover users. \( \theta_{c1} \) is the satellite elevation (users versus access nodes), and \( \theta_{c2} \) is the minimal design elevation for the system as:

\[ \beta_c = \beta_1 + \beta_2 + \beta_3 \]  

where \( \beta_1, \beta_2, \) and \( \beta_3 \) are the weighted coefficients of satellite elevation corresponding to the attenuation of atmosphere, rain and obstruction respectively.

4. Innovation for Carrying Services

How various types of services are carried in the hierarchical satellite-based network is an important methodology related to the performance of entire satellite-based networks. A novel integrated balancing mode taking the type and the traffic of services into consideration is presented so that all services including real-time services and non real-time services can be provided in the satellite-based networks. If the communication between a source node and a destination node can be implemented through one-hop routing, i.e., the source-destination nodes are in the same autonomous
routing area, and the resources of the required link (bandwidth etc.) also are sufficient, the routing should be performed using the simplest one-hop mode in one autonomous area. Otherwise, the data transmission service needs to be implemented over the core routing layer once the previous two conditions are not satisfied. The non-real time services can still be transmitted over the core switching layer so that the necessary resources can be reserved for ensuring reliable transmission for real time services. Accordingly, higher performance can be obtained from the networks. For example, the real-time services without strict bandwidth requirement such as the important short messages and voice etc. can be only transmitted over an autonomous area. On the contrary, services with wide bandwidth requirement or with long distance communication beyond one autonomous area all should be transmitted over the core grid layer. On the other hand, using this simple and flexible method, it is also of great benefits to enhance the stability and robustness of the system.

5. Benefits for Resources Utilization

The routing strategy for the hierarchical satellite-based networks meets some significant characteristics with lower consumption of signaling and storage in satellite nodes because there is no need to get the topology and status of autonomous area in core layer nodes. There is also no need to exchange the information of link-state within access layer nodes and between access layer nodes and core layer nodes. The power consumption of signals can be decreased significantly due to the smaller bandwidth consumption for exchanging link-state information between the core layer nodes in which the number is usually less than 20. Furthermore, each access layer node only stores its own information of the link-state and the routing information in which the resource node is also itself and the destination nodes are other nodes within autonomous areas. Hence, the size of the routing table and the storage is quite small. Finally, in the routing strategy, the routing computation is simple and fast since there is no routing calculation in access layer nodes and very few computation in core layer nodes.

6. Simulation

The OPNET integrated with a Radio Modeler is selected to be simulation platform of satellite-based networks. STK (satellite tool kits) is selected to be another tool for the data definition of satellite orbit that can be imported into the OPNET. A single layer model and a hierarchical model are respectively built up on the OPNET according to the constellation of the “Iridium” system and the “Teledesic” system. The single layer model represents a single grid layer network and the hierarchical model represents the proposed hierarchical space grid architecture of satellite-based networks. The performance comparison of different architectures as well as the related routing strategies then can be achieved for the satellite-based networks. The model of the hierarchical architecture is given in Figure 3, which is constructed by eight core satellite nodes and 20 access satellite nodes. The model of the single layer architecture is given in Figure 4, which is constructed by 20 LEO satellite nodes. The types of carried services in the single layer architecture and the hierarchical architecture are identical. Their performance features of evaluation are also the same. The definition of services is described as:

1. Database Access (Heavy)
2. Database Access (Light)
3. Email (Heavy)
4. Email (Light)
5. File Transfer (Heavy)
6. File Transfer (Light)
7. File Print (Heavy)
8. File Print (Light)
9. Telnet Session (Heavy)
10. Telnet Session (Light)
11. Video Conference (Heavy)
12. Video Conference (Light)
13. Voice over IP Call (PCM Quality)
14. Voice over IP Call (GSM Quality)
15. Web Browsing (Heavy HTTP 1.1)
16. Web Browsing (Light HTTP 1.1)

In Figure 5, the simulation result shows that the average features of the response time for the transmission of “ftp download” in the hierarchical model is a little better than that of in the single model, because the capability of control and transmission for the service with lower data throughput in the single model is very close to that in the hierarchical model. Hence, there is not obvious difference between the two models for the service.
In Figure 6, the simulation result shows that the average features of the end-to-end delay for the transmission of voice packet that belongs to the real-time service in the hierarchical model is better than that in the single model because higher bandwidth can be provided so as to ensure the robust capability of control and transmission for the real-time service with lower delay and time jitter in the hierarchical model.

In conclusion, the integrated performance of the hierarchical model is better than that of the single model when the proposed routing strategy is utilized in the hierarchical model, not only for the conventional traffic but also the real-time traffic. The results show the tight relation between the architecture of satellite-based networks and the related routing strategies.

![Figure 5. Average response time of FTP download (sec)](image)

![Figure 6. Average end-to-end delay of voice packets (sec)](image)

7. Conclusion

Hierarchical three-dimensional grid architecture of satellite-based networks and the related routing mechanism are presented in this paper. The multiple satellite layers can form a 3D space grid with stability and the dynamic changes. The proposed mechanism can adapt to the requirement for improving the performance of satellite-based networks such as supporting traditional IP traffic as well as real-time services effectively. In addition, the class-based service corresponding to the hierarchical 3D grid and the routing mechanism between the identical layer and different layers can reduce the complexity of the routing strategy and the storage requirement of routing nodes. In the mean time, it also promotes the flexibility and robustness of the entire network. The proposed architecture and the routing algorithms are analyzed using computer simulation on the extended OPNET platform and STK. The results show that the proposed architecture and the routing algorithms have improved performance than the current implementations. Further analysis and experiments associated with the architecture and the related algorithms will be conducted. Detailed protocols and algorithms will be analyzed, verified and confirmed on the extended version of OPNET platform for the satellite-based networks.

References