**INTRODUCTION**

New multimedia services require more cost-effective, high-quality, and high-speed telecommunication technologies. Large-scale deployment of these broadband applications in metropolitan areas with a potentially large number of users is a challenging task for terrestrial technologies. The design and development of NGEO (non-geostationary) satellite communications systems have thus gained tremendous interest during the last few years. Given the recent advances and ongoing improvements in satellite technologies, broadband satellite-based multimedia services are likely to open a promising and strong market for service providers and operators in the near future.

This article surveys the ongoing research efforts tailored to NGEO satellite communications systems. The remainder of this article is structured as follows. We give a brief description of the general configurations of NGEO satellite constellations. We highlight the key technical difficulties in the development of NGEO IP-based satellite communications systems. The article discusses routing concerns, mobility management, and transport protocols with an emphasis on TCP performance in NGEO satellite networks. Some key innovations are presented. The Recursive, Explicit, and Fair Window Adjustment (REFWA) scheme is presented as a solution to improve the efficiency and fairness of TCP in NGEO systems. An improvement to the REFWA scheme, REFWA Plus, is also described to combat link errors in satellite environments.

**General NGEO Configurations**

Internetworking with satellites began with the use of individual satellites in geostationary orbits (GEO). For more than three decades, GEO satellite systems have been successful in providing commercial services, such as television distribution and long-distance voice telephony. Despite this wide commercial usage of GEO systems, requirements for lower propagation delays, in conjunction with coverage of high-latitude regions, have turned the light on new NGEO satellite communication systems called low Earth orbit (LEO) or medium Earth orbit (MEO) satellite systems. NGEO systems promise to offer services with much lower latency and terminal power requirements than those offered by GEO systems. Table 1 lists some proposed worldwide NGEO constellations and the distinguishing features of their orbits.

Without loss of generality, satellite systems can be classified into two kinds: broadcasting (noninteractive one-way) and interactive bidirectional satellite systems. In a broadcasting satellite system, each terminal has a receive-only satellite dish to collect data delivered from a server in the high-speed satellite channel. Due to the lack of an economical satellite return channel, the reverse path to the server can be provided by a terrestrial link.

Enlightened by the idea of using satellites as a solution of the last mile problem, several com-
Companies have worked on developing return channel technologies for bidirectional interactive satellite systems. These advancements in satellite technologies have been further encouraged by the massive deployment of cost-effective very small aperture terminals (VSATs) and ultra small aperture terminals (USATs). In these systems, terminals are interactive. They are able to directly transmit data up to the satellite and receive data from the satellite.

Most proposed NGEO satellite systems are interactive bidirectional systems. Unlike bent-pipe satellite systems, most of them acquire onboard processing (OBP) and intersatellite links (ISLs) (Table 1). It should be noted that although ISL and OBP technologies enable connectivity in space and make the satellite system flexible, they lead to frequent handover occurrences and, accordingly, complex routing issues, as discussed in the next section.

While NGEO satellite systems can play a major role in providing ubiquitous Internet access, they ought not perform as an isolated network. Instead, they should be integrated with existing terrestrial networks and function as a high-speed backbone network to support and/or back them up. Figure 1 depicts a typical NGEO satellite-terrestrial hybrid system. Terminals within the reach of the ground Internet infrastructure (e.g., terrestrial networks A and B) are connected to the NGEO satellites via gateway stations (GSs). Users outside the reach of the terrestrial network have direct access to the satellites (e.g., users A and B). In addition to satellite-terrestrial hybrid networks, a hybrid GEO/NGEO network consisting of multiple satellite types (GEOS, MEOs, and LEOs) can also be of considerable interest to fully utilize the best characteristics of each orbit type. With respect to bidirectional interactive satellite systems with ISL and OBP technologies, the authors recently proposed a novel satellite constellation based on a set of quasi-GEO satellite systems interconnected via ISL links [1]. The main advantage of the constellation is its ability to provide global coverage with a significantly small number of satellites while at the same time maintaining high elevation angles (Table 1). An architecture based on a combination of this constellation and terrestrial networks was proved to be solid for building a significantly large-scale, efficient, and global video-on-demand system where the service is designated at a hybrid network made of fixed and mobile nodes [2].

