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Performance evaluation of LEO satellite constellations with inter-satellite links under self-similar and Poisson traffic

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SUMMARY

A real-time simulation study for the evaluation of traffic flow in low earth orbit (LEO) satellite constellations, used for the interconnection of high-speed networks, is presented in this paper. The proposed model simulates the traffic process end to end at the packet level, supporting successfully the implementation of self-similar traffic sources, a modelling approach that has been considered more realistic than the well-known Poisson, for real-time communications.

An in-depth study for the establishment of inter-satellite links (ISLs) and the design of the terrestrial and space segments is presented and the performance of the integrated system is evaluated in terms of delay and throughput parameters. Copyright © 1999 John Wiley & Sons, Ltd.

1. Introduction

Satellite systems represent a new ambitious solution in an attempt of interconnecting fixed networks worldwide for supporting real-time communications. Low earth orbit (LEO) constellations, specially those which implement Inter satellite links (ISLs), are foreseen to dominate the field of network interconnection. An advantage of such systems is the low delay of LEO satellites, compared to MEO and GEO. Another advantage is the high bit rate interconnections between the satellites, which enable them to provide low delay connections between two distant points on the earth surface. Despite these advantages, the delay due to the satellite altitude which is still significant and the dynamic topology of the ISL subnetwork make the problem of delay minimization, rather complicated. The analysis of a satellite system, through simulation, comprises many issues.[1–5] Some of these are the precise definition of the covered area as the satellite is moving, the establishment of the intersatellite links (if the system employs ISLs), the dynamic routing in the derived topology, the minimization of path switching, the establishment of the up-down link, the handoff conditions and finally the pattern analysis of the traffic originating from or terminating at the earth stations.

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In this study a system similar to Motorola's Celestri, is examined in terms of traffic analysis and delay performance. The orbit altitude of the proposed system is taken equal to 1381 km instead of 1400 km. This modification is necessary for the reduction of the system period (the time needed for two satellites to be placed exactly over the reference earth point) from approximately 3 days to 205·15 min. This simulation period is sufficient for the consideration of any possible combination of traffic distribution and constellation pattern. Although Motorola has announced the merging of Celestri and Teledesic, nothing is known yet about the design of the new constellation. However, the developed code is adaptable to many other systems after very slight modifications. Similar studies are rarely presented in the literature,[6] due to the high complexity and the changing topology of the system, so we tried to obtain results that can be easily used by other researchers investigating different LEO constellations.

As far as we know our packet level simulation tool is one of the first tools available in the scientific community for an in-depth study of the integrated (end-to-end) routing and traffic issue for systems with continuous changes in topology and sensitivity to transmission delays.

In Section 2 the basic steps of the structure of the simulation code is described. We reproduce the exact movement of the satellites, in relation to the earth movement and in relation to each other. The movement of the satellites in relation to earth is critical for the selection of the up-down links and the delay the packets will encounter. The movement relative to each other is important for the establishment of the inter-satellite links, and this is the second step of our code.

For the establishment of the inter-satellite links the satellites movement is evaluated by means of distance, elevation and azimuth angle. Keeping in mind the substantialness of the time varying nature of the ISL subnetwork, a topology design is elaborated in a third step.

Based on the previous study, the search for an end-to-end connection within the ISL subnetwork is examined. This investigation is based on the implementation of the Dijkstra Algorithm in a dynamic topology context. The applied routing scheme is integrated by a procedure, aimed at minimizing the switching between different paths connecting a pair of satellites, caused by the dynamics of the ISL network topology, presented in Reference 7. All these simulation steps are reported in Section 3.

In Section 4 the consideration of traffic sources located at different points on the earth's surface, is described. In the resultant up-down links the virtual connection tree architecture[8] is implemented.

In Section 5, the results obtained from the simulation of two different traffic models Poisson and self-similar are reported and discussed in detail, leading to conclusions and proposals for further analysis in Section 6.

2. Trajectory simulation

The trajectory of a satellite in a constellation depends on many factors important for the system performance such as global coverage decisions, low handoff rate requirements, acceptable transmission delay, etc. Given a satellite system, we must be able to simulate its movement relative to the earth's and to result in some conclusions about the aforementioned factors.

