QoS Routing Algorithm Applying Multi-Agent System for LEO Satellite Network

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Abstract

Satellite network is the essential part of the future generation of hybrid communication networks. Considering the surging demands for multimedia traffic across the globe, the dynamic time-varying topology of low earth orbit (LEO) satellite network and the flaws of existing QoS (Quality of Service) routing algorithms, a novel QoS routing algorithm applying multi-agent system (MAQR) for LEO satellite network is proposed in this paper. The algorithm design three types of mobile agents: node management agent (NMA), active perception agent (APA) and executive agent (EA). NMA adaptively perceives external environment and deals with traffic request and controls routing. APA is responsible for collecting information of non-local satellite nodes and links. EA is in charge of path maintenance and update. MAQR algorithm introduces link duration into a cost function and then minimizes the cost function to find optimum paths that simultaneously satisfy delay and bandwidth constrains. Besides, when current QoS path is deteriorated, new QoS path can be discovered without rerouting. Simulation results show that MAQR algorithm not only has lower call blocking probability and handover call dropping probability, but takes both routing efficiency and algorithm overhead into account as well.

Keywords: *LEO satellite network, QoS routing, multi-agent system, QoS constrains*

1. Introduction

The future generation of communication networks will be featured by their wireless mobility, global coverage and broadband high-speed transmission. Considering the tendency, satellite network as the framework in the air organically connects terrestrial networks with aerospace communication platforms and different terminals. As the Internet protocol (IP) is highly flexible and scalable for different links, satellite network combines IP with the next generation network (NGN) to form the air-space-ground integrated information network (ASGI^{2}N) oriented to the future communication, which integrates all communication platforms and terminals on the ground, on the sea, in the air and in outer space [1]. As satellite communication system is not subject to terrains and oceans, satellite communication plays an irreplaceable role in future networks. Besides, compared with geosynchronous earth orbit (GEO) satellite, LEO satellite has the advantages of polar coverage, flexible networking, low propagation loss and delay, supporting airborne devices and diverse handsets to directly communicate with satellites that have been widely deployed in many commercial systems [1].

However, as LEO satellite network is usually composed of tens of satellite, its routing problem is more complicated than GEO and medium earth orbit (MEO) satellite systems. On one hand, the high-speed movement of LEO satellite leads to fast change of topology. In the meantime, inter-plane inter-satellite link (ISL) will frequently break or recover due to fast change of topology. On the other hand, traffic of satellite network not only includes data and voice, but also covers multimedia traffic, such as image, streaming media and video-on-demand (VoD). Increasing traffic will overload satellite which serves as routing node. Due to these factors, designing QoS routing algorithm for LEO satellite network is imperative. Besides, considering on-board resources being limited, routing algorithm should be designed from a global prospect to fully utilize resources and achieves optimal balance between efficiency and overhead.

This paper proposes a QoS routing algorithm applying multi-agent system (MAQR) for LEO satellite network. Multi-agent system is generally with distributed and dynamic structure. All agents are classified into several types of unions. Each agent union completes its own function, while different agent unions cooperate with each other to complete a common task. Considering delay and bandwidth as QoS constrains, MAQR algorithm designs three types of agents and divides QoS routing into several parts. Each part is manipulated by corresponding agent unions. The ultimate QoS routing is implemented through cooperation of different agent unions.

2. Related Works

Routing of LEO satellite network has transited from connection-oriented to non-connection-oriented.

In the early stage of satellite communication, satellite serves as a supplement for terrestrial networks. Derived from connection-oriented communication [2], such as asynchronous transfer mode (ATM) commonly used in terrestrial networks [3], routing algorithms consider the periodical characteristics of satellite network topology and discretize dynamic topology. As a result, dynamic routing is transformed into static routing which includes a series of static snaps, such as discrete-time dynamic virtual topology routing [4, 5] and the routing based on finite state machine (FSM) [6]. However, such algorithms do not take link switch and subsequent rerouting into consideration. In addition, connection-oriented routing is badly compatible to non-connection-oriented protocol, such as IP.