**TECHNICAL CHALLENGES**

The recent financial failure of the Iridium system has made researchers realize that systems optimized for only voice or low data rates services may turn out unfavorable. The success of next-generation NGEO satellite networks thus hinges on their ability to provide broadband data rates applications; similar in spirit to today’s Internet. To realize the vision of an NGEO satellite-based Internet, several technical issues should be taken into account.

First, with respect to routing, a detailed description of major routing issues and possible solutions are given. Issues related to mobility management are then discussed. Finally, given the widespread acceptance of the Internet Protocol (IP), advantages and drawbacks of recent inter-working techniques to support IP in NGEO satellite systems are portrayed in detail. Some possible solutions are also suggested.

**ROUTING OVER NGEO SATELLITE SYSTEMS**

Current terrestrial Internet routing protocols, such as Open Shortest Path First (OSPF) and Routing Information Protocol (RIP), rely on exchanging topology information upon a change or setup of a connection; that is, in a connection-oriented manner. Applying such schemes to rapidly and regularly changing NGEO satellite network topologies incurs substantial overhead. Thus, several connectionless algorithms have been proposed to route data traffic over satellite constellations. They can be classified into two categories: constellation periodicity-based routing and onboard routing schemes.

The basic idea behind protocols of the first category is to make use of the periodic and predictable nature of the constellation topology.
<table>
<thead>
<tr>
<th>System</th>
<th>Organization</th>
<th>Constellation type</th>
<th>No. of satellites</th>
<th>Altitude (km)</th>
<th>Min. elevation angle</th>
<th>Coverage (%)</th>
<th>Intersatellite links</th>
</tr>
</thead>
<tbody>
<tr>
<td>NeLS</td>
<td>Japan NiCT</td>
<td>LEO</td>
<td>120</td>
<td>1200</td>
<td>20</td>
<td>79</td>
<td>Yes</td>
</tr>
<tr>
<td>Iridium</td>
<td>Motorola</td>
<td>LEO</td>
<td>66</td>
<td>780</td>
<td>8.2</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>Teledesic</td>
<td>Teledesic Co.</td>
<td>LEO</td>
<td>288</td>
<td>1375</td>
<td>40</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>Globalstar</td>
<td>Global Star Co.</td>
<td>LEO</td>
<td>48</td>
<td>1406</td>
<td>10</td>
<td>83</td>
<td>Yes</td>
</tr>
<tr>
<td>Skybridge</td>
<td>Alcatel</td>
<td>LEO</td>
<td>80</td>
<td>1469</td>
<td>10</td>
<td>86</td>
<td>No</td>
</tr>
<tr>
<td>Celestri</td>
<td>Motorola</td>
<td>LEO</td>
<td>63</td>
<td>1400</td>
<td>16</td>
<td>73</td>
<td>Yes</td>
</tr>
<tr>
<td>Spaceway</td>
<td>Hughes</td>
<td>GEO and MEO</td>
<td>16 GEO 20 MEO</td>
<td>35.786</td>
<td>20</td>
<td>86</td>
<td>Yes</td>
</tr>
<tr>
<td>Quasi-GSO</td>
<td>—</td>
<td>Quasi-GEO</td>
<td>18</td>
<td>35.786</td>
<td>40</td>
<td>96</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Table 1.** Major NGEO satellite constellations.

Various schemes fall into this category. Dynamic Virtual Topology Routing (DVTR) and Virtual Node (VN) protocols are the best known concepts. In onboard routing mechanisms, as the name infers, routing tables are calculated onboard the satellites based on real-time information related to the network state. A number of potential onboard routings have been proposed in the recent literature. While most onboard routing schemes exhibit important adaptive capabilities, they impose significant challenges for space devices in terms of the required computational and processing load. They ultimately question the scalability of their routing tables. Moreover, since these routing schemes focus on only finding paths with the shortest delays, they may become unfavorable for the support of certain QoS requirements. They are appropriate for only best effort light load traffic.

