The impact of intersatellite communication links on LEOS performance

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The Impact of Intersatellite Communication Links on LEOS Performance

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Abstract

LEOS communication systems are rapidly moving from dream to reality. When operational, the LEOS systems can offer mobile and fixed-site communications between any two points on the globe. Yet, many LEOS system design issues remain unresolved. Some of the planned systems, such as Iridium and Teledesic, rely on intersatellite communication to provide space based routing from origin to destination while others, like Globalstar, use ground based routing. This paper investigates the effect of satellite crosslink design on user-to-user delay and satellite power consumption. Delay is an important measure of quality of service and may have a significant impact on system revenues. The results indicate that the choice of crosslink architecture has a large effect on user-to-user delay. In a polar orbit LEOS system, there will be two seams from pole to pole 180° apart, where satellites in orbits on opposing sides of the seam move in opposite directions. It is demonstrated that the ability to maintain communication links across the seams is of relatively minor importance for user-to-user delay. Finally, the choice of crosslink pattern and crosslink antenna technology is shown to have no significant impact on satellite power consumption or on LEOS system capacity.

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1 Introduction

With the realization of commercial low earth orbit satellite (LEOS) communication systems, a new era in mobile communication is about to begin. From the first day of full operation, a LEOS system that provides global coverage can offer real-time communication services between mobile and stationary users at any two points on earth.

Several LEOS systems are currently under development. The smaller systems, such as Orbcomm, Starsys and Leosat, will offer services like paging, tracking, messaging and monitoring for a limited area of the globe, and store-and-forward data services on a global basis [25]. Iridium, Globalstar and other large systems will offer worldwide data and voice communication services [6]. One of the more recent initiatives, the Teledesic system, aims to offer world wide, fixed-site and mobile broadband services, including video conferencing and interactive multimedia from a system of 840 satellites in orbits at 700 km above earth [26].

Competing system architectures and technologies are being considered for the systems under development. The success or failure of a given LEOS communication system depends on how well the chosen technology performs with respect to system capacity, quality of service and cost.

LEOS communication system design factors include choice of satellite constellation and altitude, satellite power system, routing method, satellite crosslink design, and the number and location of ground stations. For a full discussion of research issues related to LEOS based communication systems see [9, 10, 11].

The satellites are arranged in a constellation with a number of satellites in prescribed orbits to provide coverage of all or parts of the globe. Proposed patterns include polar orbit constellations [1, 3], rosette constellations [2] and regular polyhedra based constellations [18, 27]. For each satellite constellation and altitude, there is a minimum number of satellites required to provide coverage of a given area of the earth.

The chosen satellite altitude also affects the expected life-time of the individual satellites as the atmospheric drag is higher at low satellite altitudes. Hence, the choice of altitude and constellation determines the required number of satellites, the frequency of initial launch and replacement of satellites and, consequently, the capital investment in the system. Methods have been developed to find optimal launch policies for the initial satellite launches [16], as well as for satellite replacement [15].

In a recent series of papers [12, 13, 14, 24], the effects of satellite altitude choice on system performance characteristics, including user-to-user delay, satellite power consumption and frequency reusability were studied. User-to-user delay is an established factor included in the Mean Opinion Score which measures quality of service in telephony. It was found that the use of low orbits (500–2,000 km) provides the shortest user-to-user delay. Deployment of low orbits also increases frequency reuse factors and reduces power consumption, which results in a much larger system capacity compared to LEOS systems in higher orbits.

A LEOS communication system can either have ground based routing or space based routing. In the former case, a satellite receives a signal from a transmitting user's handset and relays it to a ground station within the satellite coverage area. The signal is then routed through a terrestrial network until it reaches a ground station below the satellite that covers the receiving user. Finally, the signal is relayed from the ground station to the receiving user via the satellite. In the latter case, instead of using a ground network, the signal is passed from satellite to satellite until it reaches the satellite covering the receiving user.

The choice of routing method results in different satellite designs and operating characteristics. Compared to a LEOS system with space based routing, a system with ground based routing has lighter weight satellites with substantially less on-board equipment and is of lower technical complexity. This has benefits in terms of capital cost and satellite launch cost, and results in shorter average and worst-case user-to-user delay. However, it also makes the system dependent on a terrestrial network with a large number of ground stations, requires the cooperation of many ground operating companies (and licensing by the governments in the countries in which these companies operate), which leads to diversion of revenues to ground network operators.

This paper investigates the impact of crosslink architecture on the performance of a LEOS communication system with space based routing and satellites in polar orbits. Constellations with non-polar or elliptical orbits are not considered, since antenna technology that allows for satellite crosslinks in these systems is very complex and costly. It is shown that the choice of crosslink architecture in systems with space based routing has a significant impact on user-to-user delay. The results have important implications for satellite design issues related to antenna equipment.

Services similar to those offered by LEOS systems will also be offered by medium earth orbit satellite (MEOS) systems like Odyssey [23] and ICO Global. However, since the proposed MEOS systems will not employ satellite crosslink communication, they will not be considered further in this paper.

The remainder of the paper is organized as follows. In Section 2, space based routing methodology is explained and the issues related to the maintenance of crosslinks are discussed. Section 3 introduces the crosslink designs studied in this paper, while Section 4 describes the user-to-user delay model for evaluation of the different crosslink designs. Computational results for user-to-user delay are presented in Sections 5 and 6. Section 7 discusses power issues related to satellite crosslinks, and Section 8 concludes the paper.

2 Space Based Routing

This section discusses space based routing methodology. The issue of the seam in a constellation with polar orbits is addressed and necessary conditions for use of optical satellite crosslinks and cross-seam links are derived. Finally, factors limiting the use of radio fre-

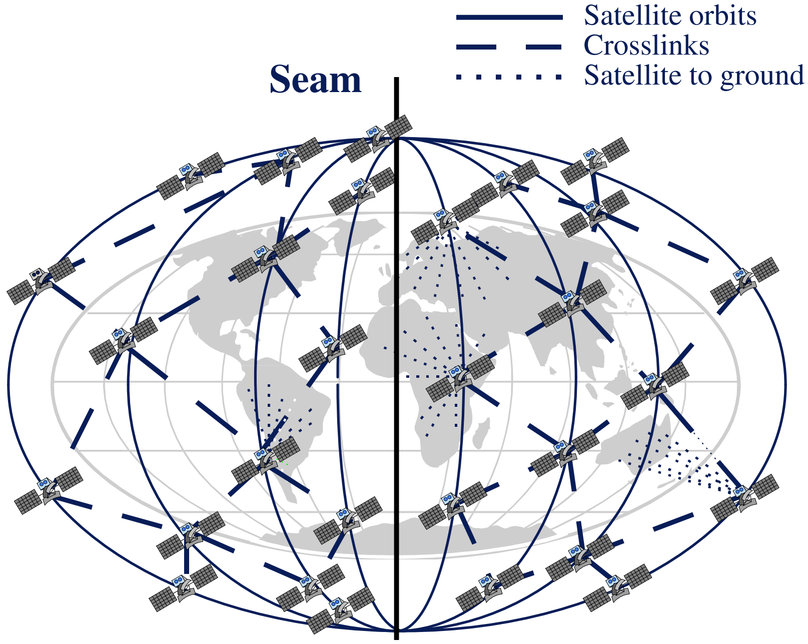

Figure 1: *LEOS communication system coverage of the earth.*

quency (RF) based crosslinks are identified and analyzed[1].

Consider a communication session between two users of a LEOS communication system. Each user transmits and receives information in the form of electromagnetic waves. In a LEOS system with space based routing, the signal will travel from the transmitting user handset to a satellite in his line of sight. Based on the destination of the signal, i.e. the location of the receiving user, the satellite decides which neighboring satellite to route the signal to. The signal propagates from satellite to satellite until it reaches one above the receiving user, from where it is relayed to the receiving user handset.

The user-to-user delay in a communication session depends on the path traveled by the signal. There are five factors composing the end to end delay, namely vocoder delay in the user handsets, queueing delay in the switching nodes, switching delay, transmission delay and signal propagation delay. Since the vocoder delay is incurred only in the user handsets, its contribution to user-to-user delay is independent of the choice of satellite altitude and crosslink pattern. The number of satellites required to provide global coverage decreases with altitude, depending on the selected satellite constellation. A higher satellite altitude reduces the fraction of user-to-user delay caused by queueing, switching and transmission. Counter balancing this reduction in switching and transmission delay is an increase in propagation time for the up- and downlinks as well as on crosslinks between satellites. Hence, a higher altitude increases the proportion of user-to-user delay caused by signal propagation.

In ATM switches, the switching time is typically about 1 ms, so that the switching delay is

[1] Technical issues pertaining to RF antenna deployment were identified after consulting with some experts listed in the Acknowledgment section.

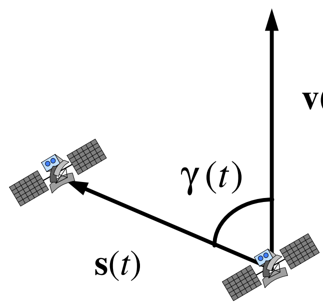

Figure 2: *Geometry of the crosslink antenna pointing angle.*

insignificant compared to the signal propagation delay. In switching and transmission with larger packet sizes, if there are no previously received packets in queue when a new packet arrives, the new packet can be switched and transmitted immediately and the rest of the frame can have empty slots. This way, switching delay can be reduced significantly even in systems with large packet size.

