An Effective QoS Integrated Weighted Cost Model for LEO/MEO Satellite IP Networks

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Abstract—With proportion of multimedia services in the IP satellite network growing, how to provide these services with effective guarantee of QoS metrics such as delay, bandwidth, delay and jitter is an urgent problem. In multi-satellite network MLSR algorithm, a typical dynamic routing algorithm, only considers a single delay parameter, is prone to congestion and difficult to meet the QoS requirements when certain link is heavily loaded. Heuristic algorithm may optimize various QoS metrics, but is difficult to meet the requirements of satellite networks in terms of the complexity of the algorithm and convergence time. LEO/MEO network have asymmetry on the requirements of the services in terms of delay, bandwidth, time and location. Aiming at the needs of multiple QoS metrics guarantee of QoS routing needs, based on the asymmetry of LEO/MEO in delay and bandwidth, and time and location, this paper design a QoS integrated weighted cost model, which tradeoffs QoS cost information of delay and bandwidth in terms of time and location, and has better adaptability for QoS guarantees of multimedia services.

Index Terms—QoS; LEO/MEO; Asymmetry; Integrated Weighted Model

I. INTRODUCTION

IP satellite network is the extension of the terrestrial Internet, and increases the coverage of terrestrial network services. The development of IP satellite network is incomparable to terrestrial networks. At present, users’ demand for high-speed multimedia services is growing and the proportion of traditional voice and low-speed data services in the future satellite communications system will gradually reduce, but Internet services and broadband multimedia services will become the main service. To meet the needs of the development, the satellite network need effective QoS guarantee. QoS may find its expressions in many aspects, such as end-to-end delay, bandwidth, throughput and packet loss rate. Because satellite network have many characteristics, routing strategy widely used in terrestrial Internet cannot be directly applied to the satellite network. Routing based on the important relationship between effective routing strategies and support for QoS, a lot of researches focus on supporting QoS routing strategy. For example, Jianjun [1] proposed an explicit compact multi-path routing algorithm, involving transmission and queuing delays based on the indicators of cost measure. The routing algorithm Tasi [2] proposed which based on the cost-effectiveness of dynamic topology networks optimized the utilization of the link. LEO satellite network routing strategy Sun [3] proposed optimized throughput from the maximization. In IP traffic load distribution algorithm in NGEO broadband satellite network Taleb [4] put forward, network traffic got better utilization and balance based on traffic load information. Cetin [5] combined and optimized end-to-end delay and the throughput of LEO satellite network, but how to add more QoS requirements was not mentioned in his article. In multi-satellite network MLSR algorithm, a typical dynamic routing algorithm [6], only considers a single delay parameter, is prone to congestion and difficult to meet the QoS requirements when certain link is heavily loaded. Heuristic algorithm may optimize various QoS metrics, but is difficult to meet the requirements of satellite networks in terms of the complexity of the algorithm and convergence time [7-9]. For example, Fei [7] employed heuristic algorithm, which may balance all QoS requirements and obtain good performance in a calculation, but the convergence time and complexity of the algorithm was not investigated, and the usability of the algorithm should be taken into consideration.

The inherent flaws of single satellite network are hard to meet these above-mentioned design requirements. In the multilayer networks, the characteristics of LEO/MEO double-layer network have unique advantages in support of broadband. Based on double-layer LEO/MEO network structure, this paper firstly not only analyzed the asymmetry of LEO and MEO in delay and bandwidth, but also analyzed the asymmetry of the requirement of the services in time and location. Next on the basis of the asymmetric feature the paper made use of the integrated weighted idea to establish QoS integrated weighted cost model when designing link weights, and carried out the design of link cost and the design of weighting coefficient.
Finally, model's performance was analyzed through the simulation.