For this purpose, data similar to those given in Table I are necessary to develop a real-time simulation software that is applicable to any circular (LEO, MEO, GEO) constellation. The software monitors a location on the earth's surface while the constellation is moving. The spherical earth model was used and the monitored point was defined in terms of its longitude and latitude which are inputs in our program. Another input is the total simulation time. Outputs of

Table I. Parameters of the celestri system

	Celestri
Orbit altitude	1400 km
Orbit period	114 min
Num. of sat.	63
Num. of planes	7
Inclination	48
Intraplane ISL per sat.	2
Interplane ISL per sat.	4
Right ascension	51, 42
Phase shift	28, 57

the software code are the real-time change of distance and elevation angle between the monitored point and the active satellite. Statistical results are also extracted, as well as real-time results for a number of other variables, such as the total/mean number of handoffs, the time intervals between handoffs and the apparent velocity of the active satellite. We must underline that the variables we can examine in our code, are practically unlimited.

3. Topological considerations and routing algorithms

To investigate the ISL segment, we must derive the exact position of the satellites at any time. Figure 2 depicts a snapshot of the system at time $t = 0$.

Important factors for the establishment of the inter-satellite links are the azimuth and elevation angles. This evaluation process and related topics can be found in References 4, 7 and 9 for different satellite systems, such as LEONET, Iridium and M-Star, and in Reference 10 for our system. In Reference 10 we proposed six permanent ISLs for the Celestri-like system: two intra-plane and four inter-plane as shown in Figure 1.

These ISLs lead to a topology with stable connections but with time-varying connection costs. To deal with this varying topology routing problem, Dijkstra's algorithm[11] is implemented in time steps of 10 s. This ensures that any topology variation is captured.

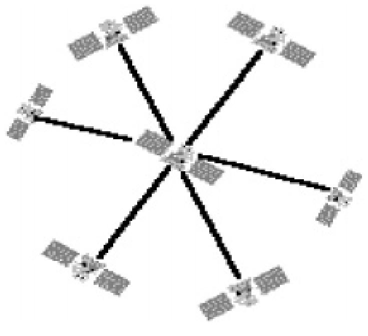

Figure 1. The proposed ISLs

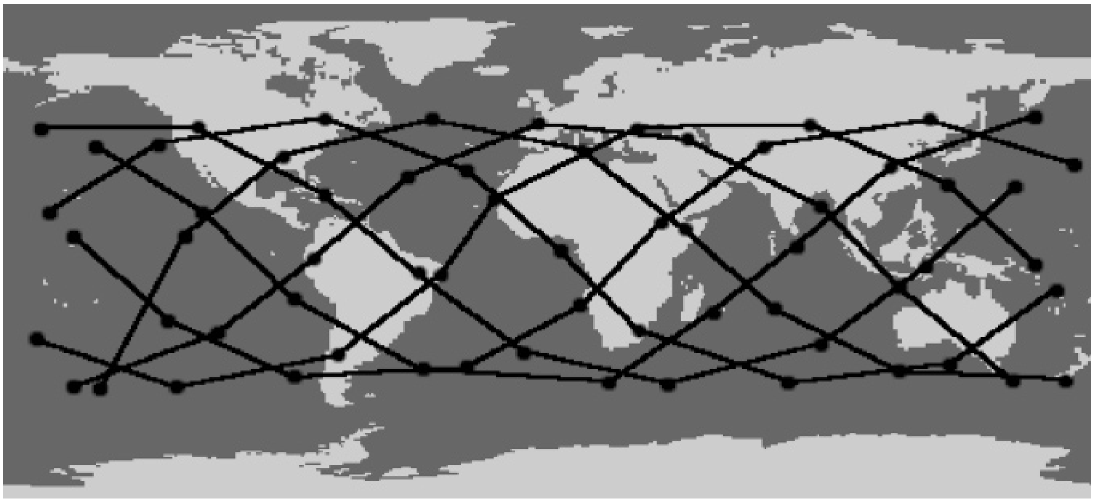

Figure 2. A snapshot of the Celestri at $t = 0$

The cost function of Dijkstra's algorithm incorporates the transmission delay in a path and the delay time imposed by each satellite hop. Denoting the transmission delay for the ith satellite link as D_i and the delay time imposed by a satellite hop as H, the cost function C is given by

$$C = \sum_{i=1}^{n} D_i + n * H$$

H is given a value of 10 ms and n is the number of satellites included in a path.