Figure 1 displays a LEOS communication system which is composed of satellites in polar orbits. In this type of constellation, all satellites rotate in the same direction. On one segment of the orbit, all satellites move from South to North, while on the opposite side of the globe, the satellites move from North to South. The first and the last orbit in the constellation will be neighbors so that the satellites in the first orbit move from North to South and the satellites in the last orbit move from South to North (or vice versa). As a result, there will be a 360° seam across which communication between satellites is difficult due to the high relative speed of satellites moving in opposite directions. When projected onto a plane, the seam will appear in two separate segments 180° apart.

The inter-satellite links can use one of several transmission technologies, including microwave radio and laser or other optical transmitters. Optical transmitters and receivers are typically very small, light weight and use low transmission power (a three terminal suite can weigh as little as 28 pounds and use a maximum of 58 W for a reach of up to 9,000 km [19]), but require very high precision pointing due to their narrow antenna beam angles [7]. Because of the frequencies they operate in, combined with their very narrow beam angles, optical transmission systems are not susceptible to interference, except for direct light exposure from the sun, moon and other light sources. However, the diodes have to be directed toward the interfering light source to be affected. Microwave transceiver systems are usually larger in size than its optical based counterparts [7], but are not as sensitive to tracking precision due to a wider beam angle.

Assuming that the earth is spherical, the angular velocity requirement of an antenna can be calculated as follows. Let $\mathbf{v}(t)$ be the velocity of a satellite and let $\mathbf{s}(t)$ be the distance vector to its neighboring satellite (Figure 2). The angle $\gamma(t)$ between the velocity vector and the distance vector is given by

$$\gamma(t) = \cos^{-1} \frac{\mathbf{v}(t) \cdot \mathbf{s}(t)}{\|\mathbf{v}(t)\| \cdot \|\mathbf{s}(t)\|}.$$

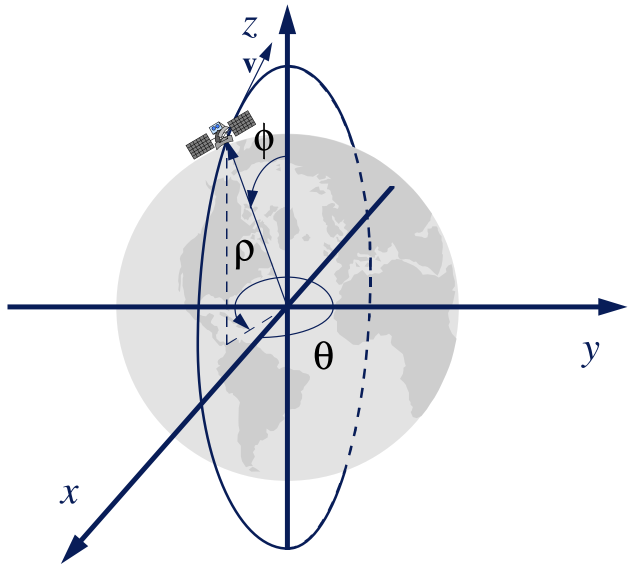

Figure 3: *The geometry of satellite position and motion.*

The position of a satellite in a Cartesian coordinate system can be conveniently expressed in spherical coordinates (Figure 3), i.e.

$$\begin{aligned} x(t) &= \rho \sin\phi(t)\cos\theta \\ y(t) &= \rho \sin\phi(t)\sin\theta \\ z(t) &= \rho\cos\phi(t), \end{aligned}$$

where $\rho = R_E + h$, $\phi(t) = \pi - 2\pi t/T$, and $T = 2\pi\sqrt{\rho^3/\mu}$ is the orbital period. Note that θ is constant since satellites remain in their respective orbital planes.

The distance between two satellites is $\mathbf{s}(t) = \langle x_2(t) - x_1(t), y_2(t) - y_1(t), z_2(t) - z_1(t)\rangle$, and using spherical coordinates, the change in distance between two satellites as they orbit the globe, $\dot{\mathbf{s}}(t)$, can be expressed in component form as

$$\begin{aligned} s_x'(t) &= -\rho\frac{2\pi}{T}(\cos\phi_2(t)\cos\theta_2 - \cos\phi_1(t)\cos\theta_1) \\ s_y'(t) &= -\rho\frac{2\pi}{T}(\cos\phi_2(t)\sin\theta_2 - \cos\phi_1(t)\sin\theta_1) \\ s_z'(t) &= \rho\frac{2\pi}{T}(\sin\phi_2(t) - \sin\phi_1(t)). \end{aligned}$$

As $\mathbf{s}(t)$ changes, so does $\|\mathbf{s}(t)\|$. By definition, $\|\mathbf{s}(t)\| = \sqrt{s_x^2(t) + s_y^2(t) + s_z^2(t)}$. Hence,

$$\begin{aligned} \frac{d}{dt}\|\mathbf{s}(t)\| &= \frac{s_x(t)s_x'(t) + s_y(t)s_y'(t) + s_z(t)s_z'(t)}{\sqrt{s_x^2(t) + s_y^2(t) + s_z^2(t)}} \\ &= \frac{\mathbf{s}(t)\cdot\dot{\mathbf{s}}(t)}{\|\mathbf{s}(t)\|}. \end{aligned}$$

Satellite latitude	Crosslink angular velocity (mrad/s)	Cross-seam angular velocity (mrad/s)	Separation angle α (degrees)	Doppler shift on a 60 GHz link (kHz)
90°S	-1.72	—	30.4	198
80°S	-1.29	22.48	44.2	372
70°S	-0.84	11.52	53.7	453
60°S	-0.49	7.99	59.4	461
50°S	-0.25	6.32	62.3	420
40°S	-0.07	5.39	63.4	346
30°S	0.06	4.85	63.0	249
20°S	0.17	4.52	61.7	139
10°S	0.25	4.35	59.6	22
Equator	-0.37	3.76	56.9	-97
10°N	-0.29	3.82	53.5	-211
20°N	-0.21	4.01	49.5	-313
30°N	-0.09	4.38	44.8	-396
40°N	0.06	4.98	38.9	-451
50°N	0.24	5.96	31.3	-463
60°N	0.35	7.71	21.4	-412
70°N	-0.59	11.33	10.0	-272
80°N	-0.23	22.38	14.2	-2,851
90°N	-2.05	—	30.4	-2,758

Table 1: *Crosslink characteristics for a LEOS communication system with 66 satellites at an altitude of 780 km.*

Similar to $\mathbf{s}(t)$, $\mathbf{v}(t)$ can also be expressed in terms of spherical coordinates, i.e.

$$\begin{aligned} v_x(t) &= \|\mathbf{v}(t)\| \sin\left(\phi_1(t) - \frac{\pi}{2}\right) \cos\theta_1 \\ v_y(t) &= \|\mathbf{v}(t)\| \sin\left(\phi_1(t) - \frac{\pi}{2}\right) \sin\theta_1 \\ v_z(t) &= \|\mathbf{v}(t)\| \cos\left(\phi_1(t) - \frac{\pi}{2}\right), \end{aligned}$$

where $\|\mathbf{v}(t)\| = \sqrt{\mu/\rho}$, which is constant in time. Taking the first derivative of $\mathbf{v}(t)$ yields

$$\begin{aligned} v'_x(t) &= -\|\mathbf{v}(t)\| \frac{2\pi}{T} \cos\left(\phi_1(t) - \frac{\pi}{2}\right) \cos\theta_1 \\ v'_y(t) &= -\|\mathbf{v}(t)\| \frac{2\pi}{T} \cos\left(\phi_1(t) - \frac{\pi}{2}\right) \sin\theta_1 \\ v'_z(t) &= \|\mathbf{v}(t)\| \frac{2\pi}{T} \sin\left(\phi_1(t) - \frac{\pi}{2}\right). \end{aligned}$$