II. CHARACTERISTICS ANALYSIS OF LEO/MEO NETWORK

A. LEO/MEO Network Structure

Kimura’s DLSC model is a representative of double networks. This model requires establishing redundant connections among satellites of every layer concerning network stability. However, DLSC model depends heavily on redundant connections to enhance network stability, and meanwhile makes the complexity of satellite network system excessively high. This section puts forward "backbone / access" model, which simplifies the structure of multi-satellite network through backbone layer and access layer. The structure of LEO/MEO double-layer satellite network is shown in Figure 1.

“Backbone / access network” model is defined as follows:

Satellite number of MEO layer is \( N_M \times M_M \). \( N_M \) stands for satellite number within every orbital plane of MEO layer, while \( M_M \) stands for the number of orbital planes. \( D_{x,y} \) represents MEO satellite, in which \( x = 1, \ldots, M_M \), \( y = 1, \ldots, N_M \).

Satellite number of MEO layer is \( N_L \times M_L \). \( N_L \) stands for satellite number within every orbital plane of LEO layer, while \( M_L \) stands for the number of orbital planes. \( L_{x,y,z} \) represents LEO satellites, in which \( x = 1, \ldots, M_L \), \( y = 1, \ldots, N_L \), and \( N_L \times M_L > N_M \times M_M \).

“Backbone / access network” model is described as follows:

1. Backbone network. As the backbone routing domain, satellites in MEO layer fulfill transmission, switching and management. Satellites in MEO layer process QoS information, complete the calculation of routing table, and transmit to LEO layer.

2. Access network. As satellites in access layer, satellites in LEO layer have advantages in short-distance communication, and local services usually have a large proportion in networks, because transmission delay of satellites in LEO layer is small. Therefore, satellites in LEO layer as an access layer of the network is quite reasonable. Satellites in LEO layer collect QoS-related information and transmit to MEO layer.

3. Satellites in MEO layer do not directly offer access services for terrestrial mobile terminal.

B. Analysis of Asymmetry of LEO/MEO Network

In the structure of the above double-layer satellite network, MEO constellation is backbone network, and LEO constellation is access network. In the face of QoS guarantee they have different characteristics, which are manifested as follows:

1. Inter-satellite link between satellites in LEO layer is the shortest. For example, one-way propagation delay of the Iridium system is about 15ms. Bandwidth in MEO layer is larger than that in than LEO layer. Therefore, the propagation delay has minimal impact on the link of LEO layer, but the bandwidth has great impact on the link of LEO layer. The bandwidth has small impact on the link of MEO layer link, but the propagation delay has great impact on the link of MEO layer link.

2. Transmission delay of double jump of satellites in MEO layer is greater than that of satellites in LEO layer, but delay performance indicators of MEO constellation, especially delay jitter performance indicators are often stronger than those of the LEO constellation when take into account MEO’s onboard processing time and inter-satellite links, satellite-ground link length etc.

3. The uneven distribution of the user in traffic, time and location. When satellites run along the orbit, the bandwidth of inter-satellite links and the number of satellites are constantly changing. Some calls are being blocked due to satellite link or insufficient channel resources. Particularly when switching, the connections are possibly blocked due to satellite link or insufficient channel resources.

All these factors determine that LEO / MEO network have asymmetry on the requirements of the services in terms of delay, bandwidth, time and location. Based on the asymmetric feature at different times and on different links, integrated weighted idea is employed to establish QoS integrated weighted cost model when designing link weights. Firstly, the definition is given as follows:

**Definition 1** cost weights of link QoS:

Satellite link \( ISL(S_i \rightarrow S_j) \) between \( S_i \) and \( S_j \) at the start of a time slot \( T_r \). \( W(x, y) \) is QoS cost weights of link \( ISL(S_i \rightarrow S_j) \) at the start of a time slot \( T_r \).

\[
    C(P) = \sum_{i=1}^{hop-2} W(ISL_{s_i}, ISL_{s_{i+1}}) 
\]

In which:

- \( S_i \) : path source node;
- \( S_j \) : destination node;
- \( hop \) : the number of that the path passes.

