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Routing and Re-Routing in a LEO/MEO Two-tier Mobile Satellite Communications System with Inter-Satellite Links

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Abstract: A novel LEO/MEO two-tier satellite communication system with inter-satellite links (ISLs) is proposed for providing multimedia services to global mobile users. This two-tier system architecture can reduce the transmission delay for long-distance users via MEO satellites while keeping the benefits of using LEO satellites as the service access nodes. The routing and re-routing during a handoff operation is simplified. Since the physical topology of the underlying network is time-dependent, routing is crucial for guaranteeing the delay and delay variation performance for interactive applications. In this paper, we decompose the routing problem into two parts, routing in the access network and routing in the core MEO ISL network. For access network, a new routing algorithm called Maximum Holding Access Protocol (MHAP) is proposed for minimizing the number of LEO handoffs. For core MEO ISL network, both Minimum Transmission Delay Routing (MTDR) and Minimum Transmission Time Jitter Routing (MTTJR) are investigated. Using computer simulations, we show that the proposed routing algorithms can reduce the probability of call re-routing and thus are very suitable for providing interactive multimedia services.

1. Introduction

The next generation mobile satellite communications systems will provide flexible and high-quality multimedia services to users at anywhere and anytime. These satellites will have powerful onboard processing and switching capabilities. Sub-communication networks with inter-satellite links (ISLs) in the space segment can also be established. The traditional Geostationary Earth Orbit (GEO) satellites are not suitable for this purpose because of the long transmission delay and high propagation loss. Instead, the Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites will be adopted in the next generation satellite systems. Teledesic, Sativod, Celestri, Sky-bridge and M-star systems [1] are some proposed examples.

Compared with the GEO satellites, the altitude of the LEO satellites is much lower. Thus the propagation loss and transmission delay are greatly reduced [8,9]. This makes the hardware implementations of both mobile terminals and satellites relatively easier. On the other hand, a LEO satellite system needs a larger number of satellites to provide global coverage. Establishing sub-networks in the space segment using ISLs (inter-satellite links) is a very complicated issue. Owing to the time varying physical topology of the ISL networks, routing in the space segment network is very difficult to manage [7]. Compared with the LEO system, the MEO system needs fewer satellites in the constellation to provide global coverage, and the ISL network is much simpler. As a result, it is easier to conduct routing and handoff in MEO systems. If a sender is far away from the receiver (e.g., one user is at Beijing, while the other is at New York), the total transmission delay using MEO systems will be less than using LEO systems.

In [2,3], schemes based on the LEO/GEO two-tier satellite architecture have been proposed as a candidate for next generation satellite communications systems to provide multimedia services. But the problem of long transmission delay caused by GEO satellites have not been solved. In this paper, we propose a novel LEO/MEO two-tier architecture for supporting multimedia communications. It consists of 16 MEO satellites in the upper tier and 63 LEO satellites in the lower tier. As we are going to show in the rest of the paper, the proposed architecture has the following major advantages:

(a) simplicity in managing the space networks formed by time-varying ISLs,
(b) reduction in call re-routing probability for end-to-end connections, and
(c) reduction in transmission delay for users using MEO satellites.

For the proposed two-tier architecture, routing is crucial for guaranteeing the quality of service (QoS) requirement on delay and delay variation for interactive applications because the underlying network topology is time-dependent. Therefore we focus on designing efficient routing algorithms in this paper.

In the next section, we present the two-tier LEO/MEO satellite system in details. In Section III, we divide the routing problem into two parts, at the access network and at the core MEO ISL network. A routing protocol called Maximum Holding Access Protocol (MHAP) is designed for minimizing the number of handoffs in the access network. For the core MEO ISL network, two routing schemes based on Dijkstra algorithm are investigated. One is the Minimum Transmission Delay Routing (MTDR) and the other is Minimum Transmission Time Jitter Routing (MTTJR). In Section IV, simulations are conducted for evaluating the proposed routing schemes. We found that the proposed routing schemes can significantly reduce the call re-routing probability. This in turn cuts down the associated signaling traffic. Finally we conclude the paper in Section V.