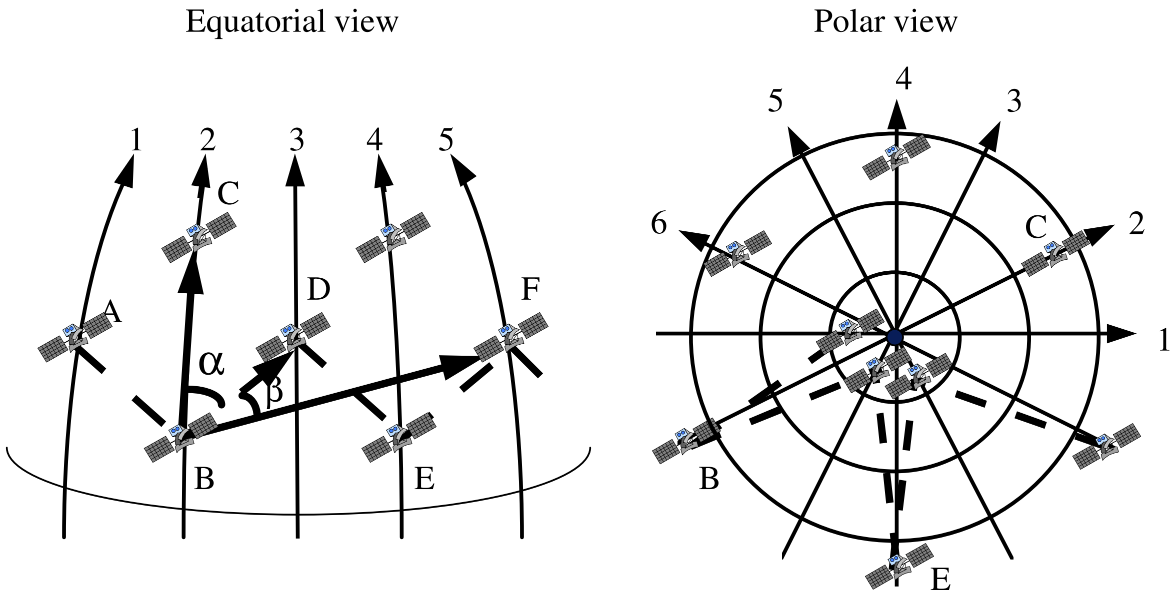

Figure 4: *Geometry of interference angles and distances.*

The angular velocity $\omega(t)$ is found by differentiation of $\gamma(t)$, i.e. $\omega(t) = d\gamma(t)/dt$. After some algebra,

$$\omega(t) \quad = \quad -\frac{\|\mathbf{s}(t)\|^2(\mathbf{v}(t)\cdot\dot{\mathbf{s}}(t) + \dot{\mathbf{v}}(t)\cdot\mathbf{s}(t)) - (\mathbf{s}(t)\cdot\dot{\mathbf{s}}(t))(\mathbf{v}(t)\cdot\mathbf{s}(t))}{\|\mathbf{s}(t)\|^2\sqrt{\|\mathbf{v}(t)\|^2\cdot\|\mathbf{s}(t)\|^2 - (\mathbf{v}(t)\cdot\mathbf{s}(t))^2}}.$$

The ability to maintain optical crosslinks between satellites in different orbits depends on the antennas' ability to adjust their pointing angle. Due to their narrow beam angles, optical antennas require a pointing precision in the range of micro radians. Table 1 shows the angular velocity of the antennas needed to maintain crosslink communication between adjacent orbits. The angular velocity increases as the satellites approach the poles. Depending on the pointing capabilities of the antennas, there will be some latitude at which the links between satellites in different orbits can no longer be maintained. At this point, a satellite is restricted to communicate only with neighboring satellites in the same orbit.

Higher speed precision pointing devices are available but are more complex in design and thereby more expensive. The third column of Table 1 shows the angular velocity requirements for cross-seam links, where the communicating satellites move in opposite directions. The table shows that the cross-seam antenna angular velocity requirements are of one order of magnitude larger than the requirements for other satellite crosslinks. Since antennas with pointing capabilities supporting cross-seam links are higher precision and therefore more expensive to deploy than those only supporting regular crosslinks, it is necessary to investigate whether the benefits of cross-seam technology justifies the higher associated cost and design complexity.

For RF links, pointing precision is less of an issue than for optical antennas since the RF beam angles are much wider. However, in contrast to optical transmission, interference and

Satellite altitude (km)	Crosslink angular velocity $\omega > 0.05°/s$	Smallest separation angle α	Doppler surge latitude	Cross-orbit interference latitude	
				$\beta = 10°$	$\beta = 5°$
500	85°N	6.0° at 78°N	79°N	71°N	75°N
600	70°N	6.0° at 78°N	79°N	58°N	75°N
700	69°N	8.2° at 73°N	74°N	64°N	70°N
800	70°N	8.2° at 73°N	74°N	61°N	70°N
900	70°N	8.2° at 73°N	74°N	54°N	69°N
1,000	68°N	9.0° at 72°N	73°N	53°N	67°N
1,200	61°N	11.2° at 67°N	68°N	50°N	62°N
1,500	63°N	11.2° at 67°N	68°N	50°N	59°N
2,000	60°N	12.8° at 63°N	65°N	51°N	57°N
2,500	54°N	14.9° at 59°N	61°N	46°N	53°N
3,000	62°N	12.7° at 63°N	65°N	58°N	61°N
3,500	57°N	14.8° at 58°N	61°N	53°N	57°N
4,000	50°N	17.6° at 51°N	55°N	47°N	50°N
5,000	52°N	17.6° at 51°N	55°N	47°N	50°N

Table 2: *Crosslink characteristics for LEOS communication systems at different satellite altitudes.*

power saturation are important concerns. The satellites in neighboring orbital planes are phased relative to each other, so that the angle between the direction of the movement of one satellite and the line of sight to its neighbor in an adjacent orbit will change as they both approach the pole. At the same time, the distance between the two satellites will decrease. The consequences of satellite movement depend on transmission technology. For instance, when satellites using RF transmission move from the equator toward a pole, the transmission between satellites B and D in Figure 4 (left) may interfere with the transmission between B and C, depending on the angle α separating satellites C and D. Table 1 displays the separation angle α at different latitudes for a system with 66 satellites in 11 orbits at an altitude of 780 km. Similarly, transmission from satellite B to D may interfere with the transmission from satellite E to F, depending on the separation angle β between satellites D and F, and their distance from B. When the satellites are very close to a pole, as in Figure 4 (right), satellites A, D and F are so close to each other that crosslink interference is inevitable. For a LEOS system with phased orbits and n satellites per orbit, this implies that crosslink communication must terminate before satellite B reaches latitude $90° - 360°/2n$ (i.e. before satellites A, D and E cross the pole), even if the antenna beam width is practically zero.

When the first of two neighboring satellites is passing a pole, the distance between the satellites changes rapidly until the second one has also crossed the pole. The rapid change in distance creates a surge in the Doppler shift of the radio signal. This surge can be as much as five to ten times the maximum Doppler shift during the rest of the satellite orbit, as shown in the last column of Table 1.

Crosslink characteristics for different satellite altitudes are summarized in Table 2. The table reveals that several factors have to be controlled simultaneously in order to maintain crosslink communication as satellites approach a pole. For instance, the separation angle and distance between satellites are reduced as the satellites approach the poles. This problem can be mitigated with the use of antennas with narrower beams. However, reducing the beam angle means that the antenna steering precision has to be improved and more stringent satellite formation tolerances become necessary, implying greater fuel requirements. The simultaneous increase in antenna pointing angle velocity increases the complexity of the control systems. Similarly, interference and power saturation of receivers can be reduced by careful transmission power control.

Although each of the factors limiting RF crosslink deployment (antenna beam angle and pointing precision, transmission power control, and Doppler shift) can be addressed individually, each of them will add a level of complexity to the satellite communication system design. With the added complexity follows increased on-board processing capability requirements, increased equipment size and weight and, in the end, added cost in terms of development, investments and satellite launches. A convenient operational decision would therefore be not to operate cross-link antennas at latitudes that require increased sophistication of the deployed technology, provided that such a decision is economically justifiable, i.e. that performance does not suffer disproportionately.

3 Crosslink Pattern Design

Satellite design involves the trade-off between many different factors that affect the operation, life-time and launch cost of the satellites [14]. Therefore, each satellite has a limited weight budget. The weight has to be carefully allocated to the different components which compose the overall satellite (solar panels, batteries, telemetry, tracking and positioning equipment, propellant, etc.). The weight constraint limits the weight allocated to, and hence the number of, crosslink antennas. Interference due to intersatellite links also plays a role in the number of crosslink antennas per satellite. Although in some designs (such as Teledesic) satellites can have more antennas, this paper concentrates on and analyzes LEOS systems consisting of four crosslink antennas per satellite. Yet, within this limit on the number of crosslink antennas, several crosslink patterns are possible. This section introduces four alternative crosslink designs for satellites with four crosslink antennas. The advantages and disadvantages of each of them are discussed.

Figures 5–8 display four possible crosslink patterns for polar orbit systems. The pictures are stylized in the sense that the earth and the satellite orbits are projected onto a plane. Also displayed is the seam that separates satellites in counter rotating directions. (Since the seam is a full circle, it also separates the first orbit in the left margins of the pictures from the last orbit in the right margins.) It is assumed that there are no cross-seam links and the number of inter-orbit links will depend on the angular velocity adjustment capability of the antenna pointing devices.