Given the important correlation between efficient routing strategies and support of QoS, tremendous research efforts have been made in recent years with respect to QoS over satellite constellations [3]. The focus of earlier research work was on the integration of dynamic satellite networks with asynchronous transfer mode (ATM). Because of its provision of different levels of QoS guarantees and its concept of the virtual path, ATM was indeed seen as a promising solution for the provision of QoS over mobile satellites. However, the rapid growth of Internet-based applications motivates satellite operators to consider IP traffic as well. For IP-based satellite constellations, a number of interesting solutions have been proposed to provide QoS over satellites. In [4] Donner et al. developed a multi-protocol label switching (MPLS) networking protocol for NGEO satellite constellations. The protocol is still in its infancy, and some important technical problems related to routing and maintenance overhead are still unsolved and deserve further study. Reference [5] proposes, on the other hand, a Traffic Class Dependent (TCD) routing algorithm. Different traffic classes are considered. The protocol differentiates between packets belonging to each traffic class and provides accordingly different levels of services. While the TCD protocol attempts to guarantee QoS for different traffic classes, it may assign a single route for a specific class with huge traffic data and ultimately result in heavily overloading the chosen path. This would intuitively affect the balance of traffic load over the entire satellite constellation.

Another issue common among most conventional routing algorithms is the fact that the route decision is based primarily on propagation delay. Given the fact that queuing delays may also contribute greatly to the total delay a packet may experience, mainly in heavy loads, a more appropriate routing cost metric has to be selected. In this context [6] proposes a Compact Explicit Multipath Routing (CEMR) algorithm based on a cost metric that involves both propagation and queuing delays. At a given satellite, the queuing delay is predicted by monitoring the number of packets in the outgoing queue of the satellite over a time interval. It is assumed that the network state over each time interval is updated before routing calculation is carried out. While the used cost metric gives good insight about the queuing delay that may be experienced by a packet at a given satellite, it does not reflect the congestion state of the next hop, nor does it estimate the queuing delay a packet may experience there. It does not reflect the likelihood of the packet to be dropped by the downstream hop either. To avoid packet drops, traffic should be distributed in a balanced way over underutilized satellites. In this context [7] proposes an Explicit Load Balancing (ELB) routing protocol based on information of traffic load at the next hop on the remainder of the path to the destination. A satellite with high traffic load sends signals to its neighboring satellites, requesting that they decrease their sending rates before it gets congested and packets are ultimately dropped. Neighboring satellites should accordingly respond and search for other alternate paths that do not include the satellite in question. By so doing, the resulting satellite constellation is a better utilized and traffic-balanced network.
It has been widely demonstrated that throughput performance comparison among REFWA Plus, REFWA, TCP Westwood, TCP Newreno, and TCP Reno for different BER values.

**Figure 2.** Throughput performance comparison among REFWA Plus, REFWA, TCP Westwood, TCP Newreno, and TCP Reno for different BER values.

**Mobility Management in NGEO Satellite Systems**

Mobility management is also a core issue in IP/NGEO satellite networks. Mobility management aims to locate mobile nodes and guarantee seamless data delivery. It consists of two procedures: binding update and data delivery. The binding operation aims to associate reachability identity (Reach.ID) and routing identity (Route.ID) of each node. The former indicates a unique name of the node and is not subject to change, whereas the latter specifies the position of the node in the network and changes in response to node movement. When a mobile node changes its position, the Route.ID changes as well, and the old binding is no longer valid. To update the binding, mobile nodes are requested to send their new Route.ID to the Location Directory (LD).

Existing IP mobility management protocols, such as Mobile IP, manage the location of mobile nodes upon every satellite handover occurrence or a slight movement of nodes. Given the high-mobility of both NGEO satellite networks (mainly LEO systems) and end systems, applying current mobility management mechanisms to NGEO satellite networks will result in the generation of a large number of binding update requests, all in a single burst. To process such bursts of binding update requests, a massive amount of network bandwidth and computational load are required. The binding update cost thus becomes extremely huge and the system turns to be unscaleable to operate. Since it is all but impossible to avoid the bursty occurrence of handovers in NGEO satellite networks, mitigation of binding update frequency can be done only by development of new mobility management protocols.

As a remedy to the above issue, the authors proposed a handover-independent mobility management scheme for NGEO satellite networks [8]. The proposed scheme purposes to exploit geographical location information to make the mobility management independent from handovers. In the proposed method, the Earth surface is divided into a number of cells, and the Route.IDs of a mobile node is associated with the cell where the mobile node resides. Mobile nodes are equipped with a Global Positioning System (GPS) receiver to find their location. A Route.ID changes and the corresponding binding update occurs only when a mobile node moves to the neighboring cell. This reduces the number of update requests and eventually increases largely the system scalability [8].

**Interworking Techniques to Support IP in NGEO Satellite Systems**

Due to the universality of IP, an in-depth understanding of IP protocols and recognition of their merits and drawbacks in satellite networks are of vital importance. The effect of such a communication environment on the working of TCP, which forms the backbone of Internet protocol communication, underpins the research work outlined in the rest of this article.

**Issues** — It has been widely demonstrated that current TCP implementations exhibit poor performance in NGEO satellite networks. The performance issues of TCP stem from the inherent characteristics of satellite links, such as long propagation delays1 and high bit error rates (BERs). In the first instance, a TCP sender takes a long time to increase its congestion window during the slow-start phase. Additionally, when multiple connections with high variance in their round-trip times (RTTs) distribution share an intersatellite link, TCP results in drastically unfair bandwidth allocations. This issue becomes more substantial in case of frequent handover occurrences, a general characteristic of NGEO satellite networks. In the second instance a TCP sender operates on the conservative assumption that any segment loss is due to congestion. This assumption ignores the possibility of transient random errors that may be due to atmospheric factors. TCP is usually incapable of detecting the nature of the error, only its result. When an error occurs, a TCP sender backs off its transmission rate and then applies a gradual increase to its reduced window size. While this backoff strategy avoids overloading the network with packets, it comes at the cost of significantly degraded goodput in case of link errors.

**Coping with Delay Related Issues** — To cope with the negative impact slow start has on the TCP performance in NGEO systems, the congestion window is initially set to a value larger than one packet but smaller than four packets in size. Despite the advantages of this operation in improving TCP throughput, there are several problems. Most notably, an increased value of the initial window would increase the burstiness of the sender and could exacerbate existing congestion in a network. Reference [9] has investigated the usage of low-priority dummy segments to probe the availability of network resources without carrying any new information to the sender. Other researchers have discussed the

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1 It should be noted that while NGEO (LEO or MEO) satellites exhibit shorter delays than do GEO satellites, a connection between two end terminals of an NGEO constellation may experience larger delays when the connection path traverses multiple ISL links.
potential of a technique called TCP Splitting based on Performance Enhancing Proxies (PEP) [10]. In this technique a router near the TCP sender prematurely acknowledges TCP segments destined for the satellite host. This operation gives the source the illusion of a short delay path, speeding up the sender's data transmission.

In standard TCP, network congestion is communicated to TCP sources via implicit signalings such as acknowledgment (Ack) packets and duplicate Ack (DupAck) packets. To communicate with explicit signaling of network congestion, several Active Queue Management (AQM) schemes such as Random Early Marking (REM) and Random Early Discard (RED) combined with Explicit Congestion Notification (ECN) have been proposed. These policies require a packet loss to create an early signal of network congestion to TCP sources. However, in the case of large delay links (e.g., satellite links), these policies become inefficient and may still cause timeouts forcing TCP senders to invoke the slow-start phase. Indeed, by the time the source starts decreasing its sending rate because of a packet loss, the network may already be overly congested. To cope with such a limitation, network policies become inefficient and may still cause TCP senders to invoke the slow-start phase.

Upon reception of a normal Ack packet, a TCP sender records the feedback value as \( \Phi_{\text{NorAck}} \). If the feedback does not increase the computed feedback rate, the sender retransmits the lost packet. The main drawback of this protocol is that it assumes a pure XCP network and requires significant modifications at the end-systems. Explicit Window Adaptation (EWA) [12] suggests an explicit congestion control scheme of the window size of TCP connections as a function of the free buffer value. Since the computed feedback is a function only of buffer occupancy and does not take into account link delay or link bandwidth, the scheme is likely to run into difficulty when faced with high bandwidth or large delay links, similar to AQMs.

In the sphere of TCP behavior under many competing flows in satellite networks, the Recursive Fair Window Adjustment (REFWA) scheme appears to be the first comprehensive work that introduces the idea of explicit signaling and jointly addresses both efficiency and fairness of TCP in NGEO broadband satellite networks [13]. The basic idea behind the proposed mechanism consists in computing the feedback value signaled via a normal Ack, \( \Phi_{\text{NorAck}} \), and comparing the feedback value signaled via theDupAck, \( \Phi_{\text{DupAck}} \), to the most recent feedback value signaled via a normal Ack, \( \Phi_{\text{NorAck}} \). The two values satisfy the inequality

\[
\Phi_{\text{NorAck}} \leq \Phi_{\text{DupAck}}
\]

the TCP sender interprets the incident as a link error occurrence and retransmits the missing packets, all in the current window, without entering the congestion avoidance phase. By so doing, unnecessary decrease of the window size can be prevented. This is based on the fact that a packet drop due to network congestion is likely to be preceded by a decrease in the computed feedback, whereas packet drop followed by increased feedback are likely to be due to link errors. The idea of retransmitting all lost packets in a single window is similar in spirit to the idea of bulk retransmit in the Go-Back-N (GBN) error recovery scheme and has the potential of recovering from lost packets within the same RTT. Bulk retransmit may, however, raise the issue of burstiness at the satellite network. One possible solution to this issue is transmission of lost packets in a steady stream (multiple small bursts) over the entire course of the RTT. To keep the network safe from congestion, each sender sets its congestion window (cwnd) and the slow start threshold (ssthresh) values to its optimal sending rate \( \Phi_{\text{DupAck}} \). On the other hand, in a high BER environment, the Retransmit Timeout (RTO) backoff algorithm used in most TCP variants doubles the RTO value until it is 64 times the original value, leading to significant waste of both bandwidth and time. To overcome long idle waiting times due to large TCP timeouts in the case of high BER environments, RTO is set to a fixed value when the sender classifies the packet loss as a link error. If Eq. 1 does not hold, the sender retransmits the
The idea of retransmitting all lost packets in a single window is similar in spirit to the idea of Bulk Retransmit of the GBN error recovery scheme and has the potential of recovering from lost packets within the same RTT. Bulk retransmit may, however, raise the issue of burstiness at the satellite network.

The ratio of the aggregate throughput of the 10 connections to the bottleneck link capacity.

The design and development of NGEO satellite communication systems have been the subject of extensive research in recent literature and gained tremendous interest even at the commercial level. In this article we address some technical challenges in providing Internet services over satellite communication systems. We discuss issues related to routing and mobility management. To demonstrate how NGEO satellite systems interoperate with IP-based technologies, a special focus was on the working of TCP over satellite networks. Two recently proposed schemes are described: REFWA and REFWA Plus. The REFWA scheme aims to jointly improve both the efficiency and fairness of TCP over satellite networks. The REFWA Plus scheme, on the other hand, further improves the performance of the REFWA scheme by reducing the effect of unnecessary shrinkage of transmission rate due to link errors on system efficiency.

In addition to what we have elaborate on in this article, some other important research issues, such as satellite resource management, QoS support, and IP routing multicast protocols over NGEO satellite networks, are still to be identified and deserve further study. Finally, it is our hope that the findings in this article may help better understanding of NGEO satellite communication systems while stimulating further work in the area.

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Biographies

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