This routing scheme is integrated with the minimization of the switching between paths connecting a pair of satellites that can be caused by the fact that D_i is time variant. This procedure has been proposed by Werner *et al.*[7] For our simulation an ATM scheme was adopted. Within ATM, a *virtual path* (VP) is understood as a logical link between two adjacent ATM nodes (satellites in our system). A VP is constituted by *virtual circuits* (VCs) between different user connections, who are using the physical channel between these two nodes. A route between a pair of satellites (start and end satellite) may consist of subsequent ISLs and is modelled as a *virtual path connection* (VPC). This implementation demands the use of a modified Dijkstra algorithm,[12] to find the k-shortest paths for a pair of any two nodes. In a dynamic topology context, switching between different VPCs for a start and an end satellite, called *VPC handover* may also occur. These handovers must be kept to a minimum because they may cause abrupt changes in the traffic load of the involved nodes, sudden changes in the path delay and therefore QoS degradation.

The code results in the selection of one path—out of an available set of best paths, found by the modified Dijkstra algorithm, for a given time interval—for every satellite pair to provide the end-to-end connection, based on two rules:

(a) If the path chosen in the last time interval is available for the present one, it should be maintained as long as its cost is smaller than the shortest path cost, increased by 30%. The choice of this percentage is highly dependent on the constellation. Due to the computational power demand of the developed code only an introductory consideration was able to be performed. However, the optimization of this percentage is subject to further investigation.

(b) If the path chosen in the last time interval is not an element of the present set, or its cost is not acceptable, the best path of the set is chosen.

4. Traffic generation

In the analysis of satellite constellations designed to interconnect fixed high-speed networks, it is substantial to keep in mind that in digital networks new services are emerging rapidly and that in order to extract realistic conclusions for the network performance, we have to concentrate in a packet-level simulation. Investigation of the conventional traffic models (Poisson, etc.) seems unable to capture, in an acceptable manner, real traffic characteristics. Thus, new traffic models were proposed, with the most promising being the self-similar models. Many measurements performed on networks,[13–16] report new characteristics of the packet traffic, as for example that packet traffic is strongly autocorrelated. Self-similar traffic is bursty across a wide range of time scales, hence it exhibits long-range dependence. This characteristic is of extreme importance for satellite networks, because they are supposed to be loaded by aggregated traffic. On the other hand, aggregated self-similar traffic may intensify burstiness rather than diminish it, with direct ramifications to the satellite switch design.

4.1. Description of the adopted self-similar process

In our study we use 50 earthstations (gateways) which forward traffic to the satellite system. The choice of limited distinct traffic sources was based on the absence of clear information about the services these networks will support in the future.

For each earthstation, we implement two different traffic models. The first is the well-known Poisson model and the second is a self-similar model proposed by Likhanov and Georganas.[17,18]

This self-similar process is a mathematical model for the superposition of an infinity of on–off sources with Pareto distribution. Each source, at scarce random moments of time, begins to generate bursts of a random number of packets. The burst length distribution is Pareto. At the end of the burst generation, the source becomes silent for a random time which is, as a rule, greater than the length of the packet generation interval. The number of individual sources is so large that it can be considered as infinite but the total intensity λ of sources is finite and of a given value. Under these conditions, the suggested mathematical model for aggregate traffic in brief is as follows.

We assume that the sources produce packets with a constant rate R. If ω_s is the sth instant of the beginning of packet generation with the constant rate R and τ_s is the length of the interval where this generation takes place, the random variables τ_s are mutually independent, independent of ω_s and are identically distributed with Pareto-type distribution:

$$P\{\tau_s \leqslant t\} = \left(\frac{\beta}{t+\beta}\right)^{\alpha}$$

where $\beta > 0$ and $1 < \alpha < 2$.

