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Abstract—In Low Earth Orbit (LEO) satellite constellation system, routing data from the source all the way to the destination constitutes a daunting challenge because LEO satellite constellation resources are spare and the high speed movement of LEO satellites results in a highly dynamic network topology. This situation limits the applicability of traditional routing approaches that rely on exchanging topology information upon change or setup of a connection. Consequently, in recent years, many routing algorithms and implementation strategies for satellite constellation networks with Inter Satellite Links (ISLs) have been proposed. In this article, we summarize and classify some of the most representative solutions according to their objectives, and discuss their advantages and disadvantages. Finally, with a look into the future, we present some of the new challenges and opportunities for LEO satellite constellations in general and routing protocols in particular.

I. INTRODUCTION

There are many advantages to satellite networks over terrestrial networks. The satellite architecture is more scalable and provides coverage in harsh environments where it is hard to have a terrestrial network. Therefore, satellite technology can enable many civilian and military applications such as disaster and environmental monitoring, managing large systems, effective data collection, disaster prevention and Internet of Things. With satellite and earth stations you can create more stable network than laying cables. LEO satellite systems in particular are of great interest as they provide lower propagation delay as well as higher throughput than geostationary orbit satellites (GEO) and medium earth orbit satellites (MEO). In general, a LEO network consists of a number of satellites organized as a constellation in orbits of 500-2000 kilometers above the earth’s surface. Orbits lower than this are not stable, and will decay rapidly because of atmospheric drag. The LEO velocity of the rotation is about 20000 kilometers per hour. It takes the satellite less than 2 hours to cycle around the earth [1]. So, the routing complexity becomes more important as LEO satellites change their coverage areas on the earth surface due to their regular motion, and accordingly have to transmit different amount of traffic load. The traffic distribution on the earth surface is not homogeneous at all because the users tend to converge in big cities compared with remote areas (Fig. 1). Given the recent advances and ongoing improvements in LEO satellite technologies, Internet-based multimedia services are added, the number of nodes in satellite networks is fixed and limited.

Like satellite networks where nodes can be easily added, the number of nodes in satellite networks is fixed and limited.

Unlike in terrestrial networks where nodes can be easily added, the number of nodes in satellite networks is fixed and limited.

LEO satellites can, economically, only provide niche services to areas inaccessible to cellular system. Hence, for mass market services there need to be an integration with terrestrial system – not to compete but to collaborate with cellular networks.

A link handover algorithm for LEO satellite network is required when the ISL connectivity changes or when the ground-satellite link becomes unavailable.

In the rest of the paper we discuss key aspects of LEO satellite constellation that influence routing protocol design. In the next two sections, we explain the features of LEO satellite networks and why existing routing protocols are unsuitable for the LEO constellation environment and review the latest solutions for space communication. We then claim that improved performance in LEO satellite constellation can be obtained with multi-layered satellite networks and cross layer design. In the final section, we conclude the article.

II. FEATURES OF LEO SATELLITE NETWORKS

LEO satellite constellation consists of a number of orbits at a certain altitude, a specific number of satellites per orbit, and
Fig. 1: A LEO satellite network with nonhomogeneous traffic distribution

links between satellite pairs, referred to as Inter-Satellite Links (ISL). Keeping the orbit closer to the earth is becoming more and more popular in research as it leads to shorter propagation delay and it allows for a reduction of the antenna size as well as the transmission power. However, these advantages for closer altitude come with a price of smaller footprint and shorter lifetime. For lower altitude constellations a higher number of satellites are required for global coverage. Additionally, lower orbit satellites move with a higher speeds relative to the speed of the earth, resulting in highly dynamic satellite topology and frequent handover occurrences. So the mobility of satellites in such constellation constitutes a major difference between LEO satellite networks and their terrestrial counterparts. Moreover, the LEO satellite nodes have different capabilities when compared to terrestrial nodes. Finally, LEO satellite constellations have specific geometric parameters, which can be leveraged by a high performance routing algorithm.

