Draft, published in Proc. of. IEEE 6th Intern. Symp. of Computer Networks (ISCN'06), June 14-16, 2006- Istanbul, Türkiye.

VoIP Performance in Multi-layered Satellite IP Networks with On-Board Processing Capability

Suzan Bayhan†, Gürkan Gür, and Fatih Alagöz
SATLAB, Dept. of Computer Engineering, Boğaziçi University, TURKEY
{bayhan, gurgurka, alagoz}@boun.edu.tr, †Corresponding author

Abstract— **In this study, Voice over IP (VoIP) performance in multi-layered satellite IP networks with on-board processing (OBP) capability is investigated. With on-board processing, a satellite can process the received data, and according to the nature of application, it can decide on the transmission properties. Specifically, considered OBP includes error-correcting coding to combat adverse channel conditions and priority queueing mechanisms for efficient use of the system resources. After a brief overview of relevant aspects of satellite networks to VoIP, VoIP performance for Non-Geostationary Earth Orbit (NGEO) single layer and multi-layered constellations are examined using a network simulation tool. The outcome of these simulations justifies the premise for the multi-layered architecture for delay-sensitive and real-time traffic such as voice. Subsequently, the effects of some quality-of-service (QoS) mechanisms in multi-layered architecture are tested using various simulation parameters. The system simulation verifies that multi-layered satellite networks with OBP capabilities and QoS mechanisms are essential for feasibility of packet-based high quality voice services which are vital components of next-generation communications networks.**

I. INTRODUCTION

VoIP services have become popular in the last decade, because of their cost effectiveness and simultaneous voice-data transmission in a single session. Satellites offer mobile and fixed services with high bandwidth and global coverage which make their usage quite attractive for telecommunications. Combining these two technologies results in state-of-the-art and efficient systems. New generation satellites, rather than old-fashioned “bent pipes”, can achieve on-board processing resulting in faster service and higher performance at the cost and complexity trade off. With the deployment of third-generation (3G) and advent of fourth-generation (4G) networks, these capabilities will be crucial for better services and help the implementation of “ubiquitous and pervasive communications” concept.

This paper discusses VoIP performance issues in multi-layered satellite IP networks with on-board processing capabilities. Performance is an important consideration of a system which renders it accepted or declined by the users. Therefore, parameters affecting the performance should be elaborated. Since voice applications are real-time applications, delay and delay variation are key parameters for the system performance. To achieve an intelligible communication, delay must be restricted to some certain values specified by the authorities (such as ITU and ETSI). For satellite networks, the significance of delay becomes more apparent where one way satellite latency is about 250–280 ms [1] for geostationary orbit (GEO) satellites. The orbit of satellite - low-earth orbit (LEO), medium-earth orbit (MEO) or GEO - affects the propagation delay, therefore the overall system performance [2]. In this study, single layer and multi-layered satellite systems, consisting of LEO and MEO, are taken into consideration. On-board processing which includes the OSI layer 1, 2 and 3 functions improves the performance of the application and tries to ensure the proposed quality. Therefore, it is crucial for any QoS-aware integrated satellite architecture. We examine VoIP performance for NGEO single layer and multi-layered constellations using a network simulation tool. The outcome of these simulations justify the premise for the multi-layered architecture for delay-sensitive and real-time traffic such as voice. Subsequently, the effects of some QoS mechanisms, namely priority queueing and error-correcting-coding (ECC), in multi-layered architecture are tested using various simulation parameters.

The paper is organized as follows: The next section presents a brief overview of VoIP and satellite networks. In Section III, the simulation setup and scenarios are described. The relevant experimental results are provided in Section IV. Finally, we conclude with discussions in Section V.

II. VOIP AND SATELLITE NETWORKS

In this section, we provide a brief overview of two relevant aspects of satellite networks to VoIP: multi-layered constellations and on-board processing.

A. *Multi-layered NGEO Satellite Networks*

The majority of satellites currently in operation are placed in GEO orbit. The GEO satellite is 35,786 km above the equator, and its revolution around the Earth is synchronized with the Earth’s rotation. While GEO satellite has the advantage of very large coverage area, it also has some drawbacks such as high orbit lift costs, requirement for large antennas and high transmission powers and, most significantly, the large propagation delay. The typical value of end-to-end propagation delay is 250-280 ms, which is undesirable for real-time traffic.