Table II. Location and magnitude of the earth stations

	Traffic levels									
Source number in	1	2	3	4	5	6	7	8	9	10
Africa	0	0	2	0	0	0	0	0	0	0
Asia	0	6	3	0	1	2	1	1	1	1
Europe	0	6	1	2	1	0	0	3	0	0
North America	0	3	4	0	0	1	2	0	2	1
Ocean.	1	0	1	0	0	0	0	0	0	0
South Amererica	0	0	0	3	1	0	0	0	0	0

The random variables

$$\xi_t = \{\text{number of time moments } \omega_s \text{ such that } \omega_s = t\}$$

form a Poisson process with intensity λ, and they are independent of τ_s. Let Y_t be the total rate of packet generation in the aggregate traffic at time t. The process Y_t is assumed to be stationary. At time t, the packet generation jumps with value $R\xi_t$ up and falls down with a value $R\kappa_t$, where κ_t is the number of active periods τ_s, terminated at time t. For this process the mean rate of packet generation is given by

$$E\{Y_t\} = R * \lambda * \alpha_t$$

and variance is given by

$$E\{(Y_t - E\{Y_t\})^2\} = R^2 * \lambda * \alpha_t$$

where α_t is the mean of the Pareto distribution.

4.2. Distribution of traffic sources

As we indicated before, we use for each earthstation the model of the aggregate traffic, described earlier, or alternatively the Poisson model.

Due to the absence of a realistic analysis of the traffic demand for such networks we choose the earth station location and traffic intensity, compatible with all the factors that modulate the global traffic demand, as the Gross Domestic Product and networks penetration.[6] In Table II the earth station distribution is presented, and in Figure 3 the exact locations of the stations are depicted.

4.3. Simulation implications

The simulation code we developed, referring to packet-level events, demands extreme computational power. So, we decided to scale down the system in both the system capacity and the traffic intensity. We shall investigate if we can endorse our conclusions. This rationale determined the traffic levels shown in Table III.

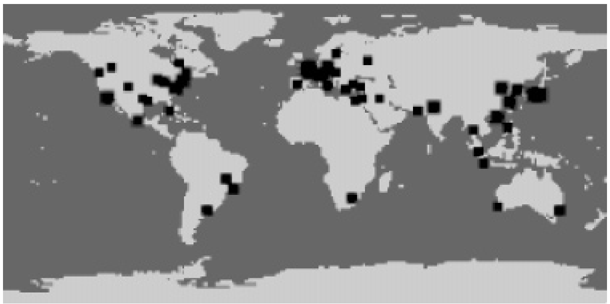

Figure 3. The location of traffic sources

Table III. Traffic levels

Traffic level	1	2	3	4	5
Packets/s	230	450	669	889	1108
Traffic level	6	7	8	9	10
Packets/s	1328	1548	1767	2206	4402

4.4. Daily variations of traffic intensity

Another point that we must focus on is the fact that the traffic intensity is characterized by variations with respect to time. Therefore, we have somehow to adjust the traffic levels. Since our model is a global one an additional problem is emerging due to the different time zones. Thus, in the adjusting procedure, we must keep in mind for each earth station the local time, determined by the time zones, defined by international organizations. The function adopted for the scaling of the traffic intensity is proposed in Reference 6 and shown in Figure 4.

The traffic intensity for an earth station is determined as the intensity which would produce within an hour a traffic volume equal to the traffic volume that the recorded intensity—namely the intensity corresponding to each earth station (Table II) and shown in Table III—would produce if it was scaled (each hour) according to Figure 4.

4.5. Packet destination

The destination address for each packet is based on the assumption that each station allocates traffic to other stations, according to the percentage of global traffic each station is representing. The self-similar process, adopted in our algorithm, allows us to simulate the destinations of the packets realistically, since all the packets that will arrive with a constant rate R within a time interval, defined by the Pareto distribution, can have the same destination. This approach seems realistic for current computer networks.

