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Optimization of Double-Link Transmission in Case of Hybrid Orbit Satellite Constellations

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Classical satellite constellations are based on the use of the geosynchronous Earth orbit, low or medium Earth orbits, or highly elliptical orbits. No single kind of architecture is able to guarantee complete global coverage along with flexible capacity. Future demand for broadband services is expected to be very unevenly distributed both in time and in space. This fact suggests that the optimal design of a constellation can be based on the simultaneous use of different kind of orbits introducing the concept of a hybrid orbit constellation. An innovative satellite system architecture is presented, composed of a low-Earth-orbit segment and a geosynchronous segment, interconnected by means of an interorbit link, to offer high data rate capability and real global coverage, while deploying a constellation of very limited size. With such an architecture the user is connected to the geosynchronous satellite through a double link. The constellation system performance has been evaluated using an ad hoc design procedure suitable to the double-link architecture. The optimum system configuration (orbit height and inclination, antenna beam aperture, and transmission delay) that was obtained with the innovative design methodology is presented.

Nomenclature

E_b/N_{0req}	=	required energy per bit over noise spectral density ratio
$T_{downlink}$	=	propagation time for the downlink
$T_{LEO-GEO}$	=	propagation delay from low-Earth-orbit satellite to geosynchronous-Earth-orbit satellite (and vice versa)
T_{packet}	=	average end-to-end delay
$T_{satproc}$	=	satellite processing time
T_{satq}	=	time a packet spends in a satellite queue
T_{trans}	=	transmission time of the packet
T_{uplink}	=	propagation time for the uplink
ϕ_{on}	=	antenna beam off nadir angle
ϕ_{on-opt}	=	optimized antenna beam off nadir angle

Introduction

MANY operational (or planned) satellite systems are aiming to provide either global coverage, typically based on low-Earth-orbit (LEO) constellations, or large bandwidth, typically based on geosynchronous-Earth-orbit (GEO) constellations. Real ubiquity and mobility for broadband services will not be achieved very soon, especially in very remote areas.

Satisfaction of all user's requirements in terms of coverage and capacity has to be traded off with overall system efficiency in terms of number of satellites over offered capacity ratio. To achieve such an optimization is quite difficult with classical architectures. Thus, innovative architectures should be studied, at least for a subset of services.

To offer truly global coverage and high data rate capabilities, the hybrid constellation concept, which is being validated in an Italian Space Agency funded project,[1] foresees the utilization of a LEO satellite component connected to a GEO satellite component. The LEO component will be in charge to provide very high data rate links offering discontinuous coverage, utilizing an interorbit-link (IOL) to exchange data with the GEO component, which will exchange data with the terrestrial networks through its gateways. Each component will collect data in store and forward mode, if no simultaneous link with the other component is available. As a first approach, a baseline architecture composed of one LEO satellite and one GEO satellite is considered.

The system design must take into account that the Earth-LEO and LEO-GEO links cannot be dimensioned separately. In fact, many parameters are common, and in any case the data collected by one component must be transferred to the other one, minimizing memory requirements onboard.[2] Previous papers[2,3] defined the architecture and evaluated performance for the case of a simplified coplanar LEO-GEO architecture. This paper will analyze the more general cases of LEO orbit assuming any inclination. (Only a discrete set will be considered.)

This paper is organized as follows. The innovative system architecture is presented. Then, an innovative ad hoc design methodology is introduced. An overview of the system design options and a description of the experiments with a presentation of the main involved parameters are presented. The main and most meaningful results achieved through an optimization process, both in terms of orbit height and inclination angle, and some results concerning performance in terms of end-to-end delay are then presented and discussed. Finally, conclusions will be drawn.

System Architecture and Services

The proposed system architecture is composed of a GEO component and a LEO component interconnected through an IOL, as depicted in Fig. 1 for the case of the baseline architecture composed of one LEO satellite and one GEO satellite. The GEO component can provide service over a typical continental coverage area (as one of the developing advanced high-capacity systems[4]). The LEO segment aims at providing an access point to the network for those users located in areas where GEOs suffer from their typical limitations, for example, where they are completely absent (poles), cannot perform at their best (high latitudes, mountain regions, shaded zones), might not be economically convenient (deserts, oceans), or might not satisfy temporary extra traffic (when occasional political, sport, or disaster events occur). In the forward link the data gathered by the LEO component from one or more Earth terminals (ET) at very high data rate (in the order of 100 Mbit/s) will reach the final destination through the IOL with the GEO segment and the serving gateway. In this case the LEO component will collect data in store and forward mode, if no simultaneous link with the GEO component is available. The gateway ensures the interconnection with terrestrial networks. In the return link the data uploaded on the GEO component from the

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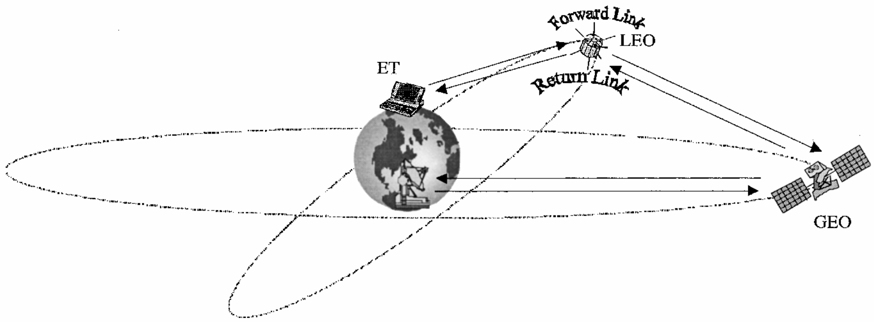

Fig. 1 Hybrid constellation basic architecture.

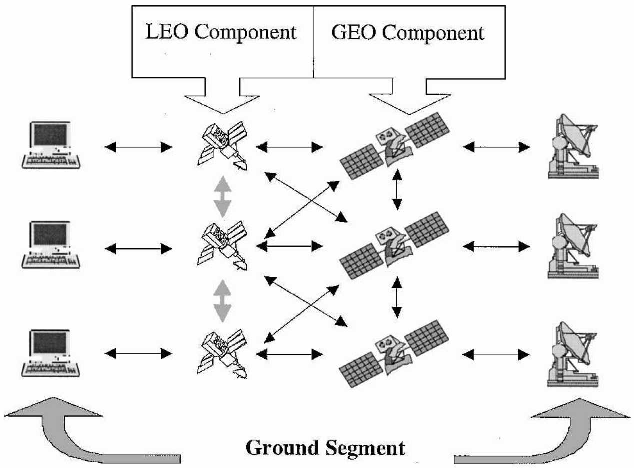

Fig. 2 Final configuration.