II. Two-tier Satellite Network Architecture

The proposed two-tier LEO/MEO satellite system consists of 63 LEO satellites in the lower tier and 16 MEO satellites in the upper tier as shown in Fig. 1. The LEO satellites provide the global coverage to the mobile users and the MEO satellites provide the switching/routing capability for inter-satellite communications (LEO-to-MEO and MEO-to-MEO). To facilitate the establishment of the inter-satellite links (ISLs), Walker constellation [4] is used in this architecture. Using Walker constellation, the topological relationship among satellites in the same tier can be maintained. Thus the ISLs between any two MEO satellites can be set up easily.
In our design, the Walker factors of the ME0 and LEO constellations are connected to four adjacent ME0 satellites, two in the same orbital plane. Consider Fig. 1.

There is no direct ISL links between any two LEO satellites. Using this architecture, a ME0 satellite acts as a switching node in the vertex-symmetric network. Each LEO satellite in the lower tier has wireless links. ME0 satellites must be involved in the end-to-end connection for routing purposes. If two mobile users covering a ME0 satellite need to communicate, a handoff operation can reduce the end-to-end transmission delay. Finally, the proposed MHAP routing strategy in the next sub-section, the ISL network topology, which results in a fixed mesh network topology for all ME0 satellites in the core ME0 ISL network. Thus multiple paths/route between any two ME0 satellites exist and therefore routing becomes necessary.

**Inter-satellite links (ISLs) between any two ME0 satellites.** These links are shared by the Walker constellation is used. Each ME0 satellite is always connected to the same four other adjacent ME0 satellites using these links. This forms a fixed mesh network topology for all ME0 satellites in the core ME0 ISL network. Thus multiple paths/routes between any two ME0 satellites exist and therefore routing becomes necessary.

**Links between ME0 satellites and ground gateway stations, denoted by GWLs.** These links are shared by those connections with one communication end on the terrestrial network. A ground gateway station is used to relay the traffic between the terrestrial network and the space segment network.

With this two-tier constellation, many advantages can be obtained. First, the switch management in the ISL networks is simplified. As we are going to show in Section IV, the call re-routing probability is also reduced. Second, the ME0 satellite management is simplified as there is no direct ISL between any two LEO satellites. All network routing functions involve ME0 satellites. Third, for long-distance users, routing through ME0 satellites can reduce the end-to-end transmission delay. Finally, the proposed LE0/ME0 two-tier system has less stringent requirements on the automatic track & point (ATP) antenna on LEO satellites for deploying ISLs. This is because the relative moving speed between a LEO and a ME0 satellite is much lower than that between two LEO satellites.

### III. Routing & Re-Routing

Since both LEO and ME0 satellites are constantly moving in their own orbits, the distance between two satellites as well as the underlying physical network topology are time-dependent. Like a conventional cellular system, when a handoff occurs, a re-routing of an on-going call is necessary for maintaining a continuous connection. For the proposed two-tier system, two types of handoff exist.

- **LE0 handoff.** A LE0 handoff happens when the footprint of a LE0 satellite can no longer cover a mobile user with an ongoing call. Then the mobile sets up a new UL to a LE0 satellite whose footprint covers it and the old UL is removed. This is a handoff from one LE0 to another LE0 satellite, so we call it LE0 handoff. When a LE0 handoff occurs, the newly selected connected LE0 satellite needs to decide which of its two ISLs to use. The ISLs should be used to carry the on-going call. According to the MHAP routing strategy in the next sub-section, the ISL connected to the LE0 satellite that provides a longer service time for the associated LE0 satellite will be selected.

1. To distinguish the coverage time of a LE0 satellite on a mobile user, we use the term service time for a LE0 satellite that is under the coverage of a ME0 satellite, where an ISL is connected.
A. Providing Routing

(1) **Providing Routing & Re-Routing at Access Network**

If a mobile user with an on-going call can always connect to the LEO satellite that provides the maximum coverage time for it, the call can be completed with the minimum number of LEO handoffs. It is clear that the LEO satellite that is the closest to the mobile user does not provide the maximum coverage time for it. In the following, a new routing protocol for minimizing the LEO handoffs at the access network, called Maximum Holding Access Protocol (MHAP), is proposed.

In the proposed two-tier architecture, it can be found that with a minimum allowable elevation angle of 10 degrees, the probability of at least two satellites simultaneously falling into a mobile user's sight is more than 90%. According to the satellite calendar, the mobile can therefore always find the satellite that provides the maximum coverage time to it. If the destination user is located in another LEO footprint or in the terrestrial system, the LEO satellite will select one of the two connecting MEO satellites that provides a longer service time to it to support this call. The service time of a MEO satellite, which ranges from 30 to 50 minutes, is much longer than the LEO satellite coverage time for a mobile, which is only about 10 minutes. It can be found that when a MEO handoff occurs, the traffic load on the affected ISL link is zero. This is because before a MEO handoff happens, all active calls on the affected ISL have already been handed off to other LEO satellites during earlier LEO handoffs. This in turn is due to the facts that (a) the LEO handoff occurs at a much higher rate than MEO handoff, and (b) during each LEO handoff, the newly selected LEO always choose the MEO satellite that provides a longer service time to it to carry the call.