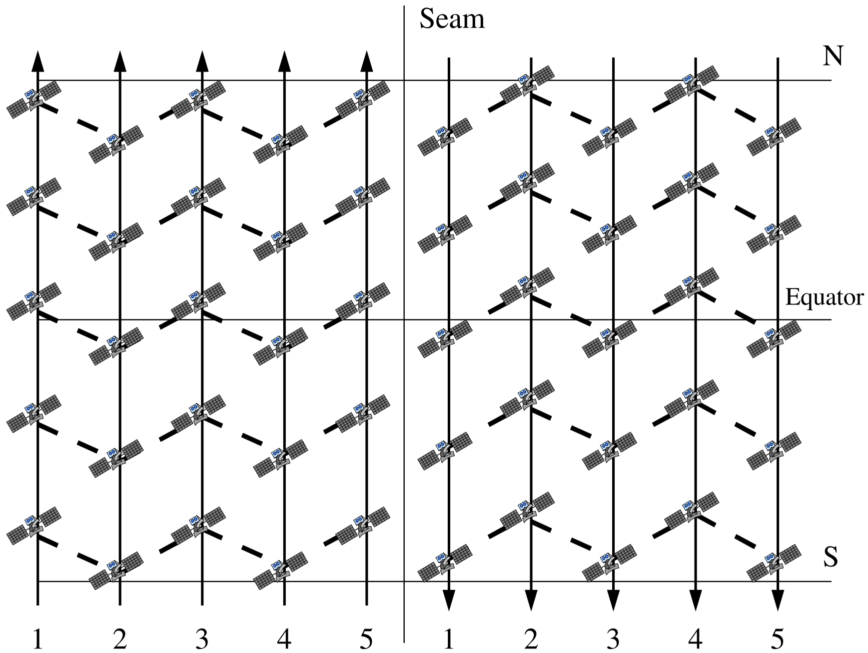

Figure 5: *Crosslink pattern A for satellites with four intersatellite antennas.*

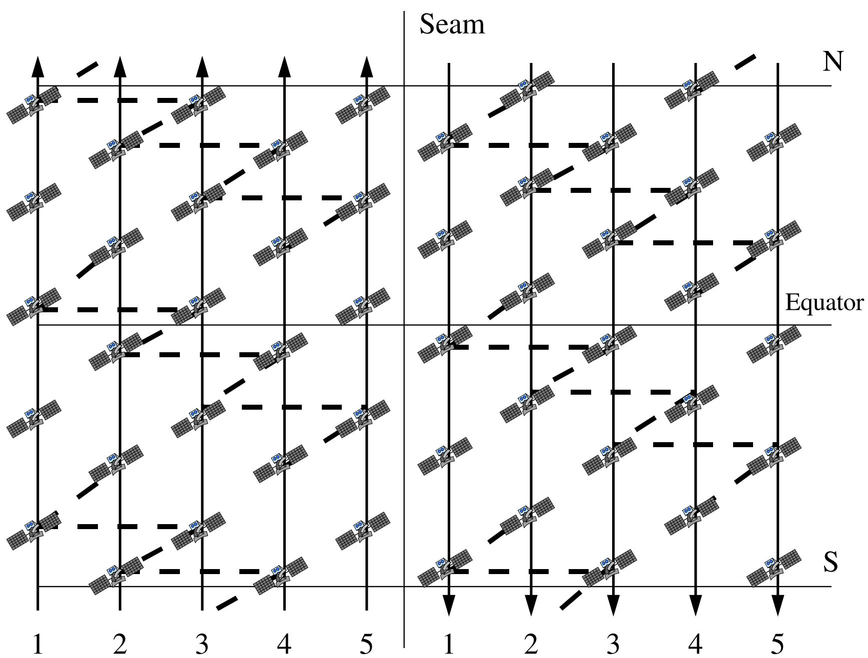

Figure 6: *Crosslink pattern B for satellites with four intersatellite antennas.*

Pattern A (Figure 5) is the simplest one with only single jumps. This pattern is beneficial when traffic demand is local in nature. Pattern B (Figure 6) has better East–West communication capabilities than pattern A, since double jumps are possible in the latitu-

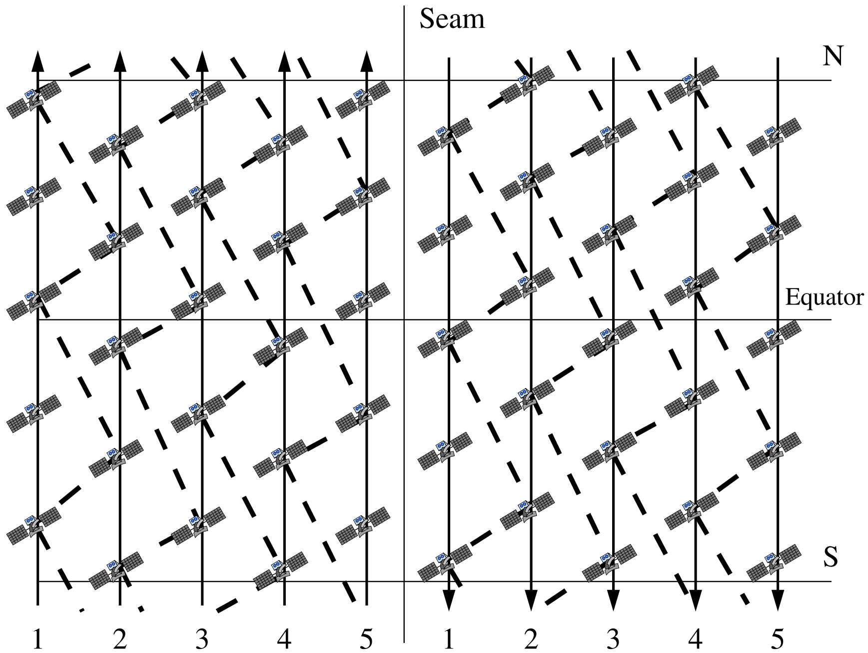

Figure 7: *Crosslink pattern C for satellites with four intersatellite antennas.*

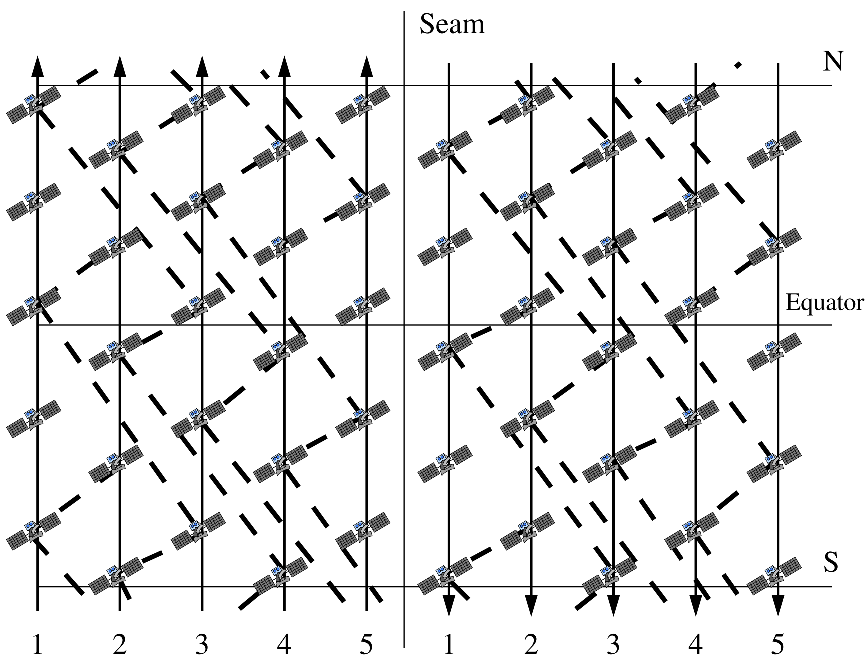

Figure 8: *Crosslink pattern D for satellites with four intersatellite antennas.*

dinal direction. However, this comes at the cost of reduced local communication efficiency. Pattern C (Figure 7) allows a double jump in the North-South direction, while pattern D (Figure 8) allows a diagonal double jump. These jumps will tend to reduce the delay for communication in the diagonal direction at the cost of reduced performance in the East–West direction. In the pure North–South direction, all patterns have the same characteristics, since the intra-orbit links are always maintained.

4 User-to-User Delay

User-to-user signal delay is an important component of quality of service measures like the Mean Opinion Score in telephony. This section develops methods for calculation of shortest, average and worst-case user-to-user delay for LEOS systems with space based routing.

Early work in LEOS communication systems [17, 21] discussed user-to-user delay. These concluded without any modeling or quantitative analysis that propagation delays in LEOS systems are minimal. Based on crude assumptions on crosslink architecture and satellite distance, an upper bound on user-to-user delay has been calculated [5]. More recently, a more comprehensive study modeled delay for a seamless LEOS system with orbits based on regular polyhedra constellations [28]. However, the angular velocity of the communication links was not established. Hence, the technical and economic feasibility of the described system remains undetermined. Similarly, a user-to-user delay study for two proposed LEOS systems with satellite crosslinks was presented in [4]. But, as in [28], the angular velocity of the crosslink communication links was not determined, and was not taken into consideration in calculating end-to-end delays.

The analysis in this section establishes more precise delay bounds, and provides measures of the average delay for different crosslink patterns. In the analysis, it is assumed that there is a constant switching time at the satellites, i.e. there is no queueing of packets in the satellites. This is a reasonable assumption for systems based on ATM switching such as Teledesic and for systems in which the capacity of intersatellite links and on-board processing is so large relative to up and down link capacities that messages will never experience significant queueing delays at intersatellite links. In the analysis, it is also assumed that the only locations in which compression/decompression takes place is in the user handsets. Under this assumption the only effect of vocoder delay is to add a constant to all delay measures.

Average delay is important because this is what a user perceives as the overall delay performance of the system. An occasional worst-case delay is usually acceptable to a user as long as the average delay is short. However, it is also desirable to keep the maximum user-to-user delay small in order to minimize delay variation and provide uniform service. Variability of delay has a negative impact on the quality of voice, video and other real-time communication.