Later, many non-connection-oriented routing algorithms had been proposed. Distributed routing algorithms were proposed in [7, 8]. It uses logic address of satellite and identifies the next-hop according to the minimum hop count. If multiple paths are alternative, the optimal path is determined according to geographical positions of satellite logic addresses. An improved IP-based routing algorithm for LEO satellite was proposed in [9]. It introduces the concept of cell into satellite network and minimizes hop count to finish addressing of up/down link (UDL) without positioning information. Factually, above algorithms are ultimately transformed into shortest path routing, but the shortest path may not be the optimal path. In addition, they often only satisfy single QoS constrain (*e.g.*, delay). To better support diverse QoS requirements of multimedia traffic, routing algorithms should satisfy multiple QoS constrains. Therefore, QoS routing has been a research frontier of LEO satellite network routing for years.

A distributed QoS routing algorithm was proposed in [10]. It uses the count of link switch as the optimization objective and revises path in terms of link duration. However, the algorithm is partly imperfect mainly because it uses minimum hop count as path evaluation metric and does not consider differences of ISLs in different latitudes. A traffic class dependent routing algorithm was put forward in [11]. In the light of different traffic QoS requirements, the algorithm categorizes traffic into three types including strict delay, reliable throughput and best-effort. Each satellite node maintains a routing table for each type of traffic. Evidently, the algorithm only offers differentiated services without QoS guarantee scheme. When traffic type is excessive, the overhead and complexity will drastically increase. Similarly, [12] presents a QoS routing algorithm for provision of E2E (end-to-end) delay guarantee, but it only has a single QoS constrain.

Above algorithms tend to pay so much attention to concrete forms of network topology that the design idea of routing algorithm is generally restricted. With the increase of network scale, such algorithms have bad scalability, especially for multi-layer satellite network. Artificial intelligence (AI), which simulates the way of living or the rule of information processing of animals in nature to actively and adaptively perceive external environment, provides a novel idea to design of QoS routing algorithm. For instance, artificial neural network (ANN) [13, 14] and ant colony optimization algorithm [15, 16] are important branches of AI routing algorithms. Though such algorithms solve a part of QoS routing problems, they are lacking in systematic researches on the theory of QoS routing, organizational structure and algorithm flow. As another emerging branch of AI, multi-agent system (MAS) presents a systematically analytic tool in complex network conditions. In MAS, a complicated task is divided into several subtasks which are separately completed by different types of agents. All agents cooperate with each other to complete the entire task. There are few QoS routing algorithms for LEO satellite network based on MAS, including [17] and [18]. The algorithm designs two types of agents that one is load balancing agent and the other is QoS guarantee agent. The former is responsible for uniformly distributing traffic of entire satellite network, while the latter is in charge of guaranteeing E2E delay of real-time traffic. One on hand, it is not ubiquitous that the premise of the algorithm is inter-plane ISLs are permanent without link switches. On the other hand, the algorithm only guarantees delay without considering multiple QoS constrains. We also proposed several QoS routing algorithms applying MAS for LEO satellite network [19-21]. Since single-path routing is apt to reducing reliability when link switches or congestion happens, [19] and [20] applying MAS categorize agents into three types, including forward agent (FA), backward agent (BA) and node agent (NA). FA has the same priority to data packet and fully knows network congestion situation, while BA has higher priority to data packet in order to return network information to source node as quickly as possible. NA is fixed in local satellite node to update routing information. Different from previous algorithms, [19] and [20] fully take link switch into account and effectively avoid loop routing. Similar to [17] and [18, 21] deliberates the spatial-temporal distribution ununiformity of ground traffic, but different from passive load balance in [17] and [18, 21] proactively predicts traffic by means of prediction agent to update routing information. However, to design a distributed routing algorithm which simultaneously considers MAS and multiple QoS constrains for LEO satellite network has been still a suspended problem to authors. As a follow-up work of our previous researches, according to different types of traffic, this paper designs a QoS routing algorithm applying MAS for LEO satellite network based on distributed multi-path routing algorithms of [19] and [20].