4.6. Virtual tree architecture

In order to provide a hitless handoff in the up-down link and to ensure the correctness of traffic flows, the *virtual tree* (VT) architecture, presented in Reference 8 is applied to the simulation. In

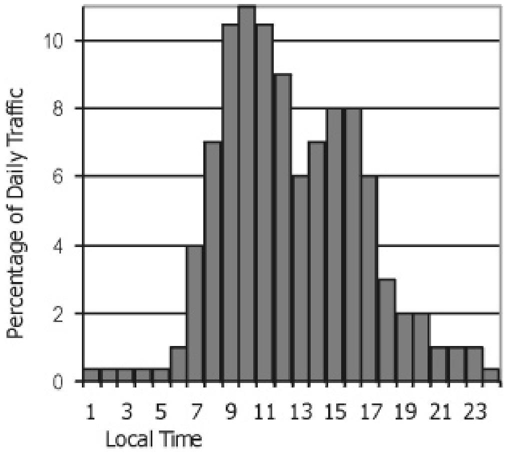

Figure 4. Daily user activity

our implementation of the *virtual tree* architecture in the dynamic satellite scenario, the v*irtual circuit trees* (VCTs) built are time dependent.[9] The leaves of the tree is a set of six satellites that are connected through the ISLs with a head satellite that is considered to be the root of the tree.

5. Performance evaluation

Despite the high demands of the developed code in computational power we were able to simulate a period of the system (that is approximately 205·15 min). This means a duration, for the execution of our code, of 11 days with a Pentium II 400 MHz.

In the following we present and discuss some of our results, underlining the most interesting points for further investigation.

5.1. End-to-end delay evaluation

The purpose of our study was to evaluate the system performance mainly by means of the end-to-end delay for different traffic distributions.[19] These factors are crucial for any efficient utilization of the network and the support of real-time communications.

For each packet the end-to-end delay consists of the propagation delay in the up-down link and the ISLs, the transmission delay in each link (dependent on the link rates, shown in Table IV)

Table IV. Rates of the celestri system

	Celestri
UD link rate	8·7 Gbps
ISL rate	4·5 Gbps
Global capacity	80 Gbps

and the onboard switch delay (*H*). The delay imposed by a satellite hop (*H*) is determined by the link rates in addition to the onboard switch structure. Due to the unknown switch structure *H* was set at a value indicating roughly the worst case.

Figure 5 shows the delay distribution of the serviced traffic. The tail of the self-similar distribution is greater than Poisson's, a result that is aligned to theoretic indications. Although the delays for the traffic generated by a Poisson process are kept within logical values, it is not the same for a considerable percentage (about 4% encounter delays greater than 160 ms) of the traffic generated by the self-similar process. In all of the presented graphs there are significant amounts of served traffic encountering long delays (4, 3·5, 5·5 and 1·5% in Figures 5–8 respectively). We believe that the main reason for this result is the non-adaptive routing algorithm used, along with the delay imposed by each satellite hop (*H*), the value of which may be considered, relatively high, due to lack of specific information about the onboard switch.