MEO’s distance from the Earth’s surface is from 3000 km up to the GEO orbit with a typical end-to-end propagation delay of 80-100 ms [3]. LEOs are located 200-3000 km above the Earth’s surface. For a LEO satellite the end-to-end delay is 20-25 ms, which is comparable to that of a terrestrial link. Since LEO/MEO satellites are closer to the Earth’s surface, the necessary antenna size and transmission power level are much smaller; but their footprints are also much smaller. A constellation of a large number of satellites is necessary for global coverage. The lower the orbit altitude, the greater the number of satellites required. In addition, since satellites travel at high speeds relative to the Earth's surface, a user may need to be handed off from satellite to satellite as they pass rapidly overhead [4].

When it comes to service delivery, each type of satellite orbit has its own set of drawbacks and advantages. For instance, in very simplistic terms, the geostationary orbit could be considered to be more suited to the provision of regionally deployed, non-delay sensitive services, whereas the low Earth orbit in comparison may be better suited for global, real-time service delivery [5]. Therefore, multi-layered satellite architectures with inter-orbital links (IOLs) between layers of satellite constellations, i.e. hybrid constellations, are of much interest as they yield much better performance than individual layers. For instance, in [6], a three-layered architecture consisting of GEOs, LEOs and high altitude platforms (HAPs) is proposed. GEOs act as backbone routers, LEOs as the second layer and HAPs to cover special areas with high and sensitive traffic such as battlefields and disaster areas. In [7], the simulation studies deduce that Satellite over Satellite (SOS) networks have better performance than that of Flat Satellite Networks (FSN).

B. *On-board Processing (OBP)*

On-board processing is a general term that refers to signal processing and routing functions implemented on-board the satellite that go beyond the amplification and frequency conversion performed in conventional, transparent satellite systems. The OBP in satellites eliminates the inherent disadvantages of the *"bent pipe"* transponders. The main advantages of satellite systems with OBP are: improved link quality with respect to transparent systems due to signal regeneration on board, efficient bandwidth and power level control by multi-beam frequency re-use which increases satellite raw capacity, discarding empty uplink time slots resulting in increased efficiency of downlink transmission, dynamic reallocation of unused bandwidth, asymmetric uplink and down link bandwidth to take advantage of traffic statistics, on-orbit management of network traffic, capacity and QoS, statistical multiplexing which supports varying degrees of bursty traffic, direct interconnections between user terminals through on-board switching [8], [9]. OBP can support high-capacity inter-satellite links (ISLs) connecting two satellites within line of sight. Switches in the satellites provide short latency and thus improve the quality of service (QoS) with regard to systems using hub stations on ground. By using a sophisticated constellation with ISLs, connectivity in space without any terrestrial resource is possible. This feature enables far more autonomous satellite networks which may be imperative especially for military purposes and post-disaster-communications situations, where ground facilities may become potential targets or be damaged. These benefits, however, demand payloads with higher complexity [8]. With more advanced and powerful integrated circuitry and microelectronics, OBP has become more feasible and sensible cost-wise. Thus it has the potential for enabling satellite networks to cope with the inherent propagation delay obstacle [10] and contribute to the performance of VoIP applications over satellite networks.

III. SIMULATION SETUP AND SCENARIOS

In our simulations, we consider a two-layered satellite network of LEO and MEO satellites and terrestrial gateway stations. This scenario may be valid for various situations such as an 802.16 WiMax access node serving a business district or research center with a direct satellite link to an integrated network service provider. Obviously, our scenario necessitates the differentiation of voice packets over other, briefly less QoS-sensitive, packet types. However, integration and deployment of QoS frameworks such as IntServ and DiffServ are beyond the scope of this work. Baseline Dijkstra's shortest path algorithm is employed for routing in the simulations. In the NGEO satellite network, location (and handoff) managements are significantly more complex than the terrestrial counterpart. Due to the continuous motion of NGEO satellites, their footprints change frequently and the location of the satellites relative to one another changes as well [3]. Previous work on that particular issue can be found in [4], [7], [11].