3. Topology Model and QoS Routing Formulation of MAQR Algorithm

3.1. Topology Model of LEO Satellite Network

As used in our previous papers, the Iridium constellation is considered in this paper. The Iridium system is composed of six separate orbit planes and each plane has eleven satellites. Thus, each satellite has four neighbor satellites: two in the same orbit plane while the other two in two neighbor orbits. The links between two satellites in the same orbits are intra-plane

ISLs. The links between satellites in different planes are inter-plane ISLs. In other words, each satellite has four ISLs. When a satellite flies over the Polar Regions, due to the relative and high speed between satellites and the Doppler frequency shift, inter-plane ISLs will be frequently broken or recovered.

3.2. QoS Constrain Formulation

In this paper, the satellite network topology model can be represented by a directed graph $G = (V, E)$, where V represents the set of satellite nodes, while E stands for the set of ISLs of the entire network. Here, real-time and best-effort traffic are taken into consideration. For the sake of simplicity and generality, bandwidth and delay related to each ISL are selected as the two QoS constrains. Specifically, delay along the path from node s to node t is no more than D, while minimum bandwidth on any path from node s to node d is no less than B. Factually, MAQR algorithm can be expanded to three or more constrains, including jitter and packet loss ratio (PLR) by revising routing strategy. The QoS routing formulation of MAQR algorithm can be expressed as:

$$delay\left(p\left(s,t\right)\right) \le D \tag{1}$$

$$\min_{\left(u,v\in path\left(s,d\right)\right)} \left(band\left(u,v\right)\right) \ge B \tag{2}$$

Above formula mean that MAQR algorithm should find the path with the minimum cost under the conditions (1) and (2) in LEO satellite network.

4. MAQR Algorithm

4.1. Design of Multi-agent System in MAQR Algorithm

In MAQR algorithm, all behaviors of satellite network are regulated by mobile agents with different subtasks. Three types agent are designed in MAQR algorithm: NMA (Node Management Agent), APA (Active Perception Agent) and EA (Executive Agent). Each type of agent performs different functions.

NMA is static and bound to local satellite node. Each NMA has a routing table to forward packets and an information table to control behaviors of APA and EA. NMA observes local information and independently determines behaviors of local satellite node. But NMA acquires non-local information by sending APA. In other words, NMA allies itself with other types of agents to jointly optimize global behaviors in LEO satellite network and find the optimal QoS path.

APA is generated by NMA and then travels in network to gather non-local information. APA uses random walk policy to discover and establish new paths. In order to send back the information to NMA as quickly as possible, APA has higher priority than data packet so that entire network can be completely searched as quickly as possible.

EA which is also generated by NMA, observes and adjusts local decision according to network conditions. Specifically, since behaviors of all NMAs are independent, distributed and concurrent, EA is obliged to globally regulate all NMAs in terms of predetermined decision.

4.2. Design of Multi-agent System in MAQR Algorithm

As the topology of LEO satellite network is time-varying, NMA should generate a large number of agents to explore the current situation of the network. Efficiency and overhead always contradict each other. Specifically, the more agents NMA generates, the more accurate real-time information of the network is, and then data packets can be transmitted along the better path. Consequently, a huge quantity of agents tends to congest satellite nodes, leading to low transmission efficiency. Therefore, MAQR algorithm makes a fully adequate tradeoff between efficiency and overhead. The concrete steps of MAQR algorithm are implemented as follows:

(1) When a new traffic request is initiated from source node s, its QoS requirements, including the requested bandwidth B and the E2E delay D, are transferred to NMA.

(2) The NMA of node s starts MAQR algorithm to search for the path to destination node d satisfying above QoS constrains. If node s has the path information, go to step (6); else, APA is generated in node s to gather routing information of satellite nodes that it passes and to establish the path to node d. Especially, the next-hop node is randomly selected in probabilities.

(3) When each of intermediate nodes receives APA, the node sends out a unicast or broadcast message to explore path. Specifically, if the node has the path information to node d, it sends out the APA through unicast; else, the node broadcasts the APA to all neighbor nodes except those where the APA comes from. So, one or multiple nodes will receive the APA or its copies.