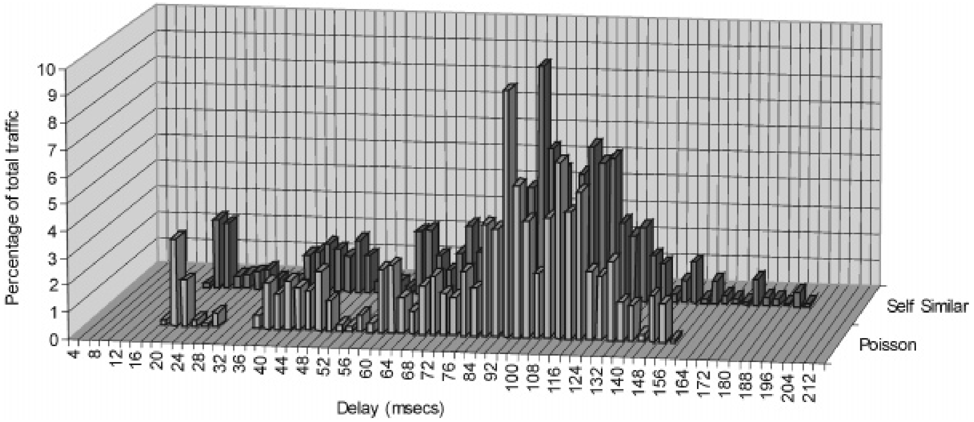

Figure 5. Delay distribution

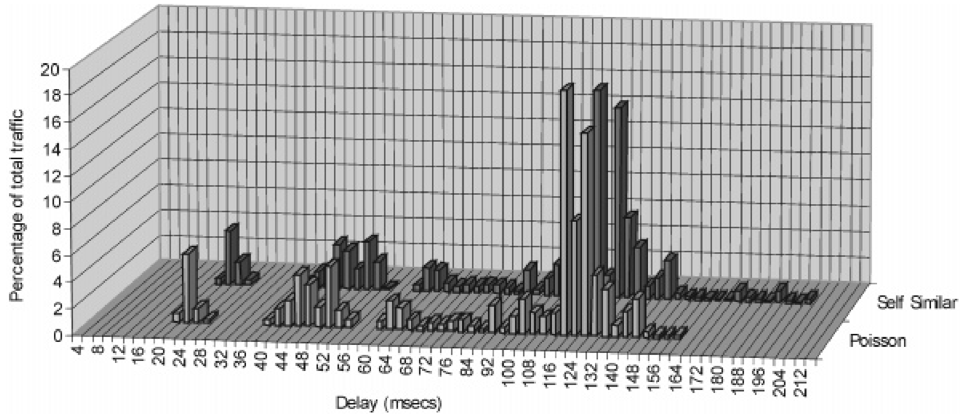

Figure 6. Delay distribution for the most active earth station

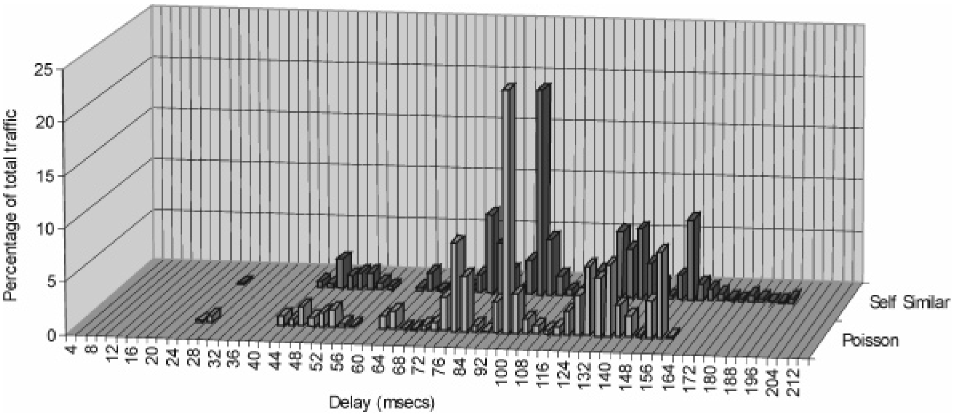

Figure 7. Delay distribution for the least active earth station

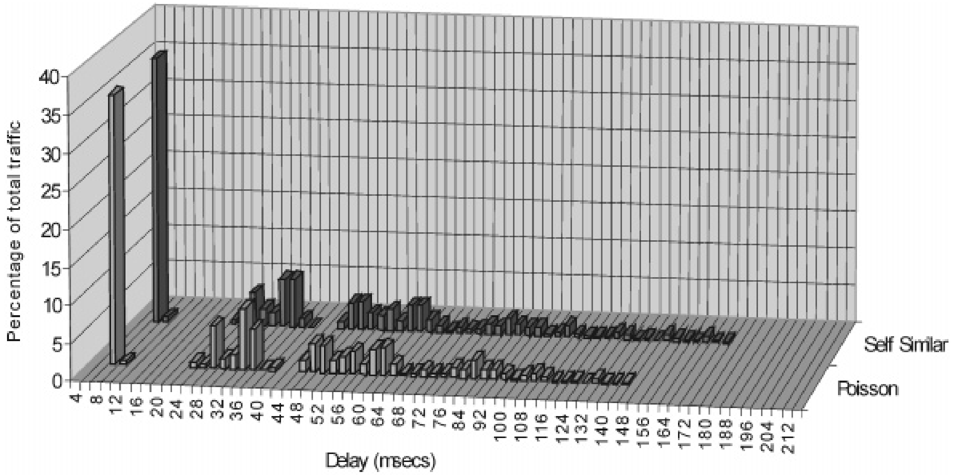

Figure 8. Delay distribution for the most loaded satellite

Relatively to the traffic adaptive routing, *shortest path algorithm*s that introduce somehow in the cost function the traffic loading each link, could be mentioned in addition to the *Flow Deviation Algorithm.*[11] A comprehensive study for the implementation of these algorithms in a satellite constellation can be found in Reference 20.