**Definition 2** link cost: link cost function \( C(P) \) is

\[
    LLSR(x, y) = \{Delay(x, y), BW(x, y)\} 
\]
In it, x represents the number of MEO manager, and y represents the y member of LEO in MEO group. \( Delay(x, y) \) means that the link delay, and \( Bw(x, y) \) means that available bandwidth.

**Definition 4** link-state report \( MLSR(x, y) \).

MEO link delay and the available bandwidth information need to be transmitted to the adjacent MEO satellites.

\[
MLSR(x, y) = \{Delay(x, y), Bw(x, y)\}
\]

In it, x indicates the number of MEO that receives link-state report, and y indicates the number of MEO that sends link-state report sent number. \( Delay(x, y) \) stands for the link delay, and \( Bw(x, y) \) means available bandwidth.

**Definition 5** link-cost report aggregation \( LSR(M_x) \).

\[
LSR(M_x) = LLSR(x, y) \cup MLSR(x, y)
\]

In it, x represents the number of MEO managers.

### III. INTEGRATED WEIGHTED COST MODEL

For the realization of the integrated weighted idea QoS integrated weighting cost coefficient \( \omega_{ij} \) is introduced to describe and represent various asymmetric features of different links. \( W(x, y) \) is QoS cost of \( ISL(S_i \rightarrow S_j) \) at the beginning of a time slot \( T_i \). QoS cost model is defined as follows:

\[
W(x, y) = \omega_{ij} \times Bw_{xy}(t) / Bw_{xy, \text{max}} + (1 - \omega_{ij}) \times Delay_{xy, \text{max}} / Delay_{xy}(t)
\]

In it:

- \( Bw_{xy}(t) \) : available bandwidth of link \( ISL(S_i \rightarrow S_j) \) at the start of a time slot \( T_i \);
- \( Delay_{xy}(t) \) : delay of link \( ISL(S_i \rightarrow S_j) \) at the start of a time slot \( T_i \);
- \( Bw_{xy, \text{max}} \) : the largest bandwidth of link \( ISL(S_i \rightarrow S_j) \);
- \( Delay_{xy, \text{max}} \) : the largest delay of link \( ISL(S_i \rightarrow S_j) \);
- \( \omega_{ij} \) : weighting coefficient, \( 0 \leq \omega_{ij} \leq 1 \);
- \( i \) : topological slot;
- \( j \) : link attributes.

**A. The Design of Link Cost**

In the above model design, there are three kinds of links: link within LEO layer, LEO / MEO interlayer link and link within MEO layer, shown in Figure 2.

How to design link cost is the primary problem to be solved. Firstly, introduce two variables: \( i \) and \( j \) in QoS integrated weighted cost coefficient \( \omega_{ij} \), in which \( i \) describes topological slot, \( j \) describes link attributes. To simplify the model, the conditions for definition should be: in the same time slot \( T_i \), cost coefficients of link of the same attributes are same [10].

\( j \) represents different link attributes. \( j = 0 \) means link within LEO layer. \( j = 1 \) means LEO / MEO interlayer link. \( j = 2 \) means link within MEO layer. If all weighting values of links within LEO layer are same, it is denoted as \( \omega_{00} \). If all weighting values of LEO / MEO interlayer links are same, it is denoted as \( \omega_{1} \). If all weighting values of links within MEO layer are same, it is denoted as \( \omega_{2} \).

In order to maintain QoS integrated weighted cost parameter \( \omega_{ij} \), add three fields in static link database [11] each MEO satellite maintains, correlated to \( T_i \). Maintenance table format of QoS integrated weighted cost coefficient is shown in Table 1:

<table>
<thead>
<tr>
<th>( T_i )</th>
<th>( \omega_{00} )</th>
<th>( \omega_{1} )</th>
<th>( \omega_{2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 )</td>
<td>( \omega_{00} )</td>
<td>( \omega_{1} )</td>
<td>( \omega_{2} )</td>
</tr>
<tr>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>( T_P )</td>
<td>( \omega_{00} )</td>
<td>( \omega_{1} )</td>
<td>( \omega_{2} )</td>
</tr>
</tbody>
</table>

In it, \( i = 0, \ldots, P-1 \); \( P \) is periodic topological sequence.