Owing to the Walker constellation adopted, when a LEO handoff occurs, the new LEO satellite will select the MEO satellite that is used by the pervious LEO satellite with a very high probability (more than 85% from our simulation results). Consequently, the reconstruction of the ISLs caused by LEO handoff mainly occurs between LEO and MEO satellites. The routing in the MEO core network will remain unchanged with a very high probability during call re-routing. This is very important for reducing the data transmission delay variation because the ISLs between MEO satellites account for the major portion of the end-to-end delay.

The procedures of Maximum Holding Access Protocol (MHAP) routing algorithm can then be summarized below:

1. When a call is initiated, the mobile selects a LEO satellite that can provide the maximum coverage time to it among all LEO satellites in sight using the satellite calendar.

2. If some MEO satellites are involved for a long distance call, the LEO satellite selected in Step (1) chooses (from the two connected MEO satellites) the MEO satellite that provides a longer service time to carry the call.

3. When a LEO handoff occurs, repeat Steps (1) and (2).

B. Providing Routing and Re-Routing at Core MEO ISL Network

The Maximum Holding Access Protocol solves the routing problem in the access network. In this section, we focus on the routing in the core MEO ISL network. For a two-tier satellite system, the transmission delay is dominated by the propagation delay between MEO satellites in the core network. An efficient core network routing can minimize the end-to-end delay as well as the delay variations. Two routing schemes based on Dijkstra algorithm are investigated. One is the Minimum Transmission Delay Routing (MTDR); the other is Minimum Transmission Time Jitter Routing (MTTJR). MTDR is simply the minimum distance routing, whereas MTTJR focuses on minimizing the transmission delay variation. In general, the end-to-end transmission delay obtained using MTTJR is bigger than that of MTDR, but MTTJR is particularly suitable for interactive multimedia services because of its small delay variation.

A routing protocol is activated for finding a path in the core network whenever a new call is established, or an on-going call is re-routed (in case of a LEO handoff). When a new call arrives, the MHAP protocol is responsible for routing in the two access network segments. In the core MEO ISL network, a minimum-distance path is found for carrying the call. When a LEO handoff occurs, if the newly selected LEO satellite connects to the same MEO satellite as the previous LEO, the path in the core network is kept. In this case, only the access network segment is re-routed by MHAP. If the newly selected LEO satellite does not connect to the same MEO satellite as
the previous LEO, the path in the core network needs to be re-routed. Using MTTJR, the path that has the minimum delay variation as compared to the original path during call set up will be selected. If MTDR is used, again the path with the minimum distance (at that moment) will be selected.

The movement of MEO and LEO satellites increases the routing complexity in the two-tier satellite architecture. However, this constellation movement is regular and periodic. We can divide the constellation period, which is the lowest common multiple of the MEO and LEO satellites rotational periods, into finite independent time slots of varying slot lengths. The network topology does not change during each slot. Then a routing table can be set up for each satellite during each slot. The routing tables can be pre-calculated by the ground station and downloaded to (or stored at) each satellite. This avoids the on-board satellite processing. According to the constellation movement, each satellite updates its routing table in each time slot.

In the studies of [5, 6], fixed length slot design is adopted. In order to guarantee the routing performance, the slot length is relatively small (10 seconds). Compared with the fixed slot design, the variable slot length design we proposed in this paper has the following advantages:

- Significant reduction in the number of routing tables because the number of slots is significantly reduced.
- The routing table is updated simultaneously with the topology re-construction of the ISL network.
- The peak traffic and ISL interference from background noises can be easily handled.

Although the routing table at each satellite is updated on a slot basis, as far as a particular end-to-end user connection is concerned, the re-routing is only performed when a LEO handoff occurs. To summarize, the procedures for end-to-end routing from mobile users A to B in a two-tier satellite system shown in Fig. 2 are:

(1) For each end user, select one LEO satellite and one MEO satellite as the access network for carrying the call using MHAP protocol.