III. ROUTING SOLUTIONS

Current terrestrial internet routing protocols, such as Routing Information Protocol (RIP) and Open Shortest Path First (OSPF), rely on exchanging topology information upon a transition or set up of a connection. Applying such schemes to the rapidly and regularly changing LEO satellite network topologies, if not done properly, can induce substantial overhead. One thing to be taken into account is that, although the topology of LEO satellite network rapidly changes, these changes are periodic and predictable due to the deterministic motion of LEO satellites. Therefore, several routing schemes have been proposed for utilizing this inherent attribute. The Virtual Topology (VT) mechanism and the Virtual Node (VN) mechanism are the best known concepts. With VT, based on the periodicity of the LEO satellite network, the system period, $T$, is divided into $n$ time intervals during each interval the network remains unchanged. The advantage of this mechanism is that, in each time interval, every satellite knows about the link state of the whole constellation. One of the main drawbacks of this mechanism is that ISLs are not always active but inactive when satellites are located in the polar areas due to adverse pointing and tracking conditions. Thus, the path might be disconnected if one of its ISLs is inactive while the connection is still live. In [2], a LEO satellite network is represented as a finite-state automaton (FSA), where the system period, $T$, is divided into states. These states are derived from the ISL connectivity data so that the LEO network has a fixed topology in each state. Due to the periodicity of the LEO constellation topology a finite number of states can be found. Then, it is proposed to execute an optimal routing strategy on each of these fixed topologies for the best use of ISL in the system. A number of routing tables are stored on-board and retrieved when topology changes. Although the messaging overhead and computational complexity is reduced, large storage capacity is required on the satellites.

Another concept worth explaining that is tailored to dynamic LEO satellite constellations is the Virtual Node (VN) [3]. In this routing mechanism the whole earth area is split into different regions and each region is given a single fixed logical address. At each fixed time point, the satellite that is closest to the center of the region is given the logical address of this region. The data packets are routed simply by including the logical address in their headers. So with the VN mechanism, a fixed virtual topology is superimposed over the physical topology to hide the mobility of the satellites from the routing protocols. However, this approach presents some interesting problems such as scalability of routing tables and high computational complexity in space devices. The one-to-one mapping of a physical topology to a virtual topology is a problem for many reasons. The most important reason is the sun outage phenomenon, where the LEO satellite serving a fixed footprint is in the same line of sight with the sun. The effects of a sun outage can include partial degradation, that is, an increase in the error rate, or total destruction of the signal. Therefore, further work is required to improve the virtual node mechanism concept.

In addition to the approaches presented so far, several
solution and implementation strategies have been proposed that utilize information on expected traffic characteristics and handover possibilities when deciding on the most appropriate path among a set of shortest paths. These routing algorithms are described in the following sections.

A. Load Balancing Routing Algorithms

Given the non-uniform distribution of users in LEO satellite footprints due to geographical and climatic constraints, some ISLs are expected to be heavily loaded with data packets while others remain underutilized. To overcome this problem, routing solutions should distribute the traffic in a balanced way over LEO constellations. We classify the load balancing routing algorithm over LEO constellations into three categories: Centralized algorithms, Distributed algorithms and Quality of Service aware algorithms.

1) Centralized Load Balancing Routing Algorithms: In centralized load balancing routing algorithms the routing table calculation is done at a central node and then pushed onto the LEO satellite nodes. This central node can be a satellite or terrestrial node. We can consider optimal routing algorithm in this context because by performing routing at a central node, better traffic engineering can be maintained using the global view of the whole network. However, the main drawback in this routing scheme is the scalability due to the capacity limits of the central node. In this routing scheme, computational complexity can be carried out at a ground node that does not suffer from power limits, but the high signaling requirement and the challenging of accurately sending traffic information make this approach difficult to apply. Furthermore, as the network size increases, the computational complexity increases at the central node.

A typical example of the centralized approach is LAOR, the location assisted on-demand routing protocol for LEO satellite networks[4]. LAOR can be viewed as a variant of the ad-hoc on-demand distance vector (AODV)[5] routing algorithm, adopted to the requirements imposed by the characteristics of LEO satellite networks. The main goal of the LAOR is to minimize the end-to-end delay and delay jitter and does this by taking into account the queueing delay in addition to the propagation delay. Depending on the information gathered from the whole network, a designated central node performs the LAOR algorithm. However, in an effort to limit the signaling overhead, LOAR limits the scope of route request control packets (RREQLs) to a specific area between the source and destination. However, this can lead to higher congestion in this particular area resulting in a drop in performance under high loads.