The above has already given value type of weighting coefficient in different time slots at different time slots and storage of the weighting coefficient. But there is a crucial problem to be solved: the selection of the weighting coefficient \( \omega_{ij} \). This issue will be determined in the design of weighting coefficient of next section.

**B. Design of Weighting Coefficient**

\( \omega_{ij} \) is restricted in many aspects, such as the differences of user traffic in the different regions and in different time slots, the trade-offs of QoS indicators like delay, bandwidth and traffic in different regions. In order to select \( \omega_{ij} \) more reasonably, next we will illustrate it through global traffic distribution.

The purpose of global traffic distribution analysis is to select the most appropriate weighting coefficient \( \omega_{ij} \).

The background of global traffic distribution is based on the difference of population density in different regions.
In the areas with relatively low population density, the volume of services is relatively small, while in commercial metropolis, there are large service density and a large number of mobile terminals, and the need for bandwidth is high [12-14]. In the areas with dense services the situation is more complex. So we should combine delay and comprehensive guarantee demand of bandwidth in order to find the most appropriate weighting coefficient \( \omega_{i,j} \). Based on the above background, the figure of global traffic distribution analysis is shown in Figure 3.

![Figure 3. The figure of global traffic distribution analysis](image)

The analysis can be described as follows: depending on the regional differences, combined with the division of time slots, the slot thinning way is used to set an appropriate value of weighting coefficient \( \omega_{i,j} \). The value of the weighting coefficient \( \omega_{i,j} \) relies on the setting of population flow. For instance, in Oceania, Africa and the Middle East, the population density is relatively small, and there are many desert areas so that traffic is very small. But in Asia, the Americas and Europe, population density is high, traffic flow is large, while the Polar Regions are almost inaccessible, and the flow is almost zero. Global traffic distribution is shown in Table 2 [15, 16].

### TABLE II. THE FORMAT OF GLOBAL TRAFFIC DISTRIBUTION

<table>
<thead>
<tr>
<th>Areas</th>
<th>Proportions of Services</th>
<th>Time Slot</th>
<th>( \omega_{0,0} )</th>
<th>( \omega_{0,1} )</th>
<th>( \omega_{0,2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>34.5</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>Europe</td>
<td>13.8</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>Africa</td>
<td>13.3</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>South America</td>
<td>10.8</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>North America</td>
<td>8.0</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>Oceania</td>
<td>2.1</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>The European Part of former Soviet Union</td>
<td>3.6</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>The European Part of former Soviet Union</td>
<td>10.7</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
<tr>
<td>Other Areas</td>
<td>0</td>
<td>( T_0 )</td>
<td>( \omega_{0,0} )</td>
<td>( \omega_{0,1} )</td>
<td>( \omega_{0,2} )</td>
</tr>
</tbody>
</table>

Based on regional traffic distribution, combining simulation experiment, the next section will choose an appropriate value of weighting coefficient \( \omega_{i,j} \) and complete the design of QoS integrated weighted cost model.

### IV. SIMULATION RESULTS

In order to facilitate simulation analysis, the preconditions of the model are firstly set: the number of satellite user within time slot is linearly proportional to the number of the population. The set is as follows: link within LEO layer, LEO/MEO interlayer link and link within MEO layer are full-duplex link. The bandwidth of link between LEO layer is 155Mb/s, the bandwidth of LEO/MEO interlayer link is 255Mb/s, and the bandwidth of link between MEO layer 255Mb/s. Set LEO satellite 25MB cache, MEO satellite 50MB cache, and 1Mbps packet size.