Most of the studies in the field such as [12]–[15], consider the system as a union of states at sufficiently small time intervals. System period T_s is the lowest common multiple of the satellite layer's orbital period and the Earth's period. This period is divided into small time intervals at which system topology is regarded as static. In this way, changing topology of the network is reduced to problem of managing states in T_s that is periodic. We also divide the constellation period into small time slots.

In this study, OPNET Modeler 10.5A [16] is used to model and simulate the network. The performance metrics are delay and jitter of each traffic type, and overall packet loss. The generally-accepted limit for good-quality voice communication delay is 150 ms end-to-end. End-to-end delay is basically composed of link, processing and queueing delays. Propagation delay is the most noticeable component of the link delay. However, in some heavily loaded links, processing delay and queueing delays may become larger. Delay values experienced by real-time and non real-time traffic are recorded under following described conditions. Effects of ECC and priority-based queueing on VoIP performance in multi-layered satellite networks have also been investigated. Three scenarios have been studied: Base scenario, scenario with weighted round robin queueing and scenario with error-correction-coding. In the base scenario, in order to compare the performance of multi-layered satellite networks to conventional single plane satellite networks, three simulation subcases are modeled. In the first subcase, an Iridium-like LEO satellite constellation is set up. In the second subcase, ICO system parameters are utilized to form a MEO constellation. Finally, two-layered satellite constellation is simulated. Queueing and ECC scenarios are based on two-layered satellite constellation. In the further sections, each scenario components and system properties are analyzed in details and relevant results are presented.

A. Base Scenarios

1) LEO constellation: In this setup, there are 66 LEO satellites distributed in 6 planes each consisting of 11 satellites. Satellites are identified by their numbers between 1-66. Each LEO is connected to two neighbors in the same plane and two other satellites in the neighboring planes by inter-satellite links (ISL). Gateway stations (GS) are directly connected to satellites via user data links (UDL). The world is divided into 6 coverage areas corresponding to each LEO plane footprint. There are 44 GSs in each region. Although the world's population, its distribution and communication patterns imply nonuniform traffic density in practice, this nonuniformity is not taken into consideration to keep scenarios simple and easy to manage. VoIP traffic patterns are created as duplex and symmetric voice communication streams. For a more realistic modeling, GSs generate also background data traffic.

Traffic source generators are based on the conventional Poisson generation process, with exponentially distributed interarrival times. Packet length is also exponentially distributed with a mean value of 1000 bytes. The capacity of all UDLs, intra and inter-plane ISLs, and IOLs are chosen as 80 Mbps. Furthermore, each outgoing link has been allocated a buffer space of 5MB. Buffer space corresponds to 5000 packets as opposed to 10000 packets/s capacity of links. Three different traffic types are modeled: short distance, long distance and random traffic. In short distance communication, each GS is in communication with another GS in close vicinity, in other words both stations are in the footprint of the same LEO. Long distance communication represents long-haul or intercontinental communication. Random communication case allows random pairs of GSs to have voice and data sessions.

When the scenario starts running, GS source-destination pairs are uniformly chosen and they generate packets for the entire duration of simulation. A GS sends packets to the corresponding LEO in sight. After LEO receives a packet, it checks the destination address to see if it is in footprint. LEOs are assumed to have knowledge about the network topology, each LEO is aware of GSs in its own footprint and also the other satellites' footprints. This information can be updated to all satellites by some special terrestrial stations or satellites can form overall network topology by some signalling exchange. If GS is in the coverage of the LEO, packets are forwarded directly to the destination GS. If not, LEO knows which is the corresponding LEO that has the destination in coverage. Since a LEO has direct communication links to only four neighboring satellites, it can route the incoming packet through one of these outgoing links. Determining the outgoing link depends on the destination satellite. Optimal shortest paths are determined using Dijkstra's Shortest Path Algorithm. Intra-plane ISL delay values are always fixed and can be calculated using Equation 1. However, the length of inter-plane ISLs are variable and thus, the propagation delay on them is changing all the time in company with the constellation [17]. There are 11 satellite delay groups alternating between 10 ms near polar regions and 29 ms near equatorial region.