For the Poisson process the delay distribution graph presents some sort of grouping of the served traffic within time intervals. This can be explained by the distribution of the traffic sources on the earth's surface. For example, pairs of distant (Europe–USA) traffic-intensive earth stations form one group, pairs of earth stations in the same continent with less intense traffic form another group, etc. For the self-similar modelling this feature is fading out as served traffic (about 2% of the total) encounters delays (around 32 ms). There are negligible or no portions of served traffic in the Poisson case (0% around 32 ms). The aformentioned behaviour of the self-similar case results in generally long queues onboard the satellites. We believe an adaptive algorithm could help very much on this point. Referring to the Poisson distribution in Figure 5 we point out that about 6% of the total traffic is found in small delay times (18–28 ms), indicating the traffic served by only one satellite (one-hop paths).

The same component is shown in Figures 6 and 8 where the delay distribution of the served traffic, by the most active earth station (namely the earth station that received the greater number of packets) and by the most loaded satellite (namely the satellite that served the largest amount of traffic—in this case the delay for each packet is recorded upon its arrival to the satellite), are presented respectively. This one-hop traffic portion is greater in Figure 6 (about 7·5%) and Figure 8 (about 43·5%) than in Figure 5, because the most active earth station (corresponding to New York) receives a large amount of traffic originating from neighbouring intensive earth stations. And in our simulation it is found that the most loaded satellite is the one which services the most active earth station for a greater time period. Thus the same one-hop traffic portion in Figure 8 is even greater.

In Figure 7, where the delay distribution of the served traffic by the earth station that received the smallest number of packets (least active earth station) is presented, the one-hop portion of traffic is fairly smaller (about 0·9%) because this earth station (corresponds to the region of Perth, Australia) is rather isolated and receives large amounts of traffic originating from other distant earth stations.

The same conclusions are applicable to the self-similar distribution, with the difference that the peaks tend to be smoothened and shifted at greater delays, because of the bursty nature of self-similar traffic. We must notice that Figure 7 has a longer tail than Figure 6 for both Poisson and self-similar traffic patterns. This is due to the isolation of the least active earth station that forces it to receive packets that encountered many hops because of their distant origination.

5.2. Onboard traffic evaluation

The implementation of satellite systems is constrained by many factors involving the satellite weight, the onboard power requirements for the maintenance of the ISLs, etc. A significant parameter to investigate is the onboard load—namely the number of cells—for the most loaded satellite, referenced in the following as *Onboard Load for the Most Loaded Satellite* (OLMLS), measured in ATM cells.

The onboard load is monitored in time steps of 20 s. In Figure 9, the maximum value of OLMLS recorded in this time interval, is displayed for both Poisson and self-similar processes. The prominent attribute of this figure is the higher peak values recorded for the self-similar process with regard to the Poisson process. This is a confirmation for the big queues onboard the satellite, an indication for the required cautious satellite design. The advantage of the application of a traffic adaptive algorithm, specifically for the self-similar case, is confirmed by Figure 9 together with Figure 5.

Figure 10 focuses on the bursty behaviour of the self-similar process. The maximum and the statistical mean of the OLMLS, recorded in time intervals of 20 s, for the self-similar process is shown in this figure. The same discussion for the Poisson process is made in Figure 11. The divergence between the two values in Figure 10 is greater than that of Figure 11, an indication of the bursty self-similar behaviour. The need for a traffic adaptive algorithm is again confirmed by these results.