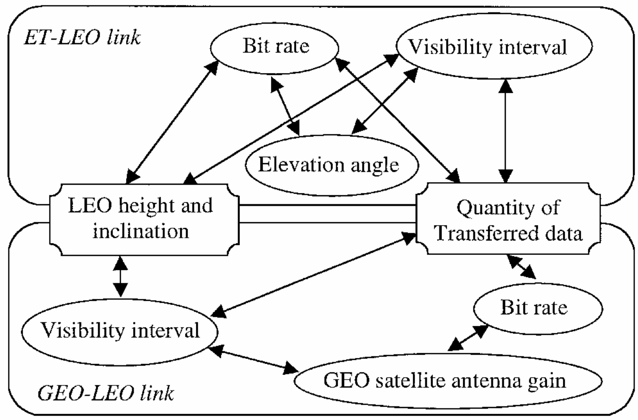

Fig. 3 Double-link design parameters.

gateway will be downloaded to the final user through the LEO component. In this case the GEO component will collect data in store and forward mode if no simultaneous link with the LEO component is available. In both cases, when a direct link is available, if onboard memory is empty direct transferring will be allowed. In any case the payload architectures (both on LEO and GEO) must be regenerative to allow storing data onboard. Thus, the link is actually composed of four links and the design methodology must aim at optimizing all of them together, fixing some parameters to determine the others.

The main goal of such an architecture is to increase total coverage and capacity while improving flexibility by adding just one, or a few, small and low-cost LEO satellites to the classical GEO architecture. Moreover, such kind of architecture allows modularity in setting up and deploying the constellation, which can be a cost-effective and winning approach. In fact, the final configuration (Fig. 2) can include several LEO satellites and several GEO satellites, according to service and traffic requirements. Furthermore, intersatellite links among GEO or LEO satellites can be foreseen, too. In this way overall performance, both in terms of throughput and delay, will improve. This kind of architecture is well suitable to offer no real-time services and applications such as file transfer (FTP), e-mail (SMTP), and access to databases (information retrieval), not excluding the possibility to provide other services and applications typically based on TCP/IP protocols.[5]

Design Methodology for Hybrid Constellations

The satellite path between one user and the gateway is composed of three links: ET-LEO link, LEO-GEO, and GEO-gateway. The first two links cannot be dimensioned separately because several parameters or constraints are common to both of them. For example, LEO height and inclination angle have an impact on the overall delay, on the link dimensioning, and on visibility intervals of both links. In fact, the LEO satellite position determines the distance ET-LEO and LEO-GEO. In the forward link the ET-LEO bit rate, and thus the maximum quantity of data collected per passage, has an impact on the bit rate of the LEO-GEO link required to satisfy the complete transfer. For this reason the best approach should foresee that all of the data transferred and stored on the LEO satellite must be uploaded on the GEO satellite before the next transfer and vice versa. In this way memory requirements onboard the LEO satellite are minimized.

In the forward link, as a working case, we shall first define the parameters of the ET-LEO link and then dimension the LEO-GEO link taking some of the parameters as design constraints. For the return link the same methodology shall be applied in the reverse order.

Figure 3 pictorially shows how different parameters and geometrical characteristics of the two links are interrelated among one another. The figure shows parameters and design elements common to both links and those, belonging to only one link, strictly correlated to them. Every element can represent the starting point of the design procedure, then the other parameters will be figured out taking into account the correlation and the other system constraints (power, antennas, frequency, etc.).

Optimization Process

The optimization process will concern the maximization of the end-to-end transferred data. The link between the ET and the gateway is composed of the ET-LEO link, the LEO-GEO link, and the GEO-gateway link. We will focus on the optimization of the double link ET-LEO-GEO (and vice versa) as the GEO-Gateway link is a classical satellite link.

To this aim, we have to evaluate the parameters of both links such that, of course, the same data transferred in the forward link from ET to LEO would be transferred to GEO and vice versa in the return link. To reach this goal, several design options can be implemented in each link and opportunely combined.

At system level two main technological alternatives have been identified: 1) fixed or adaptive bit rate transmission and 2) fixed or steerable GEO IOL antenna. The different options opportunely combined generate four study cases that will be dealt with in the following sections. Alternative 1 concerns the possibility to transmit either a fixed bit rate (the minimum allowable) or to take advantage from the time variant link geometry, while the LEO satellite is connected with the ET or with the GEO satellite. In particular, in case

Table 1 Common link parameters

Parameter	Forward link: ET-LEO link	Forward link: LEO-GEO link	Return link: GEO-LEO link	Return link: LEO-ET link
Frequency, GHz	94	27	23	92
ET antenna diameter, m	0.75	——	——	1
LEO antenna diameter, m	0.23	0.4	0.4	0.23
GEO antenna diameter, m	——	2.85	2.85	——
ET antenna efficiency	0.4	——	——	0.4
LEO antenna efficiency	0.4	0.6	0.6	0.4
GEO antenna efficiency	——	0.6	0.6	——
$E_b/N_{0\text{req}}$, dB	7	3.1	3.1	5
Min. elevation angle ET-LEO, deg	30	——	——	30
Atmospheric losses, dB	5	——	——	5
Link availability, %	95	100	100	95
Antenna pointing	Steerable (ET, LEO)	Fixed/steerable (GEO) steerable (LEO)	Fixed/steerable (GEO) steerable (LEO)	Steerable (ET, LEO)
Bit rate	Fixed/variable	Fixed/variable	Fixed/variable	Fixed/variable

of LEO-GEO link using a fixed GEO IOL antenna we can adopt adaptive bit rate transmission, taking advantage from both the variations of the distance (that implies different free space losses) and of the GEO antenna gain experienced by the LEO satellite. With this approach a greater amount of data can be transferred on the double link, at the price of a little greater complexity than the basic case. In fact, the algorithm to adapt data rate might be deterministic.

Alternative 2 concerns the possibility to use either a fixed or a steerable antenna for the IOL onboard the GEO satellite. In the steerable case the two antennas (LEO and GEO) are always pointed in the maximum gain direction.

The optimization process was based on fixing all of the radio-link parameters to figure out the best LEO orbit height, as a function of orbital plane inclination, or the best orbital plane inclination, as a function of orbit height, opportunely combining the different design options just mentioned to ensure the feasibility of the double link. The results of the optimization process as a function of different design options will be presented.

Description of the Optimization Experiments

The first set of experiments was focused on the search of LEO orbit height and inclination angle intervals to ensure the feasibility of the double link both in the forward and in the return link. For feasibility we mean that all of the data uploaded on the LEO component would be transferred to the GEO component (forward link) or to ET (return link) in less than 12 h, considered a reasonable interval taking into account the dimensioning of onboard memory.

In the simulations we evaluated the total amount of transferred data as a function of the LEO orbit height (variable in the range 600 to 1500 km) or LEO orbit inclination angle (variable in the range 0 to 90 deg) both in the forward and in the return link. The simulation period is about 72 h. The results are averaged over 12 h.

We empirically realized that the value of two geometrical parameters plays a role in increasing the visibility interval and hence the transferred data: the ET location (for the ET-LEO link) and the GEO IOL antenna beam off nadir angle (for the LEO-GEO link).

Thus, for simulations with different LEO orbit inclinations we considered different ET sites with the same longitude and the latitude assuming the same value of the LEO orbit inclination. As far as the GEO IOL antenna beam off nadir angle ϕ_{on} (Fig. 4) is concerned, we utilized a value such that the transferred data from LEO to GEO (and vice versa) was maximized. To figure out the optimum value for ϕ_{on}, an empirical procedure has been implemented. Table 1 shows the values of the common parameters utilized in the simulations, unless otherwise mentioned, whereas Tables 2 and 3 show the values of $\phi_{\text{on-opt}}$ utilized in case of fixed GEO antenna and steerable GEO antenna, respectively.