The following notation is used in calculating the user-to-user delay model:

S	is the set of all communicating source-destination pairs.
R_{sd}	is the set of intersatellite links on the route from source s to destination d, $sd \in S$.
$\widehat{h}$	is the the average ground user to satellite distance.
c	is the signal propagation speed.
w_{sd}	is the delay weighing factor for the source-destination pair $sd \in S$.
n_{sd}	is the number of satellites on the route from source s to destination d, $sd \in S$.
T_s	is the switching time.
T_t	is the transmission time. T_t depends on link capacity.
T_u	is the ground-to-satellite (uplink) signal propagation time.
T_d	is the satellite-to-ground (downlink) signal propagation time.
d_{ij}	is the distance between satellite i and satellite j.
T_{ij}	is the signal propagation time from satellite i to satellite j. T_{ij} is proportional to d_{ij}.
$T_{\min}$	is the shortest user-to-user signal delay for the given LEOS system.
$T_{\max}$	is the longest user-to-user signal delay for the given LEOS system.
T_{avg}	is the average user-to-user signal delay for the given LEOS system.

The shortest user-to-user delay occurs when both end users are covered by the same satellite. In this case, the delay is given by

$$T_{\min} = T_u + T_d + T_s + T_t, \tag{1}$$

where

$$T_u = T_d = \frac{\widehat{h}}{c}. \tag{2}$$

Hence, the delay depends only on the satellite altitude and the switching time since only one routing is possible.

The seam between orbits with satellites moving in opposite directions causes long user-to-user delays when cross-seam links are not present. Very long delays can occur even though the two communicating parties are within short distance from each other if their covering satellites are separated by the seam. The worst-case user-to-user delay is calculated from

$$T_{\max} = \max_{sd \in S} \sum_{\{ij\} \in R_{sd}} T_{ij} + T_u + T_d + n_{sd} T_s + T_t \left(n_{sd} + 1\right), \tag{3}$$

where R_{sd} is found using the shortest path algorithm [8] on the crosslink network, including switching delay on each segment.

The average user-to-user delay is calculated according to

$$T_{\text{avg}} = T_u + T_d + \sum_{sd \in S} w_{sd} \left(\sum_{\{ij\} \in R_{sd}} T_{ij} + n_{sd} T_s + T_t \left(n_{sd} + 1\right) \right). \tag{4}$$

The weights w_{sd} are used in order to capture end to end delay as experienced by the average user. For the LEOS communication companies, demand weighted delay carries information about quality of service to the average LEOS customer and is thus related to system performance and revenue generation potential.

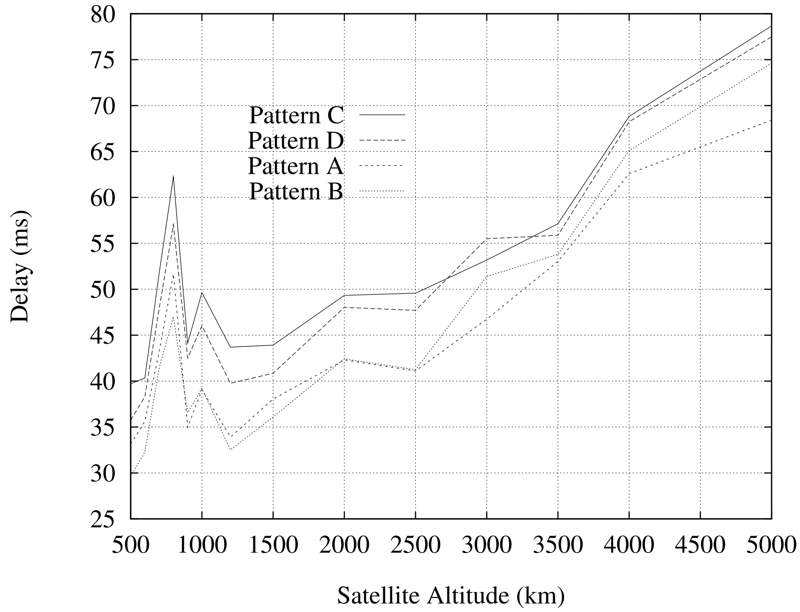

Figure 9: *Demand weighted average delay as a function of satellite altitude for the four crosslink patterns with 5 ms switching time.*

To estimate demand patterns, the following rationale is used. Economic activity forms the basis for a significant amount of the demand for communication. Therefore, a crude demand estimate can be found using trade statistics. Let E_{sd} be the exports (in some monetary unit) from the region covered by satellite s to the region covered by satellite d and let I_{sd} be the imports to s from d. Then, the weights are calculated according to

$$w_{sd} = \frac{E_{sd} + I_{sd}}{\sum_{ij \in S} w_{ij}}. \tag{5}$$

If s equals d, $E_{sd} + I_{sd}$ can be estimated as the GDP of that region. Since international trade is only a fraction of a nation's GDP, a large weight is given to local communication with this scheme.

In general, LEOS systems do not have a repeating ground track. Consequently, the placement of the seam and the relative placement of satellites above users change over time. To capture this effect, the static delay calculations described above can be repeated for a number of shifted footprints. The average of these calculations will give an accurate measure of the average user-to-user delay. Similarly, the maximum and minimum user-to-user delays over all shifted footprints will give the maximum and minimum delays for the given system.

It could be argued that a significant proportion of traffic demand will be between one mobile user and one terrestrial network based user. Given that each satellite is able to communicate with a ground station at any given time, this would imply that the local traffic component is increased. While such a demand pattern would tend to reduce the average user-to-user delay, the ranking of crosslink patterns would remain unchanged. If, on the other hand,

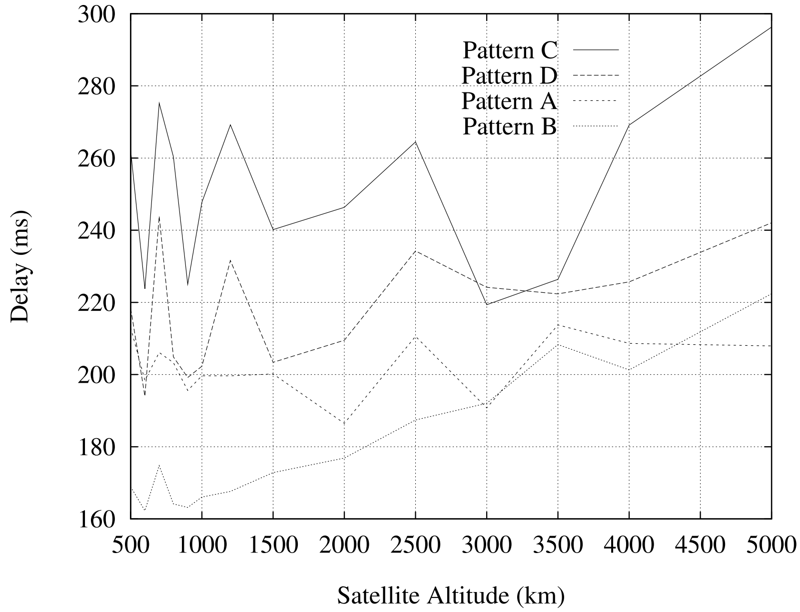

Figure 10: *Worst case delay as a function of satellite altitude for the four crosslink patterns with 5 ms switching time.*

there is not a ground station in sight from every satellite, part of the transmission would require a space routed segment. An interesting question in that case is how to find a good strategy to place ground stations. However, such a discussion is beyond the scope of this paper.

Figures 9 and 10 show the average and worst-case user-to-user delay, respectively, for the four crosslink patterns introduced in the previous section. In the calculations, a switching delay of 5 ms was used and the maximum antenna angular velocity was set to 0.05 degrees per second (beyond which the crosslink antenna is shut off). Pattern B gives the lowest user-to-user delay at satellite altitudes below 2,500 km. The main reason for this is that pattern B gives excellent delay characteristics in the latitudinal direction without suffering much in the longitudinal direction. Given the weighing scheme used in these calculations, this is especially important in the demand weighted average, since most of the long distance trade flows are in the East–West direction. The huge differences, up to 60%, in worst-case user-to-user delay are counter intuitive. The poor performance of crosslink patterns C and D is due to the cut-off of crosslinks at relatively modest latitudes, forcing much of the East–West traffic to pass close to the equator.

In real time communication, such as voice and video, delay variation causes distortion in the received signal. Thus, low variation in user-to-user delay is desirable to ensure high quality reception. Figure 11 displays the standard deviation in user-to-user delay for the four crosslink patterns when a switching delay of 5 ms is used. Again, crosslink pattern B displays the best performance, especially at the lower altitudes.