$$delay_{intra-plane} = 2 \times \frac{sin(\frac{\pi}{n_{sat}}) \times (R_{Earth} + h_{sat})}{c} \quad (1)$$

R$_{Earth}$: Radius of Earth- 6378.137 km
h$_{sat}$: Height of Satellite above Earth
n$_{sat}$: Number of satellites in a plane
c : Speed of light - 300.000 km/sn

2) MEO constellation: In this scenario, ICO is chosen as reference MEO constellation. There are 10 MEO satellites in 2 planes in ICO's constellation. Actually, ICO satellites are bent pipe satellites, but in our case, they have inter-satellite links with the neighboring satellites. Like LEO satellites considered in previous case, each MEO satellite has four ISLs- two inter-plane and two intra-plane. Similarly, two routing tables are used for inter-plane and intra-plane routing. Dijkstra's Shortest Path Algorithm is used also in this scenario.

3) Two-layered NGEO satellites constellation: Multi-layered satellite network, taken as reference constellation in our paper, consists of two satellite layers, LEO layer in the lower part and MEO layer at the top. LEO layer has the same constellation properties defined in the first scenario. MEO layer constellation is slightly different than only MEO satellite constellation case defined in the previous section. There are 6 satellites in MEO layer divided into two MEO planes, achieving global coverage. There are 3 MEOs in each MEO plane. LEO satellites in the footprint of MEO_i form a group and this LEO group is shown by LG_i. MEO_i is named as *"group manager"* and shown by GM_i. Each group has only one GM and all group members are aware of their GM. Actually a LEO might be covered by more than one satellite, but we assume that the MEO with the longest service time (depending on the satellite calendar) is designated as GM. There are ISLs among each MEO pairs. Previously mentioned LEO ISLs are still valid. Moreover, LEOs are also linked to their MEO group managers by IOLs. There are no direct links between GS and MEO, and GSs can communicate only with LEOs.

Routing strategy is now different than the previous cases. Voice packets are classified by the source LEO satellites according to the distance between the source satellite and the destination satellite. A path is assigned for each packet by the source LEO using the routing table. Shortest propagation delay path is calculated using Dijkstra's Shortest Path Algorithm. Minimum delay paths are accepted as optimal paths.

If the calculated path's delay is greater than threshold delay D$_{thrsh}$, then this voice packet is marked as *Long Distance Voice* (LDV). Otherwise, it is *Short Distance Voice* (SDV) packet. In [7], packets are classified according to the calculated path's hop count. Since ISL lengths are noticeably different from each other at different parts of the Earth i.e. at polar regions and Equator, hop count does not reflect the real delay values. Hence, we base our marking scheme on ISL delays rather than hop count of the path. Initially, SDV and *background* (non-real time traffic) packets are forwarded to the next hop of the calculated path on the LEO layer. LDV

traffic is forwarded by the source LEO to its GM. After getting the packet, MEO assigns a new path and forwards the packet to the next hop either in MEO layer or LEO layer. If the destination LEO is in its managed LEO satellite group, it directly sends packet to the destination LEO. If it is in one of other MEOs' coverage, it forwards the packet to the corresponding MEO. Using the MEO layer especially for time-sensitive traffic allows the system to meet two goals simultaneously: balance the link utilization rates and prevent excessive jitter and delay values. Depending on the values of D_{thrsh}, SDV and LDV traffic percentage will change and therefore load on LEO layer will change in return. This interaction makes determining D_{thrsh} value a design issue. In the experiments, effect of changing D_{thrsh} value is also analyzed. Table I summarizes the system parameters of the two-layered satellite network simulated in our studies. Simulations are run for 50 seconds. Moreover, system period T_s is assumed to be 50 seconds. System time interval is 5 seconds. At the beginning of each time interval, routing tables, ISL delay values and GS-LEO pairing information are updated to simulate the dynamic network topology.