2) Distributed Load Balancing Routing Algorithms: LEO satellites provide low propagation delay with the potential to support real time communication. However, most hot spots are located on the Northern Hemisphere, especially within the scope of 50°N [6]. Satellite systems have to face a challenging scenario where some of their satellites are congested while others are underutilized. Without an efficient routing algorithm, this unequal distribution of network traffic will lead to significant queueing delays and large number of packet drops in the high traffic concentration areas. Using a distributed schemes, satellites avoid congestion independently, thus can provide faster reaction to traffic changes when compared with the centralized counterparts.

T.Taleb et al. [7] claim that a better load balancing may be achieved if a congested satellite sends a signal to its neighboring satellites to decrease their sending rates, and its neighbors search for alternate paths. This method reduces the packet dropping probability. However, this method is not safe from signaling congestion due to feedback packets (even though signaling packets are sent only when it is necessary, they could be required very frequently in some conditions). In [8], the authors show a new ISL cost modification factor that considers both, the periodic topological changes as well as the geographic characteristics of traffic distribution on Earth. In order to achieve the load balancing routing, an optimized load balancing routing based on agents (OLBR) is presented for LEO satellite networks wherein mobile and stationary agents cooperate to create the routing table. Stationary agents perform ISL cost estimation and routing updates on satellites, while mobile agents gather local information of visited satellites, such as ISL cost, identifier and latitude. OLBR uses only the local traffic information, which might not reflect the entire traffic distribution. While it is possible to distribute the local information to the whole constellation and use it in local next-hop decisions this will cause extensive signaling overhead.

3) QoS Aware Load Balancing Routing Algorithms: The development trend of next generation LEO satellite network is supporting various service demand and multimedia services (video, voice, data, etc.). So QoS guarantee is one target of routing design in LEO satellite networks, which is difficult in connectionless networks because of the difficulty in accounting for the delay aspects of Quality of Service and sequencing. However, in connection-oriented networks the QoS guarantee are provided. Due to high mobility in LEO satellite constellation, it is difficult to attain path connectivity. So it is important to reduce the number of rerouting probability to very low level to achieve an acceptable QoS guarantee.

Rao et al. [6] propose a traffic class dependent routing algorithm. Three traffic classes are considered: delay sensitive application, bandwidth sensitive application and best effort application. The routing algorithm behaves differently for each class of the traffic. Each LEO satellite node has three separate outgoing queues (one for each traffic class), serving each outgoing ISL. Also, each satellite is equipped with a traffic class identifier to discriminate traffic classes from each other. In this kind of routing algorithm the selection of the traffic class identifier has a large impact on the routing performance of a particular traffic class. The traffic class dependent routing algorithm attempts to guarantee QoS for different routing classes. However, it may assign a single route for specific class with high data traffic and may heavily overload the chosen path. This may affect the traffic distribution over the entire LEO constellation. Therefore, further work is required to choose the suitable class identifier.

B. Handover Optimized Routing Algorithms

LEO satellites have an orbital period of the order of 100 minutes to orbit the earth, which means that a single satellite is “in view” of ground equipment for only a few minutes. As a consequence, if a transmission takes more than the few
minutes that any one satellite is in view, a LEO satellite system must hand over between satellites in order to complete the transmission. Moreover, because of the possibility of resource unavailability in alternate paths and the delay caused by rerouting, the forced termination probability of ongoing connections is increased. Chen et al. [9] consider minimizing handovers in their proposed routing scheme. Among the set of paths that satisfy the QoS requirements, a path that can minimize the possible number of handovers and that also is not inferior to the best possible path with a predefined degree is selected. Future LEO satellite communication networks are devoted to high quality diversified transmission service and less system handover. In view of the above situations, routing algorithm with minimizing links handover and handover delay time is needed.