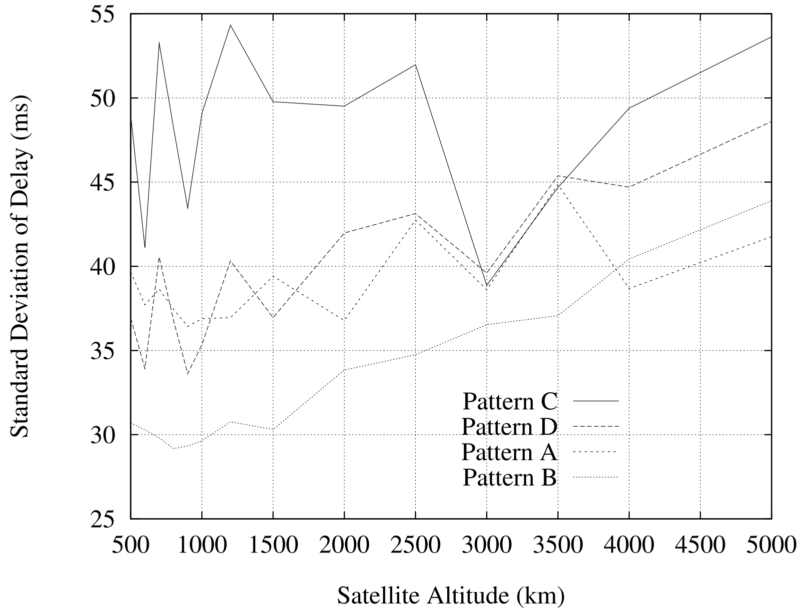

Figure 11: *Standard deviation of user-to-user delay as a function of satellite altitude for the four crosslink patterns with 5 ms switching time.*

5 Delay Effects of Crosslink Antenna Improvements

This section investigates the effect of antenna steering capabilities on user-to-user delay. Although steering capability is an issue mainly for optical antennas, the results have similar implications for RF based antenna systems. The reason is that there is a simple relationship between antenna angular velocity and satellite latitude. Depending on the desired latitude for termination of RF crosslink communication, the corresponding angular velocity can be found.

The previous section showed that crosslink pattern B was superior in terms of user-to-user delay relative to the other proposed crosslink patterns for altitudes below 2,500 km, which covers all of the useful altitudes below the inner Van Allen radiation belt. It is possible to invest in new and improved crosslink antenna pointing device technologies which can maintain crosslink communication at much higher antenna angular change rates. One of the questions is whether it is worthwhile to make the significant investment in antennas with such steering capabilities. The calculations are based on crosslink pattern B and switching delays of 1, 2, 5 and 10 ms. The gains in delay results are similar for other crosslink patterns and switching delays.

With an increase in the maximum angular velocity of the crosslink antennas, communication links can be maintained at higher latitudes between satellites in different orbits. Hence, communication in the East–West direction between users at high latitudes will experience reduced user-to-user delay, as the signal can be routed directly in the latitudinal direction without much movement in the longitudinal direction.

Satellite altitude (km)	1 ms switching time: Crosslink antenna shut-off angular velocity (deg/sec) 0.04	0.05	0.06	0.07	0.08	0.10	Max. reduction (%)	2 ms switching time: Crosslink antenna shut-off angular velocity (deg/sec) 0.04	0.05	0.06	0.07	0.08	0.10	Max. reduction (%)
500	20.10	19.19	18.81	18.38	18.27	18.02	10.35	25.43	24.40	23.98	23.50	23.37	23.10	9.16
600	22.56	21.70	21.39	21.13	21.05	20.78	7.89	27.95	27.00	26.66	26.37	26.28	25.98	7.05
700	30.73	29.82	29.15	28.94	28.60	28.60	6.93	36.62	35.62	34.89	34.66	34.32	34.32	6.28
800	36.15	34.29	33.58	33.02	32.81	32.28	10.71	42.71	40.66	39.90	39.30	39.07	38.54	9.76
900	28.55	26.72	26.44	25.37	24.99	24.23	15.13	33.63	31.64	31.34	30.19	29.79	29.00	13.77
1,000	30.38	29.22	28.11	27.36	26.82	25.96	14.55	35.45	34.21	33.01	32.21	31.65	30.75	13.26
1,200	25.89	24.71	24.27	23.62	23.62	23.62	8.77	29.87	28.61	28.14	27.47	27.47	27.47	8.03
1,500	29.82	28.33	27.60	27.40	27.08	27.08	9.19	33.81	32.21	31.45	31.24	30.90	30.90	8.61
2,000	37.18	34.70	33.04	33.04	31.91	31.91	14.17	41.16	38.56	36.82	36.82	35.66	35.66	13.36
2,500	34.99	34.52	33.70	32.39	32.39	32.39	7.43	38.38	37.89	37.03	35.67	35.67	35.67	7.06
3,000	45.03	44.11	39.83	39.83	39.83	37.90	15.83	48.71	47.75	43.33	43.33	43.33	41.30	15.21
3,500	47.07	47.07	46.57	46.57	45.65	45.65	3.02	50.44	50.44	49.92	49.92	48.97	48.97	2.91
4,000	59.11	58.00	58.00	57.80	57.80	57.80	2.22	62.69	61.55	61.55	61.34	61.34	61.34	2.15
5,000	67.52	67.52	67.30	67.30	67.30	67.30	0.33	71.07	71.07	70.84	70.84	70.84	70.84	0.32

Satellite altitude (km)	5 ms switching time: Crosslink antenna shut-off angular velocity (deg/sec) 0.04	0.05	0.06	0.07	0.08	0.10	Max. reduction (%)	10 ms switching time: Crosslink antenna shut-off angular velocity (deg/sec) 0.04	0.05	0.06	0.07	0.08	0.10	Max. reduction (%)
500	30.76	29.62	29.14	28.62	28.47	28.18	8.39	44.08	42.65	42.05	41.40	41.21	40.88	7.26
600	33.35	32.29	31.92	31.60	31.51	31.18	6.51	46.82	45.53	45.07	44.69	44.57	44.17	5.66
700	42.51	41.42	40.63	40.39	40.04	40.04	5.81	57.23	55.93	54.98	54.71	54.33	54.33	5.07
800	49.28	47.04	46.21	45.57	45.33	44.79	9.11	65.69	62.98	61.98	61.24	60.98	60.44	7.99
900	38.72	36.57	36.24	35.02	34.59	33.76	12.81	51.43	48.88	48.49	47.07	46.58	45.67	11.20
1,000	40.53	39.19	37.91	37.06	36.47	35.54	12.31	53.22	51.66	50.15	49.19	48.53	47.51	10.73
1,200	33.84	32.51	32.01	31.32	31.32	31.32	7.45	43.78	42.25	41.69	40.95	40.95	40.95	6.46
1,500	37.79	36.09	35.29	35.08	34.73	34.73	8.10	47.76	45.80	44.91	44.68	44.30	44.30	7.24
2,000	45.15	42.43	40.60	40.60	39.40	39.40	12.74	55.10	52.09	50.04	50.04	48.75	48.75	11.52
2,500	41.77	41.25	40.36	38.95	38.95	38.95	6.75	50.25	49.66	48.69	47.15	47.15	47.15	6.17
3,000	52.39	51.39	46.83	46.83	46.83	44.70	14.68	61.58	60.48	55.56	55.56	55.56	53.20	13.61
3,500	53.80	53.80	53.27	53.27	52.28	52.28	2.83	62.21	62.21	61.63	61.63	60.57	60.57	2.64
4,000	66.26	65.10	65.10	64.88	64.88	64.88	2.08	75.20	73.97	73.97	73.73	73.73	73.73	1.95
5,000	74.62	74.62	74.38	74.38	74.38	74.38	0.32	83.48	83.48	83.23	83.23	83.23	83.23	0.30

Table 3: *Demand weighted average user-to-user delay for satellite systems with crosslink pattern B at different altitudes and for different crosslink antenna shut-off angular velocities.*

Satellite altitude (km)	1 ms switching time							2 ms switching time						
	Crosslink antenna shut-off angular velocity (deg/sec)						Max. reduction (%)	Crosslink antenna shut-off angular velocity (deg/sec)						Max. reduction (%)
	0.04	0.05	0.06	0.07	0.08	0.10		0.04	0.05	0.06	0.07	0.08	0.10	
500	120.15	119.80	119.01	119.01	119.01	119.01	0.95	145.08	143.25	143.25	143.25	143.25	143.25	1.26
600	117.09	114.27	114.27	114.27	114.27	114.27	2.41	139.29	138.27	138.27	138.27	138.27	138.27	0.73
700	130.78	130.78	129.27	129.09	129.09	129.09	1.29	152.78	152.78	151.27	151.09	151.09	151.09	1.11
800	128.17	128.17	128.17	128.17	128.17	128.17	0.00	146.17	146.17	146.17	146.17	146.17	146.17	0.00
900	127.24	123.96	123.96	123.59	123.59	123.10	3.25	147.24	143.23	143.11	143.11	143.11	143.11	2.80
1,000	141.00	131.45	131.14	128.88	128.01	125.75	10.82	161.00	148.25	148.25	148.25	148.01	145.75	9.47
1,200	135.62	135.62	135.62	135.62	135.62	135.62	0.00	151.62	151.62	151.62	151.62	151.62	151.62	0.00
1,500	140.81	140.81	132.94	132.94	132.94	132.94	5.59	156.81	156.81	144.94	144.94	144.94	144.94	7.57
2,000	165.83	150.32	150.32	150.32	147.66	147.66	10.96	179.83	164.32	164.32	164.32	163.66	163.66	8.99
2,500	163.39	163.39	163.39	163.39	163.39	163.39	0.00	175.39	175.39	175.39	175.39	175.39	175.39	0.00
3,000	171.16	168.04	155.95	155.95	155.95	151.22	11.65	185.16	180.04	167.95	167.95	167.95	161.22	12.93
3,500	184.32	184.32	171.71	171.71	150.32	150.32	18.45	196.32	196.32	183.71	183.71	159.42	159.42	18.80
4,000	185.48	181.29	181.29	177.04	177.04	177.04	4.55	195.48	191.29	191.29	187.04	187.04	187.04	4.32
5,000	202.38	202.38	197.72	197.72	197.72	197.72	2.30	212.38	212.38	207.72	207.72	207.72	207.72	2.19