(4) Every intermediate node v will screen APA or its copies that they received. If APA is in line with one of the following conditions, it will be directly deleted:

①$band(s, v) < B$;

②delay$(p(s, v)) > D$;

③Current hop count of the APA is larger than a predefined time-to-live (TTL);

④When node v receives multiple APAs, if newly arriving APA has less cost function, the APA is forwarded; else, it is deleted.

(5) When APA arrives at the destination node d, APA automatically disappears. The NMA of node d generates EA, and then the EA returns to node s along the path that APA passed. EA establishes or updates the path information hop-by-hop from intermediate node s to node d in the light of following formulas:

$$T_{v\to d} = \sum_{i=\{v+1,v+2,\cdots,d\}} T_{i-1\to i} \tag{3}$$

$$T_{m\to n} = D_n^m\left(Q_l, B_l, d_l\right) = Q_l/B_l + d_l \tag{4}$$

where v represents intermediate node that EA passed; $T_{v\to d}$ stands for the delay from node m to node n; d_l is link propagation delay; Q_l and B_l represent traffic to be sent and link capacity from node m to node n, respectively.

(6) If the path from node s to node d does not exist, the new traffic request is rejected; else, when node s gets path information node d, the path establishment is over. Since path searching is concurrent, maybe multiple paths are qualified for traffic QoS requirements. Following cost function is used to refine above paths and then select one or some of them. For the case of multiple possible paths, all paths have no overlapped links.

Suppose there are k paths $P=(p_1, p_1, \cdots, p_k)$ satisfying QoS requirements from node

s to node d, for any path $p_i (i = 1, 2, \cdots, k)$, the cost function is defined as

$$C_i = \alpha \times \frac{T(p_i)}{\sum_{i=1}^{k} T(p_i)} + \beta \times \frac{\min\left(b\left(p_i\right)\right)}{\sum_{i=1}^{k} \min\left(b\left(p_i\right)\right)} + \gamma \times \frac{\min\left(L\left(p_i\right)\right)}{\sum_{i=1}^{k} \min\left(L\left(p_i\right)\right)} \tag{5}$$

where $\min(b(p_i))$ and $\min(L(p_i))$ stand for the minimum bandwidth and the shortest link duration. α, β and γ represent the weight factors for three items, respectively.

(7) Once a QoS path is established, data packets are transmitted along it. If there are multiple QoS paths, data packets will select these paths in different probabilities [19].

(8) NMA periodically sends out another type of APA named active maintenance agent (AMA) to monitor current QoS paths. AMA has the same data structure as APA, but AMA is inclined to select and maintain the established QoS paths. Only in the case of a small probability, an intermediate node will broadcast AMA to its neighbor nodes.

(9) If unicast AMA arrives at node d, EA is generated to update link information. If AMA is broadcasted, it means that AMA deserts currently optimal QoS path to search for new path. When the broadcasted AMA arrives at node d, step (5) is repeated to update backward links that AMA passing.

4.3. Link Switch Policy of LEO Satellite Network

Link switch is less discussed in previous LEO satellite routing algorithms. There are two cases being considered in this paper: link break and link recovery.

When ISL connecting two satellites breaks, these two satellites will change original routing that one satellite can not take the other one satellite as the destination node or the next-hop node. Likewise, their neighbor satellites will also change their routing. Thus, NMA of the two satellites updates local routing table and then broadcasts failure notification agent (FNA), which is a sort of EA to neighbor satellites. As FNA records a list of destination node on whose path the link is broken, all neighbor nodes that receive FNA update their routing tables. Further, if one of above neighbor nodes also changes original routing due to link break, the node sends FNA to its neighbor nodes until all nodes of satellite network know and adapt to link break.

When ISL recovers, two separate satellites can be connected by their ISL. These two satellites generate recovery notification agent (RNA), which is a sort of EA as well, to explore the recovered link. Specifically, each of two satellites updates its routing table according to the information detected by RNA and then broadcasts the update to its neighbor nodes until all nodes of satellite network know and adapt to link recovery.