TABLE I
LEO/MEO PARAMETERS

	LEO	MEO
Altitude	1200 km	10390 km
Number of satellites	66	6
Number of planes	6	2
Number of ISLs	4	5
Number of IOLs	1	11

B. Scenario II - Priority-Based Weighted Round Robin Queueing (WRRQ)

Delay and jitter sensitive voice traffic must be differentiated from delay tolerant background traffic. Due to satellites' processing limitations, queueing policy must be both simple and fast. Weighted Round Robin Queueing (WRRQ) is quite efficient for on-board processing in that sense. Strict priority may be an alternative policy. However, this policy leads to suffering of data packets of high delay values and may cause "starvation" anomaly. In this scenario, LEO satellites apply round robin queueing. Voice and data packets are placed in two separate queues after reception by a LEO. If LEO is ready to transmit, it must schedule a packet from queues. At each round robin time interval, some percentage of processor resources are shared between voice (w_V) and non-realtime background traffic (w_{Bg}). Percentage of system resources reserved for voice traffic is a design parameter which sets the trade-off point among real-time delay and data delay values.

C. Scenario III - Error Correction Coding (ECC)

Satellite channels are known to suffer relatively large bit error rates (BER) caused by losses or errors due to fading, propagation anomalies, intentional jamming, or other user interference. Packet loss due to noticeable packet errors may cause degradation in the transmission quality, if no correction mechanism is applied. However, ECC brings extra processing delay. The delay depends on the correction strength of the algorithm. We have modeled ECC by using a variable threshold for the receiver side for each link determining whether a packet is lost.

IV. EXPERIMENTAL RESULTS

ITU-T G.114 recommendation states that one-way delay for voice transmission should be less than 150 ms. Delay values between 150 ms and 400 ms are acceptable but may result in poor quality of speech. Above 400 ms, it is unacceptable because of very poor speech quality. Therefore, it is important to note that long distance delays should be minimized. As can be seen from the summary of simulation results in Table II, two-layered constellation of LEOs and MEOs can shorten delay values by forwarding packets to MEO layer preventing many LEO hops. Longest path of 9 hops defined in the LEO case is now shortened to 4 hops, LEO-MEO-MEO-LEO, resulting in much shorter delay. Similarly, jitter values also have smaller values changing between 4-16 ms. Forwarding some portion of traffic to MEO layer also facilitates load balancing. Instead of using all ISL capacities in LEO layer, MEO layer is utilized. This results in less traffic in LEO layer and less queueing delays.

TABLE II
SUMMARY OF BASE SCENARIO SIMULATION RESULTS - AVERAGE END-TO-END DELAY VALUES

Constellation	Long (ms)	Random (ms)	Short (ms)
LEO	210	200	40
MEO	280	220	90
Two-layered	170	160	30

Simulation results show that in LEO constellation, minimum delay is 30 ms which corresponds to a one-hop communication. The longest path results in a delay of approximately 214 ms in light traffic load. The average delay is 131 ms which corresponds to about 4-5 LEO hops. In MEO constellation, minimum delay - 90 ms - corresponds to one hop MEO path and maximum delay - 286 ms - belongs to the longest route of 5 MEO hops. Jitter value is nearly as high as LEO case because of multiple hops between MEOs.

All further experiments are based on two-layered constellation. In the next two sets of experiments, D_{thrsh} value is changed to analyze its effect on system performance parameters. In the first set, D_{thrsh} is set to 50 ms which causes many of the voice packets to be accepted as LDV and therefore to be routed through MEO layer. 71% of packets are marked as LDV and 29% is SDV. Due to light load on LEO satellites, SDV and background traffic do not suffer from long queueing delays. Since traffic load is quite light corresponding to 4% utilization of IOL capacity in this scenario, LDV does not experience long queueing delay. Later, D_{thrsh} is taken as 100 ms. This yields marking nearly all packets as SDV, 97% SDV and 3% LDV. Therefore, most of the load is on the LEO layer. Due to the lack of dynamic routing policy, load is not balanced between the satellites. This leads to over-utilization of some satellites and related links, and under-utilization of others. For this reason, high queueing delays are possible on those mentioned highly loaded satellites. For instance, queueing delay of LEO$_{36}$ at some time point reaches to 300 ms. Increase on delay values in Table III can be explained by this argument. Since LDV packets are routed through MEO layer, queueing delay on LEO layer does not noticeably affect LDV traffic. As can be seen from the table, LDV delay slightly changes. Jitter values are also affected by changing queueing delays of LEO satellites. Background and SDV traffic experiences about 110 ms jitter, as opposed to 12 ms of LDV jitter. In the rest of the experiments, D$_{thrsh}$ is 80 ms unless otherwise stated. It should be noted that this choice is made arbitrarily.