Satellite altitude (km)	5 ms switching time							10 ms switching time						
	Crosslink antenna shut-off angular velocity (deg/sec)						Max. reduction (%)	Crosslink antenna shut-off angular velocity (deg/sec)						Max. reduction (%)
	0.04	0.05	0.06	0.07	0.08	0.10		0.04	0.05	0.06	0.07	0.08	0.10	
500	171.08	168.88	168.88	168.88	168.88	168.88	1.29	234.14	231.20	231.20	231.20	231.20	231.20	1.26
600	162.27	162.27	162.27	162.27	162.27	162.27	0.00	217.38	217.38	217.38	217.38	217.38	217.38	0.00
700	174.78	174.78	173.27	173.09	173.09	173.09	0.97	229.78	229.78	228.27	228.09	228.09	228.09	0.74
800	164.17	164.17	164.17	164.17	164.17	164.17	0.00	211.88	210.45	209.17	209.17	209.17	209.17	1.28
900	167.24	163.15	163.10	163.10	163.10	163.10	2.48	217.24	210.96	210.96	210.96	210.96	210.96	2.89
1,000	181.00	166.05	166.05	166.05	166.05	164.35	9.20	231.00	206.05	206.05	206.05	206.05	206.05	10.80
1,200	167.62	167.62	167.62	167.62	167.62	167.62	0.00	207.62	207.62	207.62	207.62	207.62	207.62	0.00
1,500	172.81	172.81	156.94	156.94	156.94	156.94	9.18	212.81	212.81	186.94	186.94	186.94	186.94	12.16
2,000	193.83	176.85	176.85	176.85	176.85	176.85	8.76	228.83	206.85	206.85	206.85	206.85	206.85	9.61
2,500	187.39	187.39	187.39	187.39	187.39	187.39	0.00	217.39	217.39	217.39	217.39	217.39	217.39	0.00
3,000	199.16	192.04	179.95	179.95	179.95	171.22	14.03	234.16	222.04	209.95	209.95	209.95	196.22	16.20
3,500	208.32	208.32	195.71	195.71	169.42	169.42	18.67	238.32	238.32	225.71	225.71	194.42	194.42	18.42
4,000	205.48	201.29	201.29	197.04	197.04	197.04	4.11	230.48	226.29	226.29	222.04	222.04	222.04	3.66
5,000	222.38	222.38	217.72	217.72	217.72	217.72	2.10	247.38	247.38	242.72	242.72	242.72	242.72	1.88

Table 4: *Worst-case user-to-user delay for satellite systems with crosslink pattern B at different altitudes and for different crosslink antenna shut-off angular velocities.*

Tables 3 and 4 show that there is a reduction in user-to-user delay with increased antenna steering mechanism capabilities. However, the gains in demand weighted average user-to-user delay are moderate, especially for the longer switching times. The main reason for this result is that most traffic demand is from areas within 60°S to 60°N, where there are almost always inter-orbit satellite crosslinks. Similarly, the gains in maximum user-to-user delay are limited by the case where the signal has to travel half a circle in the North–South direction, as would be the case for two users located 180° apart on the equator. For some satellite constellations, improved crosslink antenna capabilities have no effect at all on worst-case user-to-user delay.

6 Delay Effects of Cross-Seam Antenna Employment

Similar to the discussion in the previous section, it is also possible to invest in antenna steering device technologies that permit communication between satellites on opposite sides of the seam. Table 2 showed that the angular velocity capability of an optical cross-seam antenna must be one order of magnitude higher than for the inter-orbit crosslink antennas. The technology to achieve such precision is more expensive than for regular crosslink antennas. Therefore, it is interesting to investigate what impact the employment of cross-seam antenna technology has on system performance. In this section, the effect of cross-seam antenna employment on user-to-user delay is studied. Again, crosslink pattern B and switching delays of 1, 2, 5 and 10 ms are used.

Tables 5 and 6 show that the reductions in both the demand weighted user-to-user delay and the maximum user-to-user delay are moderate, and less than 20% in all cases.

When making a decision on whether or not to invest in cross-seam antenna technology, other design factors must be taken into consideration. First, when different technologies are deployed on a satellite, they increase design complexity in and by themselves. Moreover, it has to be decided whether all satellites should have the same design or there should be a different design for satellites to be used in cross-seam communication. If the same design is chosen for all satellites, there may be a significant increase in satellite cost for a relatively modest gain in user-to-user delay, especially if economies of scale in satellite manufacturing is lost. Also, if satellite design is not uniform, this has important implications for satellite launch cost, as there may be a need for an increase in satellite inventory either on the ground or in parking orbit. See [15] for a thorough treatment of satellite replacement policies.

Satellite altitude (km)	1 ms switching time: Cross-seam antenna shut-off angular velocity (deg/sec) 0.00	0.02	0.05	0.10	0.20	0.40	Max. reduction (%)	2 ms switching time: Cross-seam antenna shut-off angular velocity (deg/sec) 0.00	0.02	0.05	0.10	0.20	0.40	Max. reduction (%)
500	19.19	19.19	19.09	18.93	18.06	17.59	8.34	24.40	24.40	24.27	24.07	22.91	22.34	8.44
600	21.70	21.53	21.09	20.63	20.23	20.24	6.73	27.00	26.76	26.19	25.57	25.07	25.08	7.11
700	29.82	29.80	29.29	28.84	28.30	28.27	5.20	35.62	35.59	34.91	34.35	33.73	33.71	5.36
800	34.29	34.24	33.25	32.45	32.03	31.76	7.38	40.66	40.60	39.35	38.36	37.87	37.55	7.65
900	26.72	26.69	25.85	24.96	24.37	23.87	10.67	31.64	31.61	30.60	29.53	28.85	28.32	10.49
1,000	29.22	29.22	28.80	27.09	26.83	25.95	11.19	34.21	34.21	33.71	31.68	31.38	30.46	10.96
1,200	24.71	24.38	23.85	23.57	23.01	23.26	5.87	28.61	28.21	27.59	27.25	26.62	26.94	5.84
1,500	28.33	28.19	27.70	26.79	26.66	26.74	5.61	32.21	32.05	31.47	30.44	30.31	30.39	5.65
2,000	34.70	34.24	33.57	32.51	31.98	31.98	7.84	38.56	38.04	37.29	36.12	35.58	35.58	7.73
2,500	34.52	33.38	32.95	32.41	32.05	32.13	6.92	37.89	36.67	36.20	35.60	35.23	35.31	6.81
3,000	44.11	43.45	39.75	38.54	38.54	38.54	12.63	47.75	47.04	43.13	41.89	41.89	41.89	12.27
3,500	47.07	45.56	43.94	42.37	42.37	42.37	9.99	50.44	48.88	47.19	45.59	45.59	45.59	9.62
4,000	58.00	54.61	51.74	50.01	50.01	50.01	13.78	61.55	58.12	55.16	53.41	53.41	53.41	13.23
5,000	67.52	63.17	58.92	58.95	58.95	58.95	12.69	71.07	66.67	62.30	62.37	62.37	62.37	12.24

Satellite altitude (km)	5 ms switching time: Cross-seam antenna shut-off angular velocity (deg/sec) 0.00	0.02	0.05	0.10	0.20	0.40	Max. reduction (%)	10 ms switching time: Cross-seam antenna shut-off angular velocity (deg/sec) 0.00	0.02	0.05	0.10	0.20	0.40	Max. reduction (%)
500	29.62	29.62	29.45	29.20	27.72	27.08	8.58	42.65	42.65	42.41	42.03	39.72	38.90	8.79
600	32.29	31.98	31.25	30.51	29.88	29.89	7.43	45.53	45.00	43.88	42.83	41.90	41.92	7.93
700	41.42	41.37	40.52	39.85	39.14	39.15	5.48	55.93	55.83	54.52	53.59	52.67	52.74	5.70
800	47.04	46.97	45.45	44.27	43.70	43.35	7.84	62.98	62.87	60.68	59.03	58.28	57.83	8.18
900	36.57	36.53	35.34	34.11	33.33	32.76	10.42	48.88	48.82	47.21	45.54	44.51	43.86	10.27
1,000	39.19	39.19	38.62	36.27	35.91	34.96	10.79	51.66	51.66	50.89	47.75	47.24	46.21	10.55
1,200	32.51	32.04	31.33	30.93	30.23	30.62	5.81	42.25	41.61	40.65	40.11	39.23	39.82	5.75
1,500	36.09	35.91	35.25	34.08	33.95	34.03	5.71	45.80	45.57	44.68	43.18	43.05	43.14	5.81
2,000	42.43	41.85	41.00	39.73	39.18	39.18	7.66	52.09	51.36	50.29	48.74	48.18	48.18	7.51
2,500	41.25	39.96	39.44	38.79	38.41	38.50	6.67	49.66	48.17	47.56	46.77	46.35	46.46	6.44
3,000	51.39	50.63	46.52	45.23	45.23	45.23	11.99	60.48	59.61	54.99	53.59	53.59	53.59	11.39
3,500	53.80	52.21	50.44	48.81	48.81	48.81	9.28	62.21	60.51	58.56	56.86	56.87	56.87	8.58
4,000	65.10	61.63	58.58	56.81	56.81	56.81	12.73	73.97	70.40	67.13	65.32	65.32	65.32	11.69
5,000	74.62	70.17	65.68	65.80	65.80	65.80	11.82	83.48	78.92	74.12	74.37	74.37	74.37	10.91