Optimum Dimensioning Results

The optimization process consists of figuring out the values of all of the parameters that allow the feasibility of the double link. To reach this goal, the links must be dimensioned ensuring that the data uploaded or downloaded on the LEO component (in the forward or return link, respectively) would be transferred (on the GEO or ET, respectively) in a limited time interval. Otherwise, LEO onboard memories can saturate and data can be lost. Another criterion concerns the maximization of the quantity of transferred data.

For our analysis we chose to optimize two orbital parameters: the orbit height and the orbit inclination (both being common parameters to the two links). Both parameters are very important also to determine the visibility interval. In fact, along with data rates, it

Table 2 The $\phi_{\text{on-opt}}$ in case of fixed GEO antenna

LEO orbit height, km	LEO orbit inclination, deg: 0	15	30	45	60	75	90
600	0	2.9186	5.3171	7.5495	8.8808	9.4814	9.3970
700	0	2.9684	5.6091	7.6708	9.0174	9.6208	9.5292
800	0	3.0185	5.5014	7.7925	9.1543	9.7603	9.6613
900	0	2.8689	5.7942	7.9146	9.0915	9.8998	9.7933
1000	0	3.1195	5.8873	8.0371	9.4289	10.0394	9.9252
1100	0	3.1704	5.9809	8.1600	9.3666	10.1791	10.0570
1200	0	3.2216	6.0750	8.2833	9.5045	10.3188	10.1887
1300	0	3.2731	6.1694	8.4070	9.6426	10.4586	10.3203
1400	0	3.3249	6.2643	8.5310	9.9810	10.5984	10.6517
1500	0	3.3769	6.3596	8.6555	9.9197	10.7383	10.5831

Table 3 The $\phi_{\text{on-opt}}$ in case of steerable GEO antenna

LEO orbit height, km	LEO orbit inclination, deg: 0	15	30	45	60	75	90
600	0	2.5186	5.1171	7.1495	8.4808	9.0814	8.9970
700	0	2.5684	5.2091	7.2708	8.6174	9.2208	9.1292
800	0	2.6185	5.3014	7.3925	8.7543	9.3603	9.2613
900	0	2.6689	5.3942	7.5146	8.8915	9.4998	9.3933
1000	0	2.7195	5.4873	7.6371	9.0289	9.6394	9.5252
1100	0	2.7704	5.5809	7.7600	9.1666	9.7791	9.6570
1200	0	2.8216	5.6750	7.8833	9.3045	9.9188	9.7887
1300	0	2.8731	5.7694	8.0070	9.4426	10.0586	9.9203
1400	0	2.9249	5.8643	8.1310	9.5810	10.1984	10.0517
1500	0	2.9769	5.9596	8.2555	9.7197	10.3383	10.1831

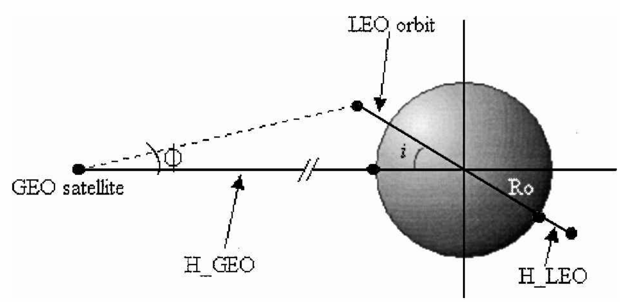

Fig. 4 GEO satellite off nadir angle ϕ.

determines the quantity of data that can be transferred. The values of the main link parameters used as baseline for the optimization process are summarized in Table 1.

Orbit Altitude Optimization

We first analyze the optimization of the orbit height for both the forward and the return path, respectively. The different design alternatives presented in the Design Methodology section have been considered.

Forward Path

We first consider the forward path (ET → LEO → GEO) in case of fixed GEO IOL antenna pointing. In this configuration the most critical link is demonstrated to be the LEO → GEO link. In fact, the resulting visibility interval is very short because of the very narrow GEO antenna beam (beam aperture of 0.5 deg). Thus, the actual intersection between the LEO orbit and the GEO conical visibility is too small to allow the transfer of all of the data collected by the LEO from the ET. To increase the quantity of transferred data, adaptive bit rate has been considered for this link while a constant bit rate has been used in the ET → LEO link. Considering a GEO antenna beam of 0.5 deg and an ET transmitted power of 0.1 W, the results of the optimization process, obtained for the forward double link, are shown in Fig. 5.

The feasibility of the link basically depends on the visibility intervals that depend on LEO orbit inclination. For the coplanar case (LEO orbit inclination of 0 deg) and for polar LEO orbits (90 deg) the feasibility of the forward double link is guaranteed for all of the LEO orbit heights. For a LEO obit inclination of 30 deg, the feasibility is guaranteed over a LEO orbit height of about 1450 km, whereas for a LEO orbit inclination of 60 deg the double link is feasible for heights higher than about 950 km.

To get even greater improvement, simulations have been performed adopting a steerable GEO antenna (alternative 2), a GEO visibility angle of 2 deg, a transmitted power from LEO → GEO of 2 W, constant bit rate in the LEO → GEO link, and adaptive bit rate in the ET → LEO link. In this case, as shown in Fig. 6, the link is always feasible because it is possible to transfer a greater quantity of data (in average four times greater) in the LEO → GEO link for any LEO orbit height and inclination. In this scenario a lot of capacity is actually wasted in LEO → GEO link and hence some constraint can be relaxed.

Return Path

The same methodology was applied to the return path GEO → LEO → ET to figure out the conditions and the range of feasibility of the double link, and similar results were obtained. All of the working conditions of the preceding cases have been confirmed, and the relative results will be for the same two alternatives: fixed GEO IOL antenna and adaptive data rate; steerable GEO IOL antenna and fixed data rate in the GEO → LEO link.

Using a fixed GEO antenna beam with a visibility angle of 0.5 deg and the same value of the selected parameters, in case of LEO orbit inclination equal to 0 deg, 90-deg feasibility of the return double link is not guaranteed. In fact, the quantity of data that it is possible to transfer from GEO to LEO is greater than the quantity that it is possible to transfer from LEO to ET, making it unfeasible to transfer all of the data in only one connection (on average). Of course, relaxing some of the parameters of GEO → LEO link the double link can be feasible.

Figure 7 shows the results referred to a transmitted power from LEO of 5 mW and an ET noise figure of 8 dB. Furthermore, an ET receiving loss of 0.8 dB, a variable bit rate in the GEO to LEO link, and a constant bit rate in the LEO to ET link have been assumed.