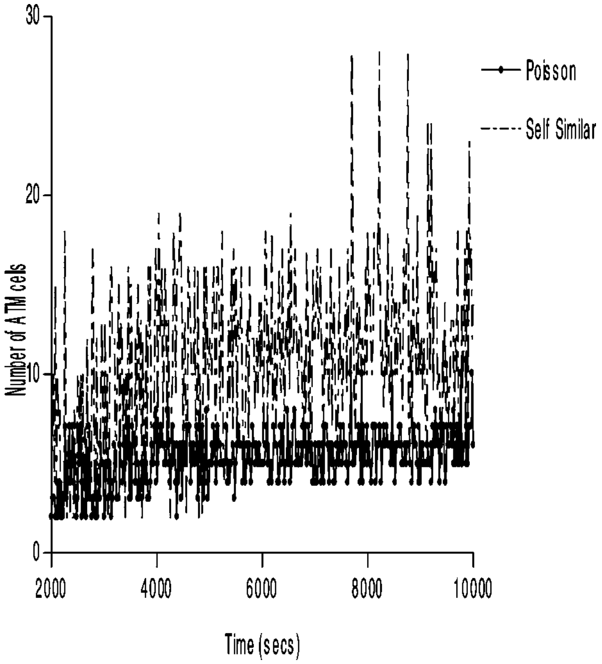

Figure 9. Maximum OLMLS for Poisson and self-similar processes

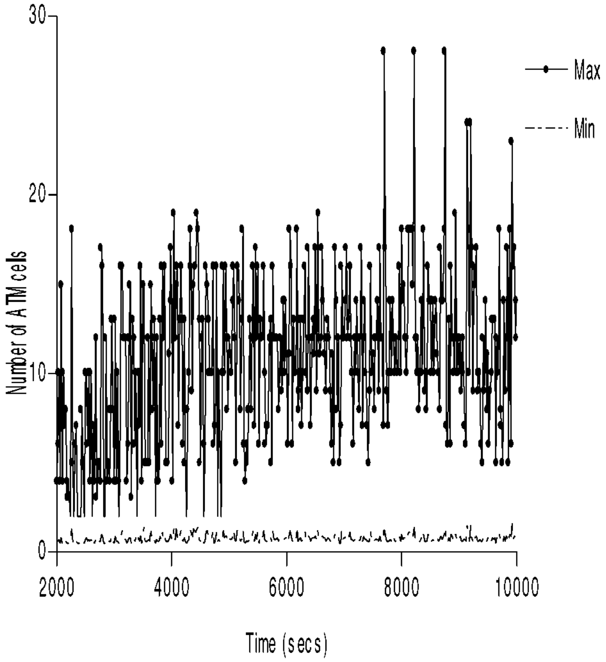

Figure 10. Maximum and mean OLMLS for the self-similar process

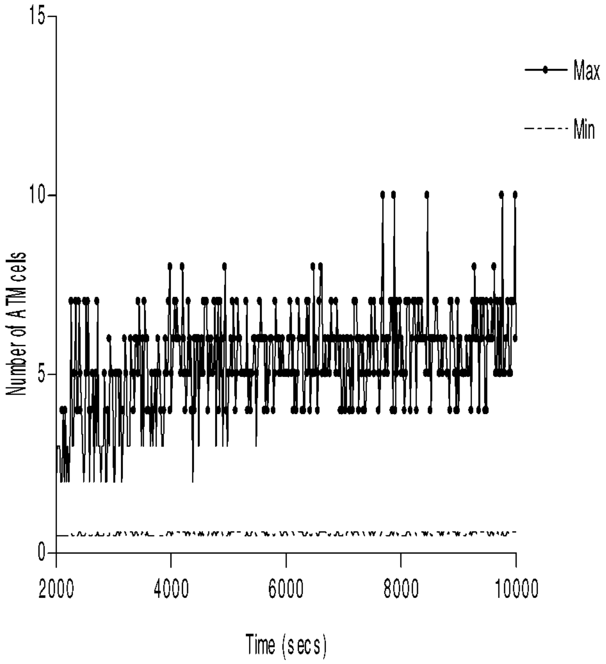

Figure 11. Maximum and mean OLMLS for Poisson process

6. Conclusions

An in-depth study for the establishment of inter-satellite links (ISLs) for LEO constellations has been presented in this paper. A successful design of the terrestrial and space systems is presented and the performance of the integrated system (space and ground) is evaluated in terms of delay and throughput parameters through real time extended simulations.

A comparison of two traffic models (Poisson and self-similar) has been made for the loading of a LEO system, through a packet-level simulation resulting in high but tolerable delays for the self-similar traffic process. We believe that an adaptive routing algorithm can smooth very effectively this result and this is exactly an interesting point for further investigation.

Acknowledgements

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