5. Simulation Results

As previously used, the Iridium satellite system is introduced to validate MAQR algorithm. Its orbit altitude is about 781 km. Inter-plane ISLs are time-varying, while intra-plane ISLs are permanent. Suppose traffic distribution on the ground is uniform that 50 ground terminals generate new traffic call with the same probability. Call duration obeys negative exponential distribution with the mean 180s. Capacity of ISL is 50 simultaneous calls. Other parameters are configured as $\alpha = \beta = \gamma = 1$, $q' = 0.01$.

In this paper, MAQR algorithm is compared with two recently proposed algorithms, *i.e.*, [22] and [23]. The first is a QoS routing scheme based on ground station for LEO satellite network and abbreviated as AO because it uses algebraic optimization routing policy. The second is a QoS routing based on genetic algorithm for LEO satellite network abbreviated as GSRP (Genetic Satellite Routing Protocol). In addition, two types of calls are considered: new calls and handover calls. The latter refers to online call suffering from broken link on its original path. A new call will be blocked or a handover call will be rejected due to unavailable bandwidth or unqualified delay. Call blocking probability (CBP) is defined as the ratio of the number of blocked new calls to the number of total new calls, while call dropping probability (CDP) is defined as the ratio of the number of rejected handover calls to the number of total handover calls.

Figure 1 and 2 plot CBP and CDP under 300ms delay constrain, respectively. It is apparent that MAQR algorithm has lower CBP and CDP because it takes both E2E delay and bandwidth into account. Specifically, MAQR algorithm avoids excessive calls being blocked because it not only allows multi-path scheme to search for QoS path, but is fully utilizes bandwidth as well. In addition, EA establishes and updates path hop-by-hop, in the meanwhile, as FNA and RNA promptly broadcast link switch to all satellite nodes, and then new QoS path can be quickly found, online calls also avoid being dropped. Therefore, compared with AO and GSR, MAQR algorithm has lower CBP and CDP.