For a LEO orbit inclination of 30 deg, the feasibility of the double link is guaranteed for an orbit height higher than about 1460 km. For a LEO inclination of 60 deg, there are two feasibility intervals from 600 to 850 km and from 950 to 1050 km. The quantity of data that it is possible to transfer in all of the cases in which feasibility is achieved is in the range 90–170 Mbyte. Figure 8 presents the results achieved using a steerable GEO antenna beam with a GEO visibility angle of 2 deg. Furthermore, a transmitted power from GEO equal to 2 W, a constant bit rate in the GEO to LEO link, and a variable bit rate in the LEO to ET link, have been assumed. In the cases represented in Fig. 8, the quantity of data that it is possible to transfer from LEO to ET is greater than the quantity that it is possible to transfer from GEO to LEO for all of the analyzed LEO orbit heights and all of the LEO orbit inclinations. The quantity of transferred data is in the range 0.9–1.5 Gbyte for medium latitudes and orbit inclinations equal to 30 and 60 deg and more, about 4–5 Gbyte, for LEO orbit inclinations of 0 and 90 deg.

Orbit Inclination Optimization

After having optimized in terms of orbit height, the same approach can be applied to optimize in terms of orbit inclination. This process has been applied to both the forward and the return link,

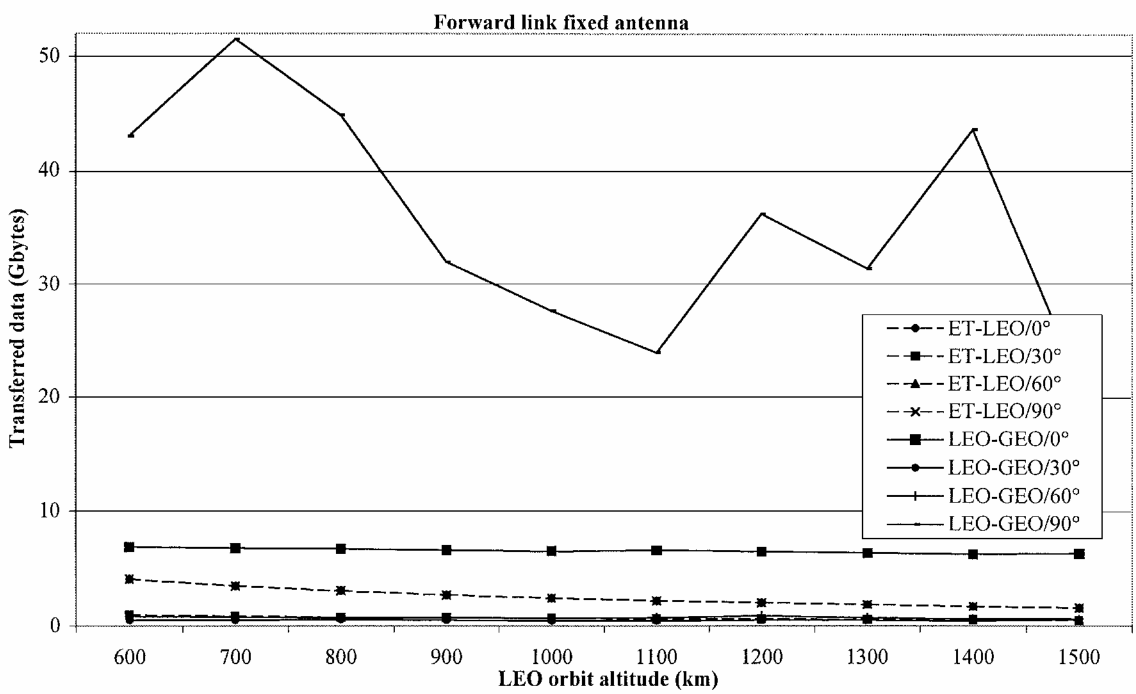

Fig. 5 Transferred data in the forward link using a fixed GEO antenna.

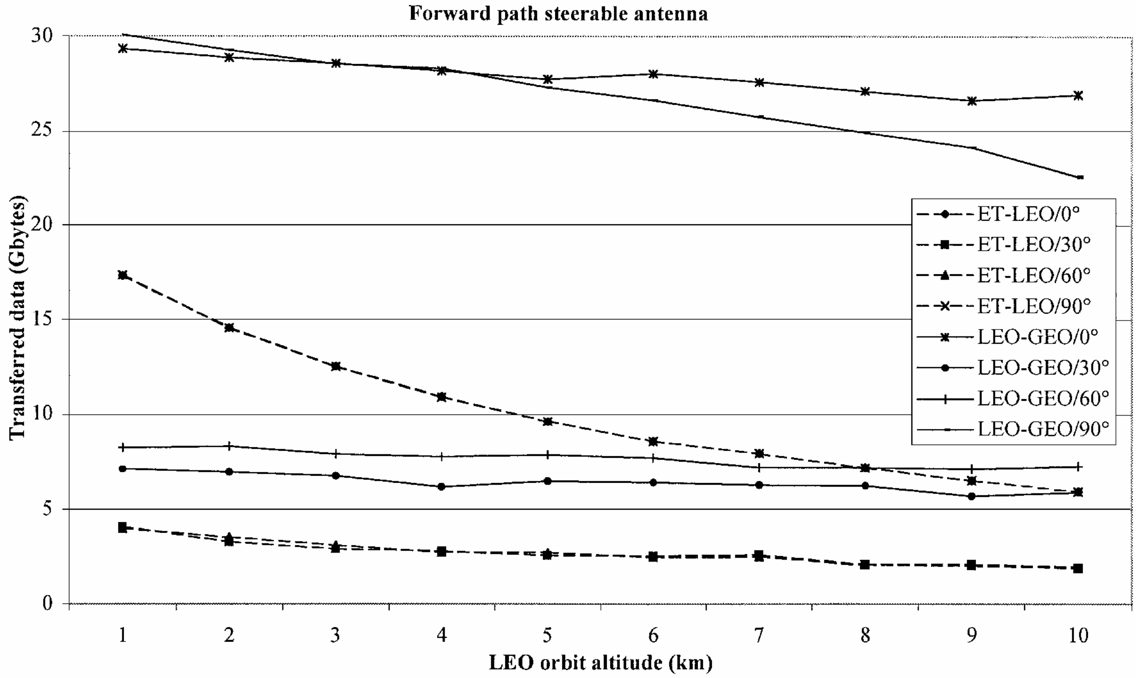

Fig. 6 Transferred data in the forward link using a steerable GEO antenna.