#### A. Simulation Analysis of Weighting Cost Parameter

According to the size of the traffic select three representative areas: Area 1 (Asia), Area 2 (Europe), and Area 3 (Oceania). Different traffic corresponds to utilization rate of different link. Utilization rates of links in three regions are respectively 90%, 70% and 60%. In the model description, we conclude that LEO belongs to the satellite of the access layer, and link within the layer are the most sensitive to QoS parameters. Without loss of generality, \( \omega_{0,1} \) and \( \omega_{0,2} \) are set to 0.5, the mean. Under this circumstance, we use simulation analysis, shown in Figure 4.

![Figure 4. Diagram of simulation analysis of cost parameters within LEO layer](image)

According to the above simulation results, when throughput performance of Area 1 (Asia) is optimal, \( \omega_{0,0} \) is approximately 0.76. When throughput performance of Area 2 (Europe) is optimal, \( \omega_{0,0} \) approaches to the mean, about 0.52. When throughput performance of Area 3 (Oceania) is optimal, \( \omega_{0,0} \) is approximately 0.23. That is to say, the traffic in the area that the traffic is greater, \( \omega_{0,0} \) should select the larger value.

#### Figure 5. Diagram of simulation analysis of cost parameters interlayer of LEO/MEO

According to the above simulation results, when throughput performance of Area 1 (Asia) is optimal, \( \omega_{0,0} \) is approximately 0.76. When throughput performance of Area 2 (Europe) is optimal, \( \omega_{0,0} \) approaches to the mean, about 0.52. When throughput performance of Area 3 (Oceania) is optimal, \( \omega_{0,0} \) is approximately 0.23. That is to say, the traffic in the area that the traffic is greater, \( \omega_{0,0} \) should select the larger value.
Take the same measure to analyze $\omega_{i,1}$ and $\omega_{i,2}$, $\omega_{i,0}$ uses the value obtained in the above analysis, as shown in Figures 5 and 6.

From Figure 4 and Figure 5, we can conclude that the selection principle of cost parameter of interlayer LEO/MEO, the selection principle of cost parameter of layer within MEO and the selection principle of cost parameter of layer within LEO are similar. That is to say, in the area where the traffic is greater, the value of link cost parameter should selected larger one.

**B. Comparative Analysis of Throughput**

Select three representative areas: Area 1 (Asia), Area 2 (Europe), and Area 3 (Oceania). According to the previous section select link cost parameters, as shown in Table 5-3.

<table>
<thead>
<tr>
<th>Area</th>
<th>Service proportion</th>
<th>$\omega_{i,0}$</th>
<th>$\omega_{i,1}$</th>
<th>$\omega_{i,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>34.5</td>
<td>0.76</td>
<td>0.71</td>
<td>0.69</td>
</tr>
<tr>
<td>Europe</td>
<td>13.8</td>
<td>0.52</td>
<td>0.49</td>
<td>0.43</td>
</tr>
<tr>
<td>Oceania</td>
<td>2.1</td>
<td>0.23</td>
<td>0.22</td>
<td>0.21</td>
</tr>
</tbody>
</table>

When $\omega_{i,j}=0$, the model becomes a single delay parameter, equal to MLSR algorithms. Setting link utilization rate from normal load to overload, the compare the throughput of QoS integrated weighted cost model and the throughput of a single delay model of MLSR algorithm, shown in Figure 7.

From the above simulation results, we can see that when the link utilization rate is less than 80%, the throughput of QoS cost model is slightly bigger than that of MLSR single delay model. When the link utilization rate is greater than 80%, the throughput of QoS integrated weighted cost model takes priority. When the link utilization rate is greater than 95%, overload occurs, and throughput declines sharply, but the declining rate of the throughput of QoS integrated weighted cost model is much slower than that of MLSR single delay model.

**V. CONCLUSION**

In sum, MLSR algorithm which uses the link parameters only takes the delay into consideration, ignoring the bandwidth so that it is prone to congestion when the link is heavily loaded. QoS integrated weighted cost model considers asymmetric feature of services requirement in delay, bandwidth, time and location, so when the link is heavily loaded adaptability to congestion is much stronger.

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