TABLE III

EFFECT OF CHANGING THRESHOLD DELAY

Traffic Type	D_{thresh}=50 (ms)	D_{thresh}=100 (ms)
Background	54	175
Conversational	111	150
LDV	146	154
SDV	34	150

In the latter experiments, effect of traffic load is analyzed by changing GS background traffic generation rate. Initially, background traffic packet interarrival rate is exponentially distributed with mean 0.03. Second, identical background and voice traffic are generated with mean interarrival of 0.01. Finally, background traffic rate is set twice the previous case. Rather than overall traffic delay and jitter values, three GS pairs are taken as reference communication and their corresponding performance metrics are recorded. Percentage load specified on the x-axis of the graphs in Fig.s 1, 2 and 3 corresponds to the percentage utilization of GS uplink capacities. GS$_{58}$ communicates with GS$_{121}$ which is quite far resulting in 8 LEO hops in the static topology. GS$_{98}$ and GS$_{230}$ have sessions with closer parties in different regions, GS$_{185}$ and GS$_{146}$ respectively. Fig.s 1, 2 and 3 elucidate the simulation results. Values above bars in the graphs indicate the jitter values of each traffic type.

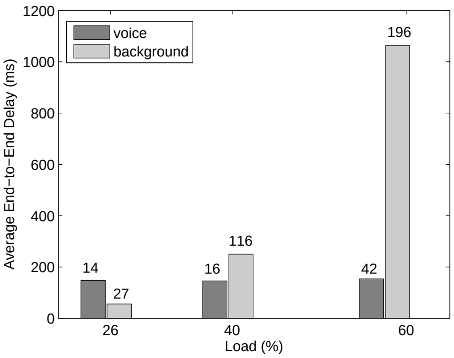

Fig. 1. GS$_{58}$ communicates with a GS far from it. Values above bars are the delay jitter values of each traffic type.

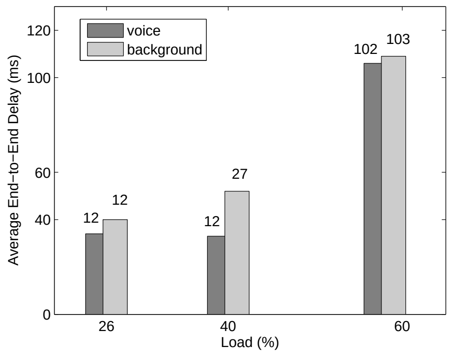

Fig. 2. GS$_{98}$ and short distance communication of a few LEO hops. Jitter increases with increasing load.

Increasing the load will increase the queueing delays depending on the load on a satellite, therefore overall delay values. With the same reasoning, buffers of overloaded links and satellites will become full and some packets will be dropped. Assuming perfect satellite channels with no errors, when load is 26%, overall packet loss is 2%. This value increases to 10% and 28% with the increase on load to 40% and 60% respectively. From Fig.s 1, 2 and 3, it is seen that with the increase in load, packet delay also increases. But this increase rate may be different depending on the route followed by the packets and intermediate satellite nodes' states. For instance, GS$_{230}$ and GS$_{98}$ do not experience drastic change in delay values since their path consists of fewer number of satellites and these relatively lightly loaded ones. Voice and background traffic delay values change similarly in these communications for the reason that voice packets are marked as SDV and are routed through LEO layer just as background data traffic. On the other hand, GS$_{58}$ which represents a long-haul communication party, is subject to very long queueing delays on its route. When load is 40%, voice and background delays are about 148 and 250 ms respectively. However, when load is 60%, background delay jumps to values around 1000 seconds, whilst voice delay does not change. This is due to the routing policy of LDV packets being forwarded to the MEO layer and being not exposed to congestion. Although not taken as reference communication, mentioning GS$_{141}$ delay values is beneficial to understand the need of prioritizing time-sensitive real-time traffic than non-realtime traffic. GS$_{141}$ voice traffic also experiences as high queueing delays as background traffic in case of 60% load, resulting delay values about 340 ms and 70 ms delay jitter of both traffic type. Both delay and delay jitter values are beyond the acceptable good-quality speech since average one-way jitter should be targeted at less than 30 ms [18]. Hence, onboard queueing policy must be changed from first-in first-out policy to WRRQ policy.