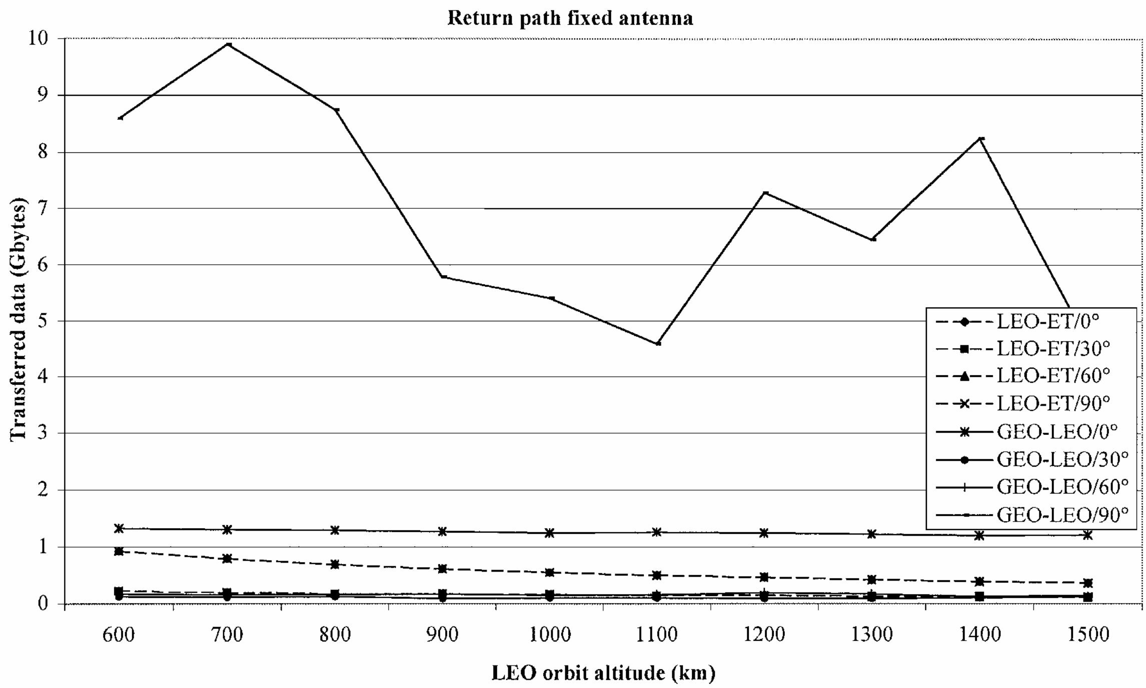

Fig. 7 Transferred data in the return link using a fixed GEO antenna.

and the relative results will be presented. Two different cases have been considered depending on the characteristics of the GEO IOL antenna (fixed or steerable), and two different orbit heights have been selected (600 and 1000 km, respectively).

For all four of the cases, the curves showing the quantity of data that can be transferred in each link present a minimum located at the medium latitudes. The presence of the minimum depends on the fact that for the lower (0–15 deg) and the higher (75–90 deg) latitudes the visibility intervals are larger than at medium latitudes. Hence, the quantity of data that is possible to transfer is greater. A significant difference between the forward path case and the return one is present. In the former the quantity of transferred data is much greater (about two to five times in the fixed GEO antenna case and about three times in the steerable GEO antenna case) because of the already mentioned technological constraints (mainly transmitted power from satellite). For each of the four cases, a brief description of the system's characteristics will be provided.

Forward Path

The results shown in Fig. 9 have been achieved using a constant bit rate in the link ET → LEO, an adaptive bit rate in the link LEO → GEO, a GEO visibility angle of 0.5 deg, a transmitted power from the ET equal to 0.1 W and the two mentioned values of the LEO orbit altitude.

The results referred to a steerable GEO antenna, shown in Fig. 9, have been achieved using an adaptive bit rate in the link ET → LEO,

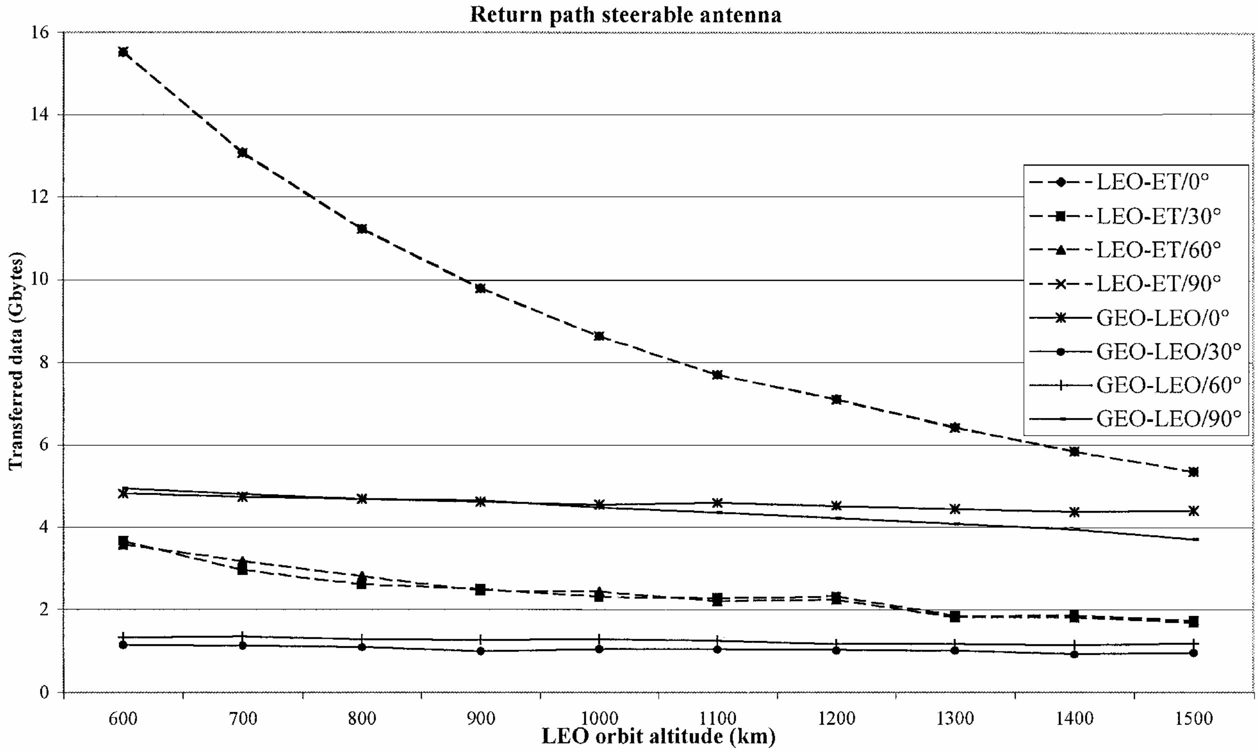

Fig. 8 Transferred data in the return link using a steerable GEO antenna.