C. Hierarchical Routing Algorithms

Hierarchical (multi-layered) satellite architectures were proposed in the recent past as a practical architecture for next generation satellite networks. Multi-Layer Satellite Networks (MLSNs) are constructed by integrating several satellite networks within a hierarchical structure. The MLSNs aim to reduce the computational complexity on the satellites, the communication load on the networks, and enable better adaptation to traffic changes. Recently, an innovative communication technology based on high-altitude platforms (HAPs) has gained traction as it preserves many advantages of both terrestrial and satellite systems while also providing unique advantages of its own. These platforms are positioned at an altitudes of 22 km and have the potential to deliver broadband services cost effectively. Compared with satellites that are difficult to upgrade, HAPs cost are relatively inexpensive can be easily relocated based on needs and due to their smaller footprints scale better. HAPs are considered nowadays as a substantial part of the future integrated terrestrial/satellite networks for providing wireless communication services. In addition, HAPs may be used in other applications such as disaster monitoring and mitigation and global positioning [10].

Fig. 2 depicts a multi-layer architecture. In [11], a three layered satellite architecture. Traffic is usually differentiated based on the distance between the source and the destination satellite. For routing purposes, LEO satellites covered by a MEO satellite belong to the same domain. For the intra-domain communication, packets are transferred only through the links between LEO satellites. For the inter-domain communication, packets are transferred via the MEO layer. In the proposed routing algorithm, short distance dependent traffic is transmitted through lower layer satellites while long distance dependent traffic is transmitted through inter-orbital links (IOL) up to the MEO layer to minimize the average number of satellite hops and resource consumption. One of the main drawbacks of the MLSN is that, when a high layer satellite establishes a link with low layer satellite that is in sight, it needs more link transceiver equipment. This increases the difficulty for the satellite design, and the structure of multi-layer satellite network is complicated. In addition, with MLSN, a path from source to destination can cross several layers so that the path calculation becomes more complex.

D. Multicast Routing Algorithms

Routing in multicast is to deliver information to a group of nodes at different locations simultaneously with efficient strategies. This provides a tremendous amount of savings in bandwidth when compared to traditional unicast transmissions which sends messages to multiple nodes through replication of the message to each node. Multicast routing algorithm over LEO satellites has become a very active research topic as it gives the ability of LEO satellites to broadcast large amounts of data over a very wide area. Current multicast routing schemes are not suitable for LEO satellite networks because they employ some type of message exchanges to form or maintain the multicast tree. Applying such schemes to rapidly and regularly changing LEO satellite network is not favorable due to the physical limitations of LEO satellites. In [12], the algorithm is based on the virtual node concept, which we covered previously. This algorithm must has the information of all the multicast users before constructing the multicast tree, and their multicast tree is constructed on the virtual static topology, which makes their signaling and memory overhead very high.

There are several issues in multicast routing over LEO satellite networks that remain open: construction of multicast tree suitable for LEO satellite topology, how to merge differentiated services and multicast technology, issues such as the QoS protocols for members joining and leaving trees, and optimal path selection.

IV. FUTURE DIRECTIONS FOR LEO SATELLITE NETWORKS

A. Beyond the Niche

The success of next-generation LEO satellite networks hinges on their ability to be an integral part of the future global telecommunication infrastructure rather than individual entities. LEO satellite constellations are successful because of their large coverage area, which can become a crucial added value to the global telecommunication networks. Niche areas like coverage of oceans will persist. But elsewhere convergence
of cables, mobile and broadcasting will dictate that the only way for ahead for LEO satellites is in an integrated format with terrestrial networks. IPv6 is the next generation Internet preferred protocol architecture for replacing IPv4. To support the integration of LEO satellite and terrestrial networks, the usage of IPv6 seems to be very appropriate in IP/LEO satellite networks. It provides broader innovation space for design of mobile routing. As a developing protocol system, the research of IPv6 over LEO constellation is not hindered by the operation conditions of the current LEO network. Applying new theories and mechanisms is needed to apply the IPv6 over such constellations. In addition, addressing and routing of IPv6 over LEO constellation need more research on how to apply IPv6 technology effectively for network resources management, deal with mobility, provide IP QoS and support multicast routing.