In case of light-load traffic, since packets do not experience severe queueing overhead in the network nodes (LEOs and MEOs), WRRQ does not noticeably improve delays. However in heavy-load traffic case, giving priority to voice packets for processing shortens voice delays while increasing data delays. In the next two experiments, GS uplink utilization is about 60% which may be accepted as heavy-load. At each round robin time interval, first 60% of processor time is reserved for voice traffic and later 70%. The voice delay value of GS$_{141}$,

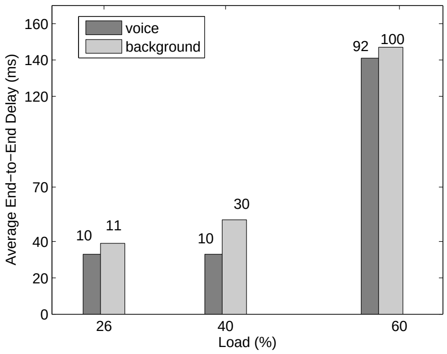

Fig. 3. GS_{230} and short distance communication of a few LEO hops.

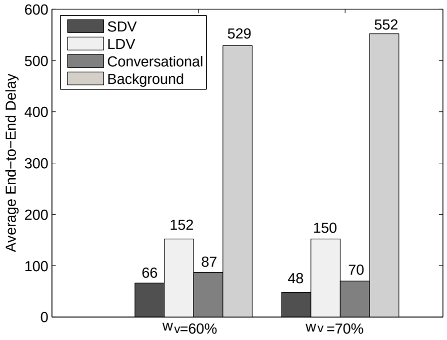

Fig. 4. Overall average end-to-end delay of each traffic is depicted with two different voice percentages (w_V) for WRRQ case. Values above bars are average delay values of each traffic type.

now decreases from 340 ms to 72 ms and 39 ms, respectively. Moreover, voice traffic jitter goes down to 47 and 10 ms, respectively. Background delay values increase from 340 ms to 556 ms and 600 ms with the increase in jitter from 72 ms to 156 and 167. Fig. 4 depicts the average delay values with two different WRRQ weights. With the increase on w_V, overall background delay increases from 529 to 552 ms, while average conversational (LDV and SDV) delay decreases from 87 to 70 ms.

Finally, radio links are modeled to have Gaussian bit errors and satellite receivers' ECC thresholds are altered. Due to channel impairments such as fading and atmospheric effects, satellite links have high BERs compared to terrestrial links and these high BERs cause packet losses. To some extent, packet loss can be tolerated by real-time applications. It is recommended to have packet loss rate less than 5% for good quality and 1% for toll quality communication. Simulation results indicate about 30% loss rate in case of no ECC, which is no way acceptable. To decrease loss rate and make communication more intelligible, some error correction must be applied on-board the satellite. Depending on the power of error correction algorithm, loss rate can be decreased to some desired tolerable level. On the other hand, ECC incurs extra processing delay to packet delay. This delay depends on the strength of ECC algorithm. However, packet loss is decreased to a much acceptable level of 12%. These results illustrate the delay-error correction trade-off when ECC is employed.