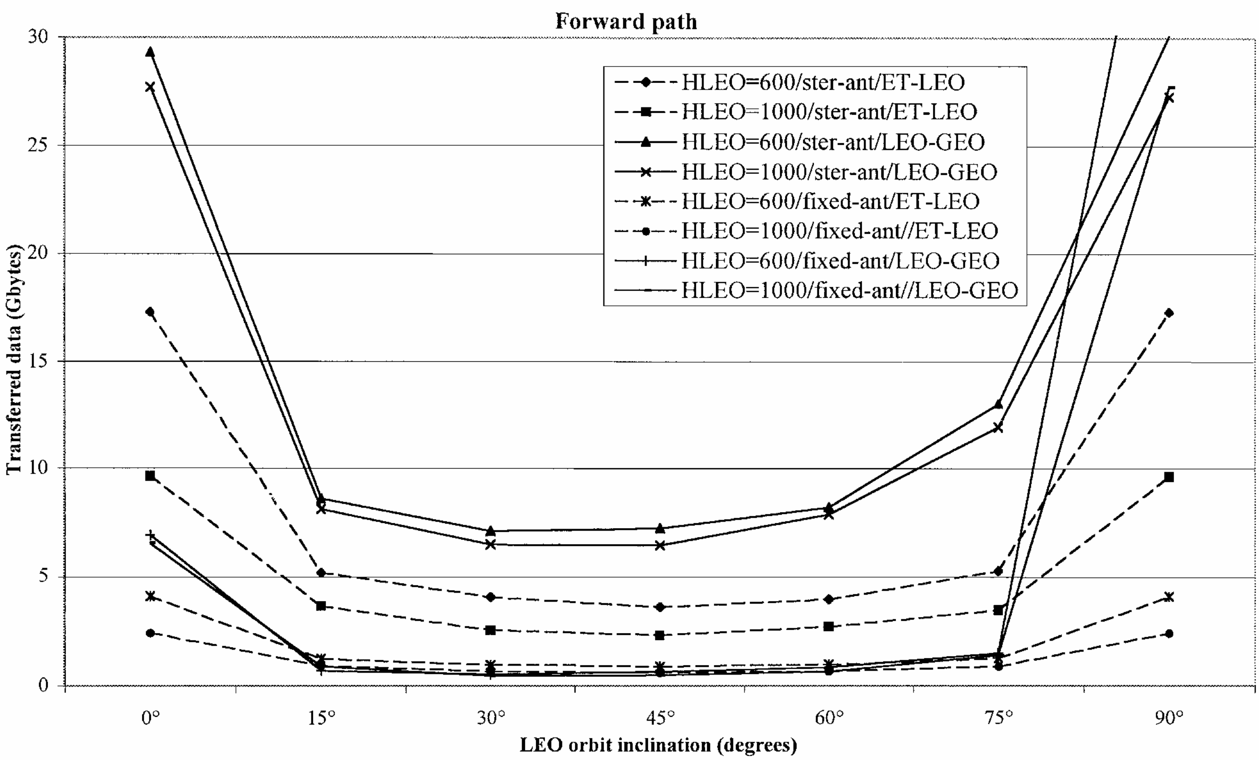

Fig. 9 Transferred data in the forward link as a function of LEO orbit inclination.

a constant bit rate in the link LEO → GEO, a GEO visibility angle of 2 deg, and a transmitted power from the LEO satellite equal to 2 W, for the same two orbit heights of the preceding case.

Return Path

The results referred to a fixed GEO antenna are shown in Fig. 10. They have been achieved using a constant bit rate in the link ET → LEO, a variable bit rate in the link LEO → GEO, and a transmitted power from LEO satellite to ET equal to 5 mW (instead of 10 mW of the preceding case). Moreover, ET noise figure equal to 8 dB, ET receiving losses equal to 0.8 dB, and the two orbit heights have been assumed.

The results referred to a steerable GEO antenna are shown in Fig. 10, too. They have been achieved using a variable bit rate in the link ET → LEO, a constant bit rate in the link LEO → GEO, and a transmitted power from GEO satellite to LEO equal to 2 W (instead of 4 W of the preceding case). Furthermore, a GEO visibility angle of 2 deg and the same two orbit heights have been assumed.

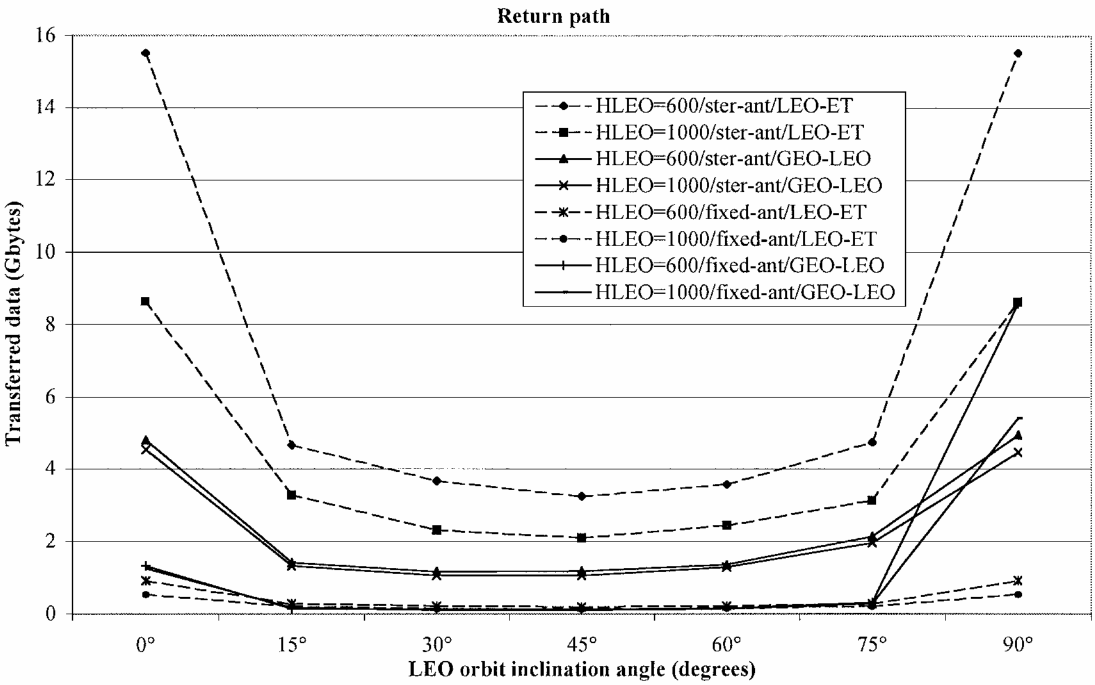

Fig. 10 Transferred data in the return link as a function of LEO orbit inclination.

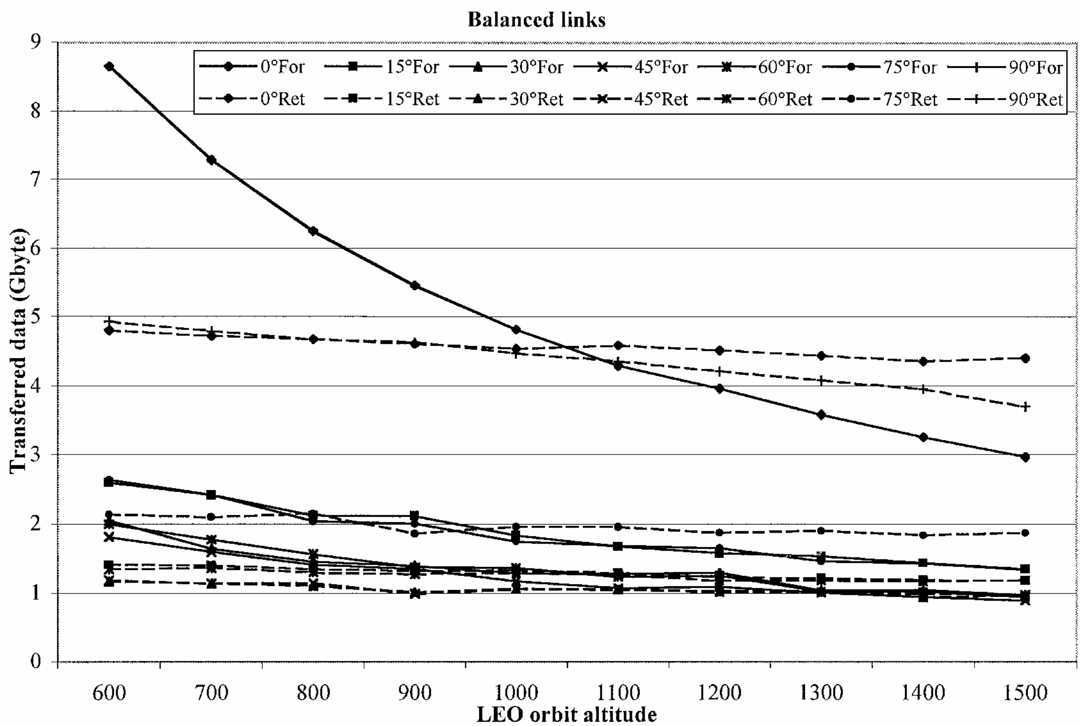

Fig. 11 Balanced link.