B. New Hybrid Architectures
LEO satellite networks promise a new era of global connectivity and multimedia services, but also present new challenges to common routing algorithms. Moreover, the constellation containing LEO satellites, MEO satellites and HAPs is the trend for development in the future. Compared to single layer satellite networks, multi-layer satellite networks need more topological management and maintenance. And the multicast routing algorithms for multi-layered satellite networks still is an appealing research area. Nevertheless, it is not easy to offer QoS guarantees over LEO networks without reducing the rerouting probability to very low levels. As mentioned previously, the virtual node concept can be used to remove topology changes. But, this approach also has its drawbacks. Therefore, the virtual node topic requires further studies.

C. Cellular: Friend not Foe
The LEO satellite system can still maintain exclusive status in the niche areas, but elsewhere LEO satellites have not been shown to compete well with the cellular network. Thus, the integration between terrestrial in urban/ suburban areas and LEO satellite in rural areas is logical. This would point that the cognitive radio networks are an outstanding solution to improve efficiency of using spectrum in LEO satellite networks. Secondary users in cognitive networks may select from a set of available channels to use provided that the occupancy does not affect the prioritized primary users. However, cognitive radio over LEO satellites produce unique routing challenges due to the high fluctuation in the available spectrum as well as diverse QoS requirements, so thoughts of cognitive radio routing protocols gradually come into research field in LEO networks [13]. In [14] a secondary user can operate at the LEO satellite bands using the cognitive radio principles to avoid the interference with the primary satellite system. The satellite system becomes more intelligent by applying cognitive radio approach in it. It is even possible that the satellite system accesses the band used by another communication system and operates as a secondary user in that band. As the spectrum access is across countries issue like spectrum hacking can take place. Hence the security challenges over LEO routing has to be well studied.

D. New Approaches to Protocol Design
To realize the vision of an LEO satellite-based internet, cross-layer routing algorithm should be taken into account. Since most of the research on LEO communication protocol design so far has followed the traditional layered approach, which was originally developed for wired networks, improved performance in LEO networks can be obtained with a cross-layer design. That is, by violating a strictly layered architecture, especially in harsh environment such as space. For example, the use of link quality information to avoid establishing unstable ISLs will lead for improving routing algorithms in LEO networks. But, unbridled cross layer interactions can cause conflicts or loops, since a small modification in one layer may lead to a series of changes affecting other layers.

Delay tolerant networking (DTN) technology offers a new solution to highly stressed communication environments such as space. So it is becoming a hot research area in wireless computer networks and space communications. The routing algorithms in DTN are generally designed under the assumption of the absence of guarantees about the existence of continuous end-to-end paths between source and destination nodes. The connectivity in the Internet is generally continuous and the propagation delay is very small. This means that changes in network topology can be detected dynamically and communicated to routers in time to correct computed routes before a lot of traffic is misdirected. Reasonably this is also true of terrestrial DTNs, making it logical to use routing protocols such as Probabilistic Routing Protocol using History of Encounters and Transitivity (PROPHET) [15]. But these conditions do not hold in LEO space communications, so the types of routing protocols that work well in the Internet or even in some terrestrial DTNs are of slight utility in LEO satellite network. So new routing algorithms are needed for DTN for LEO satellite communications.

E. Greening Satellites
The LEO satellite network routing strategies are profoundly influenced by the power and onboard processing capability. As more complex processing is carried out on LEO satellites, they consume more power at the cost of the satellite lifetime. So the energy management in LEO satellites is a critical issue that can translate directly into cost savings. Satellites with lower energy requirements requires smaller solar panels, smaller rechargeable batteries, and small antennas. All of the previous reasons translate into weight savings, which will provide economic benefits.

V. CONCLUSION
In this work, we provided a summary of the challenges posed when designing routing for LEO satellite networks and some of the representative solutions proposed in literature. We found that the characteristics of LEO satellite constellation greatly affect the performance of routing. With an eye into the future we described relevant technical issues for use in the next LEO satellite generation network: Reducing numerous losses in handover, providing QoS guarantee, multicast routing performance, cross layer design, multi-layered satellite network. Finally, it is our hope that the findings in this paper may help better understanding of routing over LEO satellite networks while stimulating future work in the area.
REFERENCES