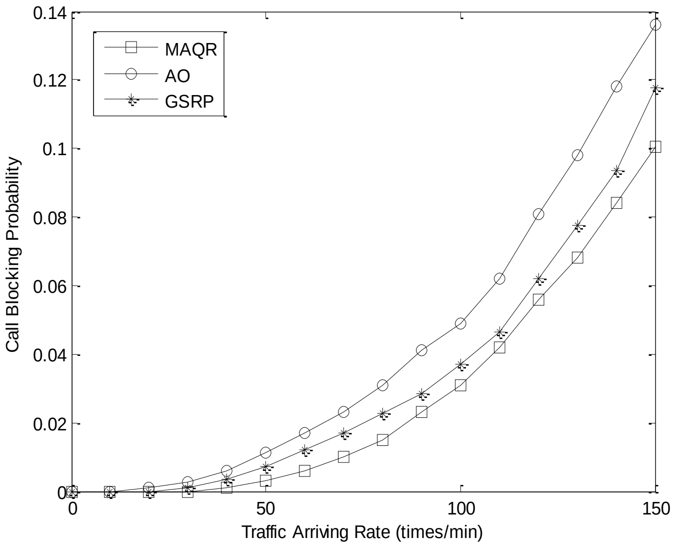

Figure 1. Call Blocking Probability under 300ms Delay Constrain

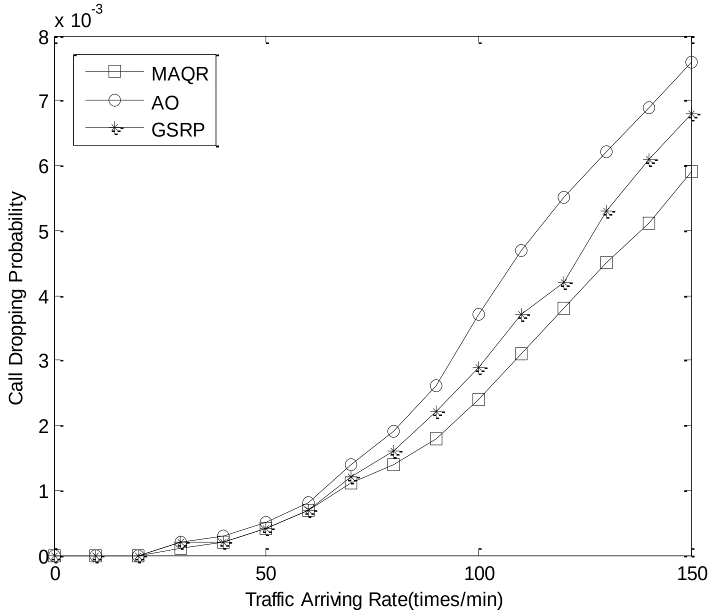

Figure 2. Call Dropping Probability under 300ms Delay Constrain

Figure 3 and Figure 4 present CBP and CDP under 200ms delay constrain. In contrast to the previous case, as shown in Figure 3, CBP greatly increases while CDP has slight increases for three algorithms, but MAQR algorithm still has the lowest CBP and CDP. As network resources are limited, paths satisfying traffic QoS requirements decrease so that new traffic calls are highly blocked. However, for handover calls, MAQR algorithm tends to select paths with longer duration because path duration is introduced into the algorithm to compute QoS path. Therefore, MAQR algorithm greatly reduces the impact of link switch to handover calls.

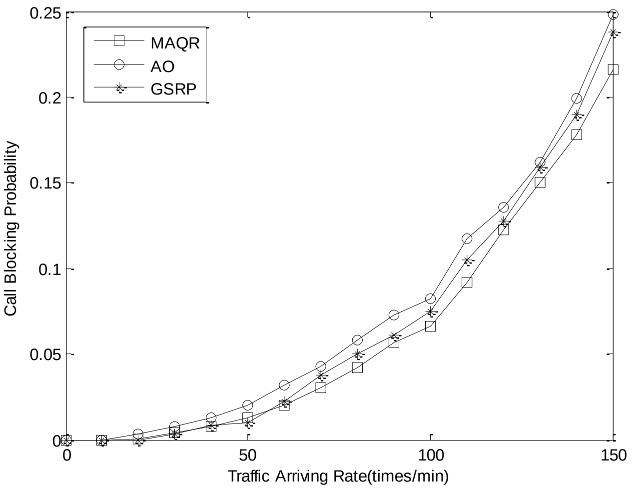

Figure 3. Call Blocking Probability under 200ms Delay Constrain

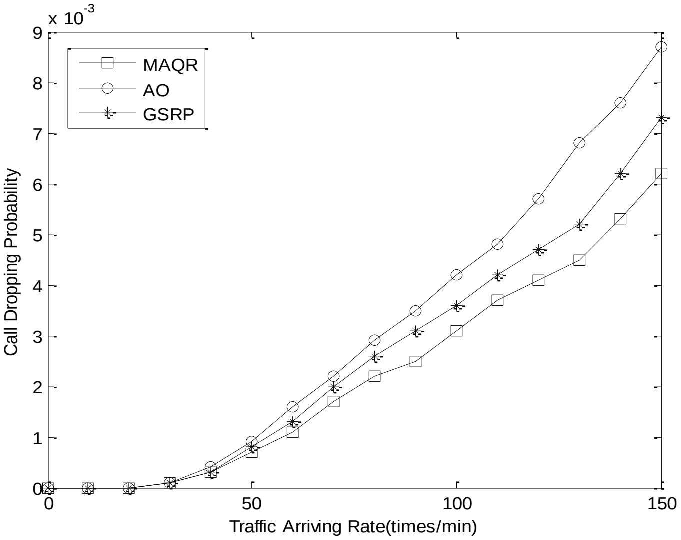

Figure 4. Call Dropping Probability under 200ms Delay Constrain

Figure 5 and Figure 6 illustrate normalized routing efficiency and routing overhead for MAQR algorithm. Routing efficiency is defined as the ratio of throughput to packet delay. As data in satellite network include both information data and mobile agents, routing overhead is defined as the ratio of the data amount of the former to the latter. The horizontal axis in Figures 5 and 6 represents the sending interval that satellites generate agents. Figure 5 demonstrates that the smaller sending interval is, the higher routing overhead is. In contrast, routing efficiency has an arched variation trend. Apparently, excessive agents occupy more transmission bandwidth resulting in less transmission of data packets. Inversely, too little agents cannot promptly perceive link switch and topology variation, leading to the fact that data packets are transmitted along