Balanced Links

The preceding analysis, other than figuring out optimal working conditions for either the forward or the return path, has highlighted the great imbalance between the two paths. This imbalance is mainly caused by physical and technological constraints regarding LEO transmitted power and antenna gain. This means that the transmission conditions are more favorable for the forward path than the return path.

In the case of balanced communication, some parameters fixed for the forward path in the preceding simulations must be relaxed: the transmitted power from ET (forward link) has been reduced to 0.1 W instead of 0.2 W used as a baseline. The new results achieved after having run the optimization process again are reported in Fig. 11 for LEO orbit inclination angle ranging from 0 up to 90 deg. The optimizations have been performed only for the case of a steerable GEO antenna because it showed the best performance.

Definitively, the system, having asymmetric characteristics in terms of data transfer capability, can also provide symmetric exchange relaxing for example power requirements. To improve power efficiency, adaptive power control could be usefully implemented.

Transmission Delay

For a satellite system based on a hybrid LEO-GEO constellation, the average end-to-end delay T_{packet} is represented symbolically by the following equation:

$$T_{\text{packet}} = T_{\text{trans}} + T_{\text{uplink}} + T_{\text{satproc}} + T_{\text{satq}} + T_{\text{downlink}} + T_{\text{LEO-GEO}} \quad (1)$$

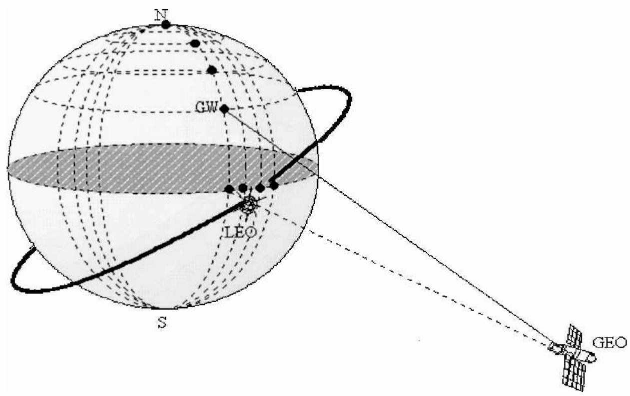

Fig. 12 Positions of the ET (black points) in the first two simulations.

The packet transmission (T_{trans}), satellite processing and route selection ($T_{satproc}$ and T_{satq}) can be neglected because the propagation time in the different links is predominant.

Simulation Results

As far as the delay analysis is concerned, three different simulations have been performed considering several positions of the ET. To implement these simulations, the Earth has been represented with a grid of uniformly distributed points. In the first simulation the ET assumes different positions along the meridian of the gateway. In the second simulation the ET assumes different positions along the equator (Fig. 12). For each position the end-to-end delay has been calculated. In the third simulation the cumulative distributions of the delay has been extracted. To this aim, the whole grid has been considered, and for each point the end-to-end delay has been calculated. The main simulation parameters are listed in Table 4.

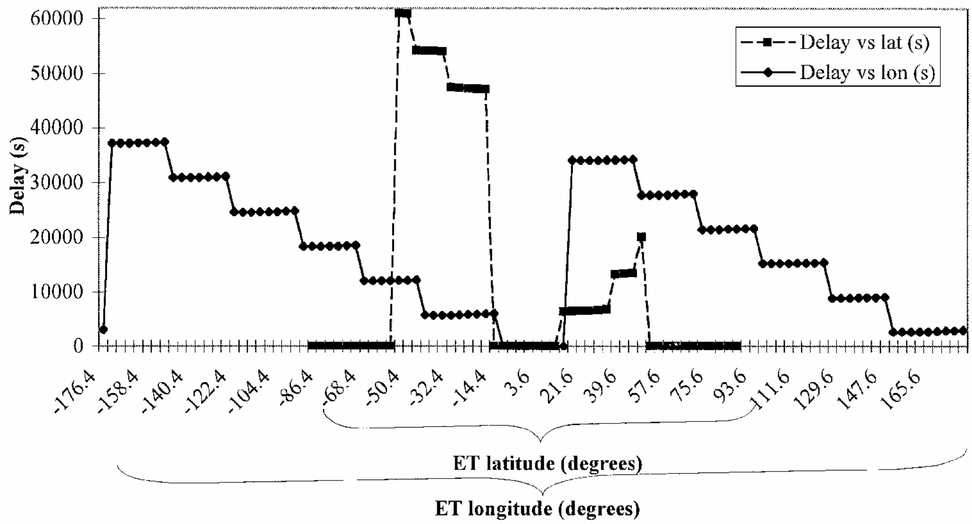

Fig. 13 Transmission delay as a function of latitude and longitude.

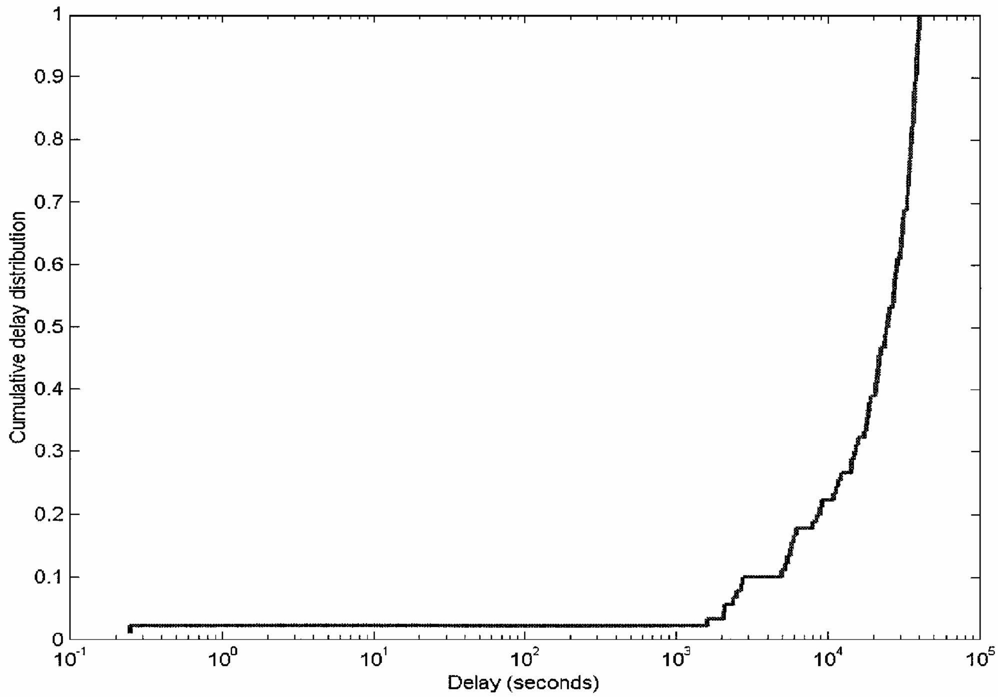

Fig. 14 Cumulative delay distribution.