V. CONCLUSION AND FUTURE WORK

In this paper, we have investigated the VoIP performance issues and the effects of some QoS mechanisms on VoIP performance in multi-layered satellite IP networks. The results verify that OBP, enabling multi-layered satellite systems and QoS mechanisms, are crucial for performance enhancement in these networks. With this ability, good-quality VoIP over satellite is feasible. Integrated satellite networks with ECC and priority-queueing capabilities can provide a viable solution for voice service using packet-based networks. Due to changing topology of NGEO satellite networks and nonuniform traffic distribution in satellite footprints, there is a need for dynamic routing policy depending on the network state and QoS metrics. We are currently working on these switching and routing issues of an integrated NGEO satellite network using an empirical IP traffic pattern.

REFERENCES

[1] Y. Hu and V. O. K. Li, "Satellite-based Internet: A tutorial," *IEEE Communications Magazine*, vol. 39, no. 3, p. 154, 2001.

[2] H. Oouchi, T. Takenaga, H. Sugawara, and M. Masugi, "Study on appropriate voice data length of IP packets for VoIP network adjustment," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM 2002)*, November 2002.

[3] M. Ibnkahla, Q. Rahman, A. Sulyman, H. Al-Asady, Y. Jun, and A. Safwat, "High speed satellite mobile communications: Technologies and challenges," *Proc. IEEE, Special issue on Gigabit wireless communications: Technologies and Challenges*, pp. 312–339, February 2004.

[4] C. Chen and E. Ekici, "A routing protocol for hierarchical LEO/MEO satellite IP networks," *ACM/Kluwer Wireless Networks Journal*, vol. 11, pp. 507–521, July 2005.

[5] R. E. Sheriff and Y. F. Hu, *Mobile Satellite Communication Networks*. John Wiley & Sons, 2001.

[6] A. Durresi, D. S. Dash, B. Anderson, R. Kannan, S. Kota, and R. Jain, "Routing of VoIP traffic in multi-layered satellite networks," in *Proc. Performance and Control of Next-Generation Communications Networks*, 2003, pp. 65–75.

[7] J. Lee and S. Kang, "Satellite Over Satellite (SOS) network: A novel architecture for satellite network," in *Proc. IEEE INFOCOM 2000*, 2000, pp. 315–320.

[8] G. Eckhardt, "On-board processing," *Space Communications*, vol. 17, pp. 1–3, 2001.

[9] A. R. D. Gupta and K. S. D. Gupta, "The emerging trends in satellite and wireless communications technologies," in *Indian Academy of Sciences 69th Annual Meeting*, Guwahati, India, November 2003.

[10] J. Janssen, D. D. Vleeschauwer, G. H. Petit, R. W., and J. Leroy, "Delay bounds for voice over IP calls transported over satellite access networks," *Mobile Networks and Applications*, vol. 7, no. 1, pp. 79–89, 2002.

[11] D. S. Dash, A. Durresi, and R. Jain, "Routing of VoIP traffic in multi-layered satellite networks," in *Proc. Performance and Control of Next-Generation Communications Networks*, September 2003, pp. 65–75.

[12] B.Jianjun, L.Xicheng, L.Zexin, and P.Wei, "A distributed hierarchical routing protocol for non-GEO satellite networks," 2004, pp. 148–154.

[13] C. Chen, E. Ekici, and I. Akyildiz, "Satellite grouping and routing protocol for LEO/MEO satellite IP networks," Atlanta, Georgia, September 2002, pp. 109–116.

[14] B. Jianjuan, "Explicit multi-path routing for LEO satellite networks," Hong Kong, China, May 2005.

[15] G. McMahon, R. Septiawan, and S. Sugden, "A multiservice traffic allocation model for LEO satellite communication networks," *IEEE Journal on Selected Areas in Communication*, vol. 22, no. 3, pp. 501–507, April 2004.

[16] OPNET Modeler, http://www.opnet.com.

[17] B. Jianjun, L. Xicheng, L. Zexin, and P. Wei, "Compact explicit multi-path routing for LEO satellite networks," *Proc. 2005 IEEE Wksp. High Perf. Switching and Routing*, May 2005.

[18] R. Toegl, U. Birnbacher, and O. Koudelka, "Deploying IP telephony over satellite links," in *Proc. Int. Workshop on Satellite and Space Communications (IWSSC 2005)*, Siena, Italy, September 2005.