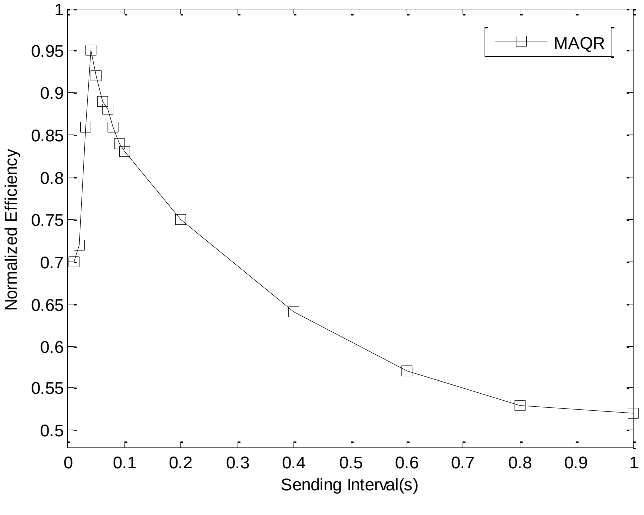

Figure 5. Normalized Routing Efficiency of MAQR Algorithm

inferior paths with low routing efficiency. Considering both routing efficiency and overhead, the reasonable interval of sending agents should be between 0.01 and 0.1s.

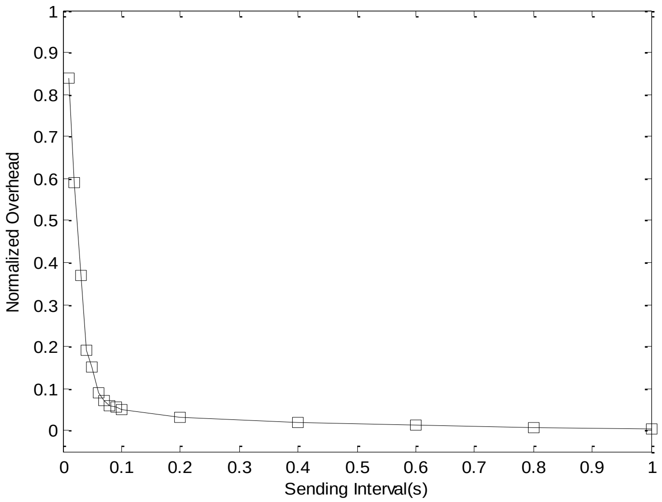

Figure 6. Normalized Routing Overhead of MAQR Algorithm

From above results, it can be seen that MAQR algorithm has three features. First, for path establishing, MAQR algorithm adopts on-demand policy to decrease routing overhead. Second, MAQR algorithm has higher resource utilization. In the last, MAQR algorithm is more adaptive to time-varying network topology of LEO satellite network.

6. Conclusions

In view of the lack of effective QoS routing algorithm for LEO satellite network, a QoS routing algorithm applying multi-agent system (MAQR) for LEO satellite network is proposed in this paper. By means of multi-agent system, NMA, APA and EA are designed according to different functions. Thus, the QoS routing problem is divided into several stages, including routing establishment, path exploration, path maintenance, link recovery and link switch. Each stage is performed by corresponding agent. Combining broadcast with unicast, MAQR algorithm is an on-demand algorithm that it monitors currently deteriorated paths and explores new paths. When ISL breaks or recovers, the algorithm informs the link variation to entire network, leading to MAQR algorithm has fast convergence speed. Introducing link duration, MAQR algorithm tends to select the link with longer duration and then reduce rerouting resulting from satellite network topology variation. Therefore, its adaptability is highly enhanced. In addition, MAQR algorithm has satisfactory scalability that only a minor revision to MAQR is enough for multiple or different QoS constrains.

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