Table 4 Delay simulation parameters

Parameter	Value
LEO orbit inclination	40 deg
LEO orbit height	1000 km
LEO nadir starting coordinates	0° lat, 0° long.
Gateway coordinates	43.2° N lat, 0° long.
ET minimum elevation angle	30 deg
GEO visibility angle	6 deg
Number of stations (simulations 1 and 2)	3186
Number of stations (simulation 3)	46
Simulation duration	23 h 56 min 4s
Sampling rate	5 s

The results obtained from the first two simulations are presented in Fig. 13 for the case in which the ET is shifted on the equatorial plane and on the meridian of the gateway, respectively. The curves shown in Fig. 13 highlight two different situations. The former is referred to the case in which a direct connection is established among the ET and the LEO satellite; the GEO satellite and the gateway. In this case the delay is about the same as the classical GEO system delay and is of the order of 250 ms. The latter is referred to the case in which a nondirect connection is established from ET to the gateway. In this case the transmission delay is much greater and in the order of thousand seconds (from ~3000 to ~60,000 s).

Figure 14 provides the cumulative delay distribution of the transmission delay. In Figs. 15 and 16 the delay distributions are shown:

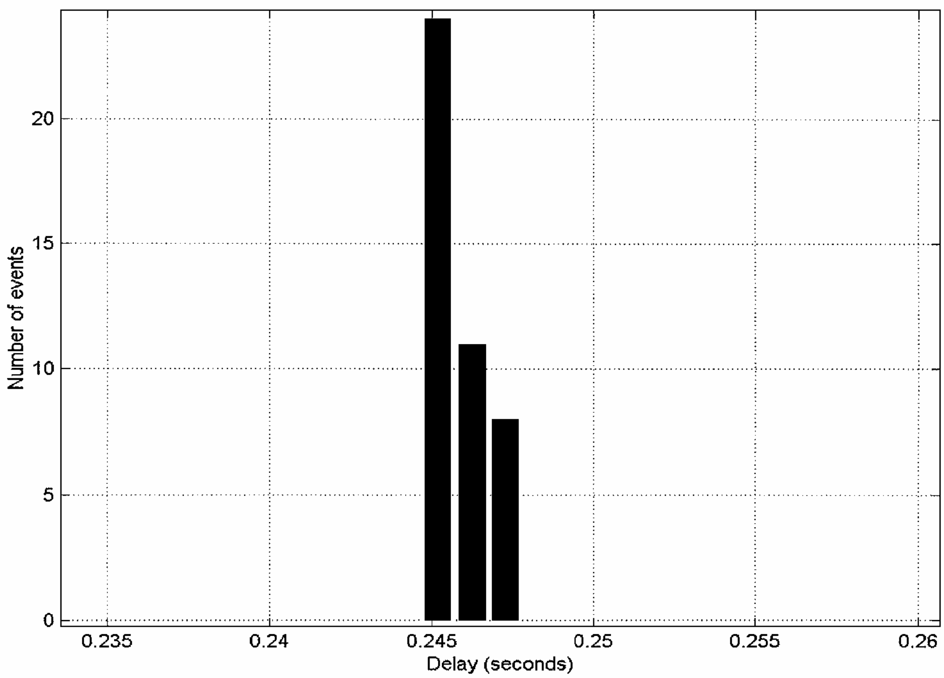

Fig. 15 Delay in the direct transferring case.

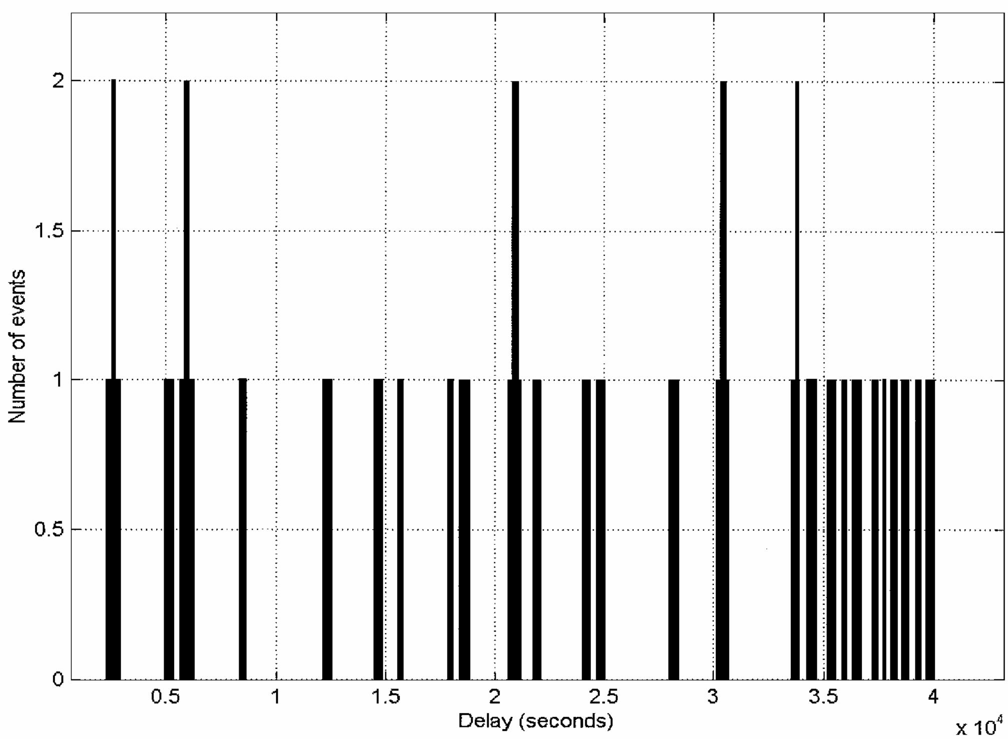

Fig. 16 Delay in no-direct transferring case.

the first figure is referred to the end-to-end direct connection, whereas the second is referred to the case of no-direct connection.

Performance in terms of average and worst-case delay needed to transfer data looks not so acceptable if compared to performance of classical satellite configurations. As a matter of fact, the system is addressed to users not having a better chance to access telecommunication services and, even less, broadband capacity. Moreover, implementing the final configuration with several LEOs and several GEOs overall performance in terms of delay is expected to greatly improve as a result of the presence of multiple satellites.

Conclusions

To improve flexibility and modularity in satellite constellations and service provision, the innovative concept of hybrid orbit architecture has been proposed and analyzed. Some optimization processes have been implemented. The best LEO orbit height and inclination to maximize the transferred data have been identified and presented. Performance of such system configuration in terms of transmission delay has also been evaluated. The overall performance seems very attractive even though optimization of the architecture, especially to improve the time delay, has yet to be pursued.

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