(2) Find an optimal path through the MEO ISL core network using either MTDR or MTTJR.

(3) If user A or user B requests a LEO handoff, select a new LEO satellite for it using MHAP. If the newly selected LEO satellite uses the same MEO satellite as the previous LEO, the path in the MEO ISL core network remains unchanged; otherwise, find a new path in the core network using either MTDR or MTTJR.

IV. Simulation Results

In this section, the performance of the routing protocols proposed in Section III is studied using computer simulations. In particular, a connection between two distant users is simulated, where one user is at Beijing, China and the other one is at New York, USA. Multiple hops in the core MEO ISL network is needed for this connection. In the simulation, the constellation operation is a continuous procedure, and the user access is random. A hybrid simulation method is used. The simulation length is two constellation periods. The multi-beam antenna and "cell-fixed" method are used in the simulation. Based on the study in [10], we know that the beam handoff is equal to satellite handoff in a cell-fixed system. Therefore, we focus only on the LEO satellite handoff.

The probability distribution function of the average transmission delay for the two users is shown in Fig. 3. The average transmission delay for using MTDR ranges from 120 to 320 ms. The average transmission delay for MTTJR ranges from 200 to 360 ms. The probabilities that average transmission delays are less than 300 and 320 ms are 0.91 and 0.999 respectively using MTDR. Using MTTJR, the corresponding probabilities are 0.93 and 0.999. We can see from Fig. 3 that the average transmission delay of MTDR is smaller than MTTJR.

Next we consider the delay variation performance in Fig. 4. The transmission delay variation is caused by two factors: (a) the time-varying distance between satellites, and (b) traffic following different paths caused by re-routing during a call. We call the former path variation (PV) and the latter re-routing variation (RV). The probability density functions (PDF) for these two variations are shown in Fig. 4 for both MTDR and MTTJR. The call holding time is exponentially distributed with mean 3 minutes. From Fig. 4, we can find that using MTDR, the probabilities of path variation less than 100 and 10 ms are 0.99 and 0.97 respectively, and the probabilities of re-routing variation less than 100 and 10 ms are 0.96 and 0.95 respectively. Using MTTJR protocol, the probabilities of the path variation less than 100 and 10 ms are 0.999 and 0.98, and the probabilities of the re-routing variation less than 100 and 10 ms are 0.99 and 0.97. We can see that the re-routing variation and thus the total transmission delay variation of MTTJR is less than that of MTDR. For supporting interactive multimedia services, a small transmission delay variation is essential.

Fig. 5 shows the performance of the total transmission delay variation (path variation plus re-routing variation) experienced by a random user with fixed call holding time of 2 minutes, 4 minutes and
30 minutes, respectively. In our simulations, we assumed that a fixed size window slides through an orbital period. The size of the window is equal to the fixed call holding time. The transmission delay variations are then found from the collected transmission delays in each window. From Fig. 5 we can see that if the MTDR is used, the probabilities that the transmission variation is less than 90 ms are 0.999, 0.975 and 0.581 for window sizes (or call holding times) of 2, 4 and 30 minutes. For MTTJR, the probabilities that the transmission variation is less than 40 ms for the three call holding times are 0.99, 0.98 and 0.68 respectively. From these results, we can see that (a) the longer the call duration, the higher the delay variation, and (b) using MTTJR, a mobile user experiences less transmission variation.

Fig. 6 shows the call re-routing probabilities. The call re-routing probability is defined as the probability that the call experiences at least one re-routing during its call holding time. As expected, we can see that the re-routing probability increases with the mean call holding time (exponentially distributed). Besides, the re-routing probability using MTDR is a little bit less than that of MTTJR. A small re-routing probability implies less signaling traffic for re-routing calls. Compared with that in [7], the re-routing probabilities of using MTDR and MTTJR are smaller. This is because all re-routings in our proposed two-tier satellite system are caused by the LEO handoffs only.

V. Conclusion

Combining the advantages of LEO and MEO satellites, a novel LEO/MEO two-tier mobile satellite communications architecture with inter-satellite links was proposed in this paper. The routing and re-routing problem in the proposed two-tier satellite system has been studied. For routing in the access network, a new protocol called maximum holding access protocol was proposed. For routing in the MEO core network, two algorithms MDTDR and MTTJR have been investigated. The simulation results showed that the proposed routing/re-routing schemes can reduce the probability of call re-routing and is therefore suitable for providing multimedia services for global mobile users.

References: