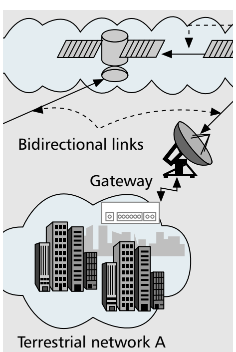
RECENT TRENDS IN IP/NGEO SATELLITE COMMUNICATION SYSTEMS: TRANSPORT, ROUTING, AND MOBILITY MANAGEMENT CONCERNS

TARIK TALEB, NEI KATO, AND YOSHIAKI NEMOTO, TOHOKU UNIVERSITY



Non-Geostationary satellite communication systems are seen as an attractive solution to realize the vision of anywhere, anytime pervasive access to the Internet. Their design and development have thus gained a tremendous interest during the last few years.

ABSTRACT

Non-geostationary (NGEO) satellite communication systems are seen as an attractive solution to realize the vision of anywhere, anytime pervasive access to the Internet. Their design and development have thus gained tremendous interest in the last few years. Commencing with a brief overview of general NGEO satellite configurations, this article next addresses 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.

INTRODUCTION

New multimedia services require more cost-effective, high-quality, and high-speed telecommunication technologies. Large-scale deployment of these wideband applications in metropolitan areas with a potentially large number of users is a challenging task for terrestrial technologies. New Internet infrastructure and technologies are required to accommodate these multimedia services with diverse quality of service (QoS) requirements. Furthermore, appropriate mobility support is also needed to provide ubiquitous Internet access.

Because of their extensive geographic reach, flexible and rapid deployment features, and inherent multicast capabilities, non-geostationary (NGEO) satellite network systems are seen as an attractive solution to realize the vision of a global broadband multimedia infrastructure. 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 issues in the development of NGEO broadband satellite communication systems. We also present some recently proposed solutions to these issues. The article concludes with a summary recapping the most important research issues elaborated on in this article.

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-

1536-1284/05/$20.00

Current terrestrial Internet routing protocols rely on exchanging topology information upon a change or set-up of a connection, that is, in a connection-oriented manner. Applying such schemes to the rapidly and regularly changing NGEO satellite network topologies incurs substantial overhead.

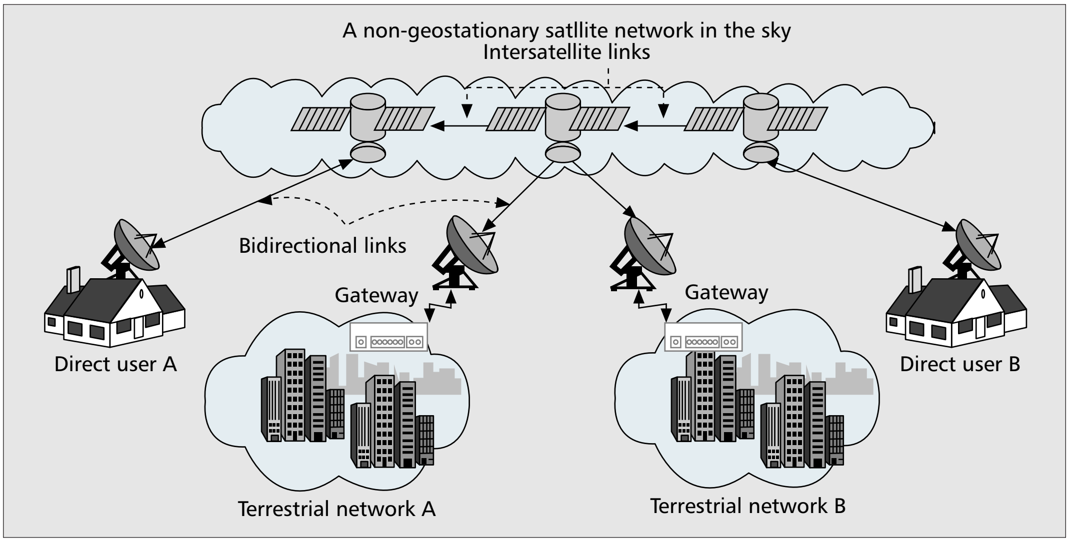


Figure 1. *An example of an interactive bidirectional NGEO satellite system with OBP and ISLs.*

panies 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 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.

System	Organization	Constellation type	No. of satellites	Altitude (km)	Min. elevation angle	Coverage (%)	Intersatellite links
NeLS	Japan NiCT	LEO	120	1200	20	79	Yes
Iridium	Motorola	LEO	66	780	8.2	100	Yes
Teledesic	Teledesic Co.	LEO	288	1375	40	100	Yes
Globalstar	Global Star Co.	LEO	48	1406	10	83	Yes
Skybridge	Alcatel	LEO	80	1469	10	86	No
Celestri	Motorola	LEO	63	1400	16	73	Yes
Spaceway	Hughes	GEO and MEO	16 GEO 20 MEO	35.786 10.352	20	86	Yes
Quasi-GSO	—	Quasi-GEO	18	35.786	40	96	Yes

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 multiprotocol label switching (MPLS) networking protocol for NGEO satellite constellations. The protocol is still in its infancy, and some important practical problems related to rerouting 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 likeliness 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.

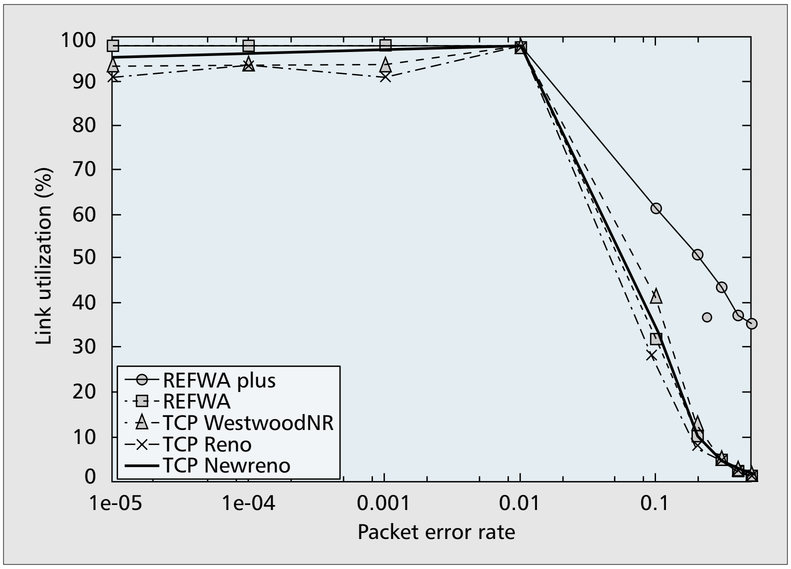


Figure 2. *Throughput performance comparison among REFWA Plus, REFWA, TCP Westwood, TCP Newreno, and TCP Reno for different BER values.*

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 unscalable 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 delays[1] 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

[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 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 elements between a TCP source and a TCP destination should be able to acknowledge the source with its optimal sending rate. In this context, Katabi *et al.* [11] proposed a new congestion control scheme, Explicit Control Protocol (XCP). The scheme substantially outperforms TCP in terms of efficiency in high bandwidth-delay product environments. However, 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, Explicit, and 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 REFWA scheme is to match the sum of window sizes of all active TCP connections sharing a bottleneck link to the effective bandwidth-delay product of the network. The REFWA scheme improves the system minmax fairness by assigning for each flow a weight proportional to its RTT. In a satellite constellation, the REFWA scheme is implemented at each satellite. The REFWA scheme provides each active TCP flow with a feedback proportional to its RTT. The feedback value is the optimum window size at which a TCP sender should send data not to overload the network with packets. Feedbacks are computed periodically to improve system efficiency and fairness. The sum of the feedbacks of all active TCP connections sharing the same bottleneck is equal to the effective network bandwidth-delay product of the bottleneck. A detailed description of the feedback computation method can be found in [13]. Feedbacks are signaled to TCP sources via the receiver's advertised window (RWND) field in the TCP header of Acks. Senders should accordingly regulate their sending rates.

Coping with Link Errors in NGEO Systems — In the absence of a reliable algorithm that can distinguish between congestion and errors, there is a need to find ways to let TCP senders know that segment loss is due to transmission errors, not congestion, and thus they should not reduce their sending rate. Several improvements have been devised in recent literature to overcome such issues. In the remainder of this section we introduce an error recovery mechanism, REFWA Plus [14], which is proposed as an enhancement to the REFWA scheme to avoid the unnecessary shrinkage of transmission rate due to link errors and to further improve the performance of the REFWA scheme. The basic idea behind the proposed mechanism consists in comparing the old and new feedback values signaled by the REFWA scheme to a TCP sender. Upon reception of a normal Ack packet, a TCP sender records the feedback value as Φ_{NorAck}. When the sender receives a DupAck, the sender compares the feedback value signaled via the DupAck, Φ_{DupAck}, to the most recent feedback value signaled via a normal Ack, Φ_{NorAck}. If the two values satisfy the inequality

$$\Phi_{NorAck} \leq \Phi_{DupAck}, \qquad (1)$$

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 drops 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 Φ_{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

In the sphere of TCP behavior under many competing flows in satellite networks, the 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.

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.

dropped packets and reduces its window size to half. In other words, it proceeds in the same way as an ordinary TCP sender. Observe that the proposed operation can be accomplished without changing the protocol and requires merely a simple modification only at the sending terminal.

For the performance evaluation of the REFWA Plus scheme, a simple simulation is conducted using Network Simulator (ns). The satellite network is modeled as a one-network bottleneck shared by 10 connections. The bottleneck link is composed of three satellites. All uplinks, downlinks, and intersatellite links are given a capacity equal to 10 Mb/s. Their delays are set to 20 ms (e.g., Teledesic constellation). In the performance evaluation, TCP Reno, TCP NewReno, TCP WestwoodNR [15], and REFWA are used as comparison terms. The reason behind the choice of the TCP WestwoodNR and TCP NewReno over other TCP implementations underlies the fact that they achieve faster recovery from multiple losses within the same window and have the potential of significantly improving TCP's performance in bursty losses. In each simulation TCP sources adopt the same protocol. We model TCP connections as greedy long-lived FTP flows. Simulations were all run for 120 s, a duration long enough to ensure that the system has reached a consistent behavior. Link errors are randomly derived from a uniform distribution-based loss model, and are applied to uplinks. The loss probability, expressed in packet units and referred to as packet error rate (PER), is varied within the range [10^{-5}; 0.5].

Figure 2 shows the bottleneck link utilization[2] using the five schemes for different BERs. In the figure the link utilization obtained using REFWA Plus is always higher than that obtained in case of REFWA, TCP Reno, Newreno, or TCP WestwoodNR. When the error probability is low, the link utilization of REFWA Plus is the same as that of REFWA. This is due to the fact that packet losses due to link errors are rare, and most of packet drops are due to network congestion. However for higher bit error rates, the REFWA Plus achieves significantly better link utilization than the other schemes. In deed, the link utilization improvement of REFWA Plus over the other four schemes for PER values higher than 10^{-2} is higher than 50 percent. Furthermore, we observe that in significantly higher PER environments (e.g., PER $\geq$ 0.1), the link utilization experienced in case of REFWA, TCP Reno, TCP Newreno, and TCP WestwoodNR is almost null, whereas the REFWA Plus scheme succeeds in making use of more than 35 percent of the network resources.

This good performance is mainly due to the ability of the REFWA Plus scheme to distinguish between packet losses due to link errors and those due to network congestion. The low link utilization of REFWA, TCP Reno, TCP Newreno, and TCP WestwoodNR is due to the fact that senders misinterpret packet losses as network congestion and halve their window sizes sometimes multiple times due to multiple losses within one window of data. Indeed, in heavy errors, ssthresh tends to take values (say one to four packets) significantly smaller than the optimal values. Reducing the cwnd to the ssthresh value, as in standard TCP, drastically throttles TCP throughput. The throughput degradation becomes more significant as the idle waiting time becomes longer due to the RTO backoff algorithm. On the other hand, with REFWA Plus TCP senders keep on transmitting data more aggressively at cwnds equal to Φ_{DupAck}. Although many packets get lost on the way because of link errors, some manage to reach the destination. This explains the 35 percent utilization experienced with REFWA Plus.

[2] *The ratio of the aggregate throughput of the 10 connections to the bottleneck link capacity.*

Concluding Remarks

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.

Acknowledgment

The authors take great pleasure in acknowledging the financial aid of the Koden Electronics Co., Ltd. to conduct part of this research work.

References

[1] T. Taleb *et al.*, "A Geographical Location Based Satellite Selection Scheme for a Novel Constellation Composed of Quasi-Geostationary Satellites," *Proc. ICC 2005*, Seoul, Korea, May 2005.

[2] T. Taleb, N. Kato, and Y. Nemoto "On-Demand Media Streaming to Hybrid Wired/Wireless Networks over Quasi-Geo Stationary Satellite Systems," *Elsevier J. Comp. Net.*, vol. 47, no. 2, Feb. 2005. pp 287–306.

[3] A. Molinaro *et al.*, "A Scalable Framework for End-to-end QoS Assurance in IP-oriented Terrestrial-GEO Satellite Networks," *IEEE Commun. Mag.*, vol. 43, no. 4, Apr. 2005, pp. 130–37.

[4] A. Donner, M. Berioli, and M. Werner, "MPLS-Based Satellite Constellation Networks," *IEEE JSAC*, vol. 22, no. 3, Apr. 2004, pp. 438-48.

[5] A. Svigelj *et al.*, "Routing in ISL Networks Considering Empirical IP Traffic," *IEEE JSAC*, vol. 22, no. 2, Feb. 2004, pp. 261–72.

[6] B. Jianjun *et al.*, "Compact Explicit Multi-path Routing for LEO Satellite Networks," *Proc. 2005 IEEE Wksp. High Perf. Switching and Routing*, Hong Kong, P.R. China, May 2005.

[7] T. Taleb *et al.*, "IP Traffic Load Distribution in NGEO Broadband Satellite Networks," *Proc. 20th Int'l. Symp. Comp. and Info. Sci.*, Istanbul, Turkey, Oct. 2005.
[8] H. Tsunoda *et al.*, "Supporting IP/LEO Satellite Networks by Handover-Independent IP Mobility Management," *IEEE JSAC*, vol. 22, no. 2, Feb. 2004, pp. 300–07.
[9] I. F. Akyildiz, G. Morabito, and S. Palazzo, "TCP-Peach: A New Congestion Control Scheme for Satellite IP Networks," *IEEE/ACM Trans. Net.*, vol. 9, no. 3, June 2001.
[10] M. Marchese, M. Rossi, and G. Morabito, "PETRA: Performance Enhancing Transport Architecture for Satellite Communications," *IEEE JSAC*, vol. 22, no. 2, Feb. 2004, pp. 320–22.
[11] D. Katabi, M. Handley, and C. Rohrs, "Congestion Control for High Bandwidth-Delay Product Networks," *Proc. SIGCOMM*, 2002.
[12] L. Kalampoukas, A. Varma, and K. K. Ramakrishnan, "Explicit Window Adaptation: A Method to Enhance TCP Performance," *IEEE/ACM Trans. Net.*, vol. 10, no. 3, June 2002.
[13] T. Taleb, N. Kato, and Y. Nemoto, "An Explicit and Fair Window Adjustment Method to Enhance TCP Efficiency and Fairness over Multi- Hops Satellite Networks," *IEEE JSAC*, vol. 22, no. 2, Feb. 2004, pp. 371–87.
[14] T. Taleb, N. Kato, and Y. Nemoto, "REFWA Plus: Enhancement of REFWA to Combat Link Errors in LEO Satellite Networks," *Proc. 2005 IEEE Wksp. High Perf. Switching and Routing*, Hong Kong, P.R. China, May 2005.
[15] S. Mascolo *et al.*, "TCP Westwood: Bandwidth Estimation for Enhanced Transport over Wireless Links," *Proc. ACM SIGMOBILE 2001*, Rome, Italy, July 2001, pp. 287–97.

BIOGRAPHIES

TARIK TALEB (taleb@nemoto.ecei.tohoku.ac.jp) is currently working as an associate researcher with the Intelligent Cosmos Research Institute, Japan. He received his Ph.D., M.E., and B.E. degrees with distinction in computer sciences from the Graduate School of Information Sciences, Tohoku University, Japan, in 2005, 2003, and 2001, respectively. His research interests lie in the fields of wireless networking, intervehicular communications, satellite and space communications, congestion control protocols, and network security. His recent research has focused on on-demand media transmission in multicast environments and mobility management.

NEI KATO [SM] (kato @nemoto.ecei.tohoku.ac.jp) received his M.S. and Ph.D. degrees from the Graduate School of Information Sciences, Tohoku University, in 1988 and 1991, respectively. He has been working for Tohoku University since then and is currently a full professor at the Graduate School of Information Sciences. He has been engaged in research on computer networking, wireless mobile communications, image processing, and neural networks. He is a member of the Information Processing Society of Japan. He has served on the technical program and organizing committees of a large number of international conferences.

YOSHIAKI NEMOTO [SM] (nemoto@nemoto.ecei.tohoku.ac.jp) received his B.E., M.E., and Ph.D. degrees from Tohoku University in 1968, 1970, and 1973, respectively. He is a full professor with the Graduate School of Information Sciences, and served as director of the Information Synergy Center, Tohoku University. He has been engaged in research work on microwave networks, communication systems, computer network systems, image processing, and handwritten character recognition. He is a co-recipient of the 1982 Microwave Prize from the IEEE Microwave Theory and Techniques Society. He is a member of IEICE, and a fellow of the Information Processing Society of Japan.

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, improves the performance of the REFWA scheme.