Table 5: *Demand weighted average user-to-user delay for satellite systems with a crosslink antenna shut-off angular velocity of* $0.05°/s$ *and crosslink pattern B at different altitudes and for different cross-seam antenna shut-off angular velocities.*

Satellite altitude (km)	1 ms switching time							2 ms switching time						
	Cross-seam antenna shut-off angular velocity (deg/sec)						Max. reduction (%)	Cross-seam antenna shut-off angular velocity (deg/sec)						Max. reduction (%)
	0.00	0.02	0.05	0.10	0.20	0.40		0.00	0.02	0.05	0.10	0.20	0.40	
500	119.80	119.80	119.80	119.80	104.82	103.41	13.68	143.25	143.25	143.25	143.25	125.41	125.41	12.45
600	114.27	113.50	111.27	110.31	104.01	106.28	6.99	138.27	137.50	131.45	130.38	125.93	126.28	8.67
700	130.78	130.78	127.88	120.87	108.19	108.19	17.27	152.78	152.78	147.93	138.87	126.19	126.19	17.40
800	128.17	128.17	122.79	118.31	115.14	115.14	10.17	146.17	146.17	139.02	138.31	133.14	133.14	8.91
900	123.96	123.96	123.96	115.03	107.83	105.18	15.15	143.23	143.23	142.05	131.03	121.83	121.18	15.39
1,000	131.45	131.45	131.45	113.55	112.57	113.55	13.62	148.25	148.25	148.25	128.57	128.57	128.57	13.27
1,200	135.62	132.19	123.65	123.65	116.56	113.93	15.99	151.62	148.19	135.65	135.65	132.09	127.93	15.62
1,500	140.81	140.81	130.51	126.08	126.08	126.08	10.46	156.81	156.81	144.51	140.08	140.08	140.08	10.67
2,000	150.32	140.91	138.84	133.00	126.77	126.77	15.67	164.32	154.91	152.84	145.00	138.77	138.77	15.55
2,500	163.39	153.85	153.85	139.64	132.78	132.78	18.73	175.39	165.85	165.85	149.64	142.78	142.78	18.59
3,000	168.04	168.04	159.00	148.53	148.53	148.53	11.61	180.04	180.04	171.00	158.53	158.53	158.53	11.95
3,500	184.32	158.41	154.79	149.42	150.37	150.37	18.42	196.32	170.41	164.79	159.42	160.37	160.37	18.31
4,000	181.29	169.38	159.12	152.20	152.20	152.20	16.05	191.29	179.38	169.12	160.20	160.20	160.20	16.25
5,000	202.38	189.32	170.58	170.58	170.58	170.58	15.71	212.38	199.32	178.58	178.58	178.58	178.58	15.91

Satellite altitude (km)	5 ms switching time							10 ms switching time						
	Cross-seam antenna shut-off angular velocity (deg/sec)						Max. reduction (%)	Cross-seam antenna shut-off angular velocity (deg/sec)						Max. reduction (%)
	0.00	0.02	0.05	0.10	0.20	0.40		0.00	0.02	0.05	0.10	0.20	0.40	
500	168.88	168.88	168.88	168.88	147.41	147.41	12.71	231.20	231.20	231.20	231.20	202.41	202.41	12.45
600	162.27	160.03	152.38	152.38	145.93	146.68	9.61	217.38	215.03	207.38	207.38	199.49	199.49	8.23
700	174.78	174.78	169.93	157.19	144.19	144.19	17.50	229.78	229.78	224.93	203.76	186.80	186.80	18.70
800	164.17	164.17	158.31	158.31	151.14	151.14	7.94	210.45	209.17	205.63	205.63	191.38	191.38	9.06
900	163.15	163.15	160.96	147.30	137.72	137.18	15.92	210.96	210.96	210.96	190.20	177.18	177.18	16.01
1,000	166.05	166.05	166.05	144.57	143.67	143.67	13.48	206.05	206.05	206.05	184.57	183.67	183.67	10.86
1,200	167.62	164.19	147.65	147.65	147.65	141.93	15.33	207.62	204.19	177.65	177.65	177.65	176.93	14.78
1,500	172.81	172.81	156.94	154.08	154.08	154.08	10.84	212.81	212.81	189.08	189.08	189.08	189.08	11.15
2,000	176.85	168.91	166.84	157.00	150.77	150.77	14.75	206.85	203.91	201.84	187.00	180.77	180.77	12.61
2,500	187.39	177.85	177.85	159.64	152.78	152.78	18.47	217.39	207.85	207.85	184.64	177.78	177.78	18.22
3,000	192.04	192.04	183.00	168.53	168.53	168.53	12.24	222.04	222.04	213.00	197.02	197.02	197.02	11.27
3,500	208.32	182.41	174.79	169.42	170.37	170.37	18.22	238.32	212.41	199.79	194.42	195.37	195.37	18.02
4,000	201.29	189.38	179.12	170.13	170.13	170.13	15.48	226.29	214.38	204.12	195.13	195.13	195.13	13.77
5,000	222.38	209.32	188.22	188.22	188.22	188.22	15.36	247.38	234.32	213.22	213.22	213.22	213.22	13.81

Table 6: *Worst-case user-to-user delay for satellite systems with a crosslink antenna shut-off angular velocity of* $0.05°/s$ *and crosslink pattern B at different altitudes and for different cross-seam antenna shut-off angular velocities.*

Satellite altitude (km)	Number of satellites	Time in shadow per orbit (h)	Time in sunlight per orbit (h)
500	135	0.49	1.08
600	105	0.48	1.13
700	88	0.47	1.18
800	77	0.45	1.23
900	66	0.44	1.27
1,000	60	0.44	1.31
1,200	48	0.42	1.40
1,500	40	0.40	1.53
2,000	28	0.37	1.75
2,500	24	0.35	1.96
3,000	21	0.34	2.17
3,500	18	0.32	2.39
4,000	15	0.31	2.61
5,000	15	0.29	3.06

Table 7: *Average satellite time spent in sunlight and shadow per orbit for LEOS communication systems with different satellite altitudes.*

7 Transmission Power Consumption and System Capacity

The transmission power requirement is a function of the distance between transmitter and receiver. Each satellite must handle the up- and downlink traffic generated by end users in its coverage area. In addition, the satellite must accommodate the crosslink traffic generated by other satellites. Overall satellite power consumption hence includes up- and downlink power, crosslink power and housekeeping power consumption. Up-, down- and crosslink power consumption depends on the traffic demand pattern and the routing pattern of signals from end user to end user. In this section, the impact of choice of crosslink pattern and routing methodology on power consumption and system capacity is investigated.

In order to receive and transmit signals, the satellites must have a power system. This power system has to be able to collect sufficient amounts of energy to power the communication and housekeeping equipment on board. In the following, it is assumed that communication demand is uniform over a 24-hour period.

Assuming constant antenna gain, the transmitter power consumption of an electromagnetic wave with a specified receiver power level depends on the square of the distance between transmitter and receiver. For a satellite altitude of 800 km, the power consumption for a 64 kbps voice grade line is 600 mW [20]. Between two satellites in orbit, the power consumption per voice grade line is substantially less for a comparable distance. This is due to the fact

Satellite altitude (km)	Total power per user (W)	Battery weight per user (g)	Solar panel weight per user (g)
500	0.24	4	15
600	0.34	5	21
700	0.46	7	28
800	0.60	9	35
900	0.76	11	43
1,000	0.94	14	52
1,200	1.35	19	72
1,500	2.11	28	107
2,000	3.75	47	178
2,500	5.87	69	266
3,000	8.44	94	368
3,500	11.49	123	486
4,000	15.01	154	619
5,000	23.45	225	929

Table 8: *Average transmission power consumption per user and power equipment weight requirement per user for LEOS communication systems with different satellite altitudes.*

that in space, the signal travels in vacuum and does not suffer from diffraction caused by collisions with particles. The required RF power output per 700 Mbps over a distance of 3,000 km in space has been estimated at 4.0 mW [22]. Using a conservative estimate of 10% power efficiency of the transmitter equipment, a total of 40 mW is consumed for the transmission of 700 Mbps over 3,000 km.

Orbiting the globe, satellites are from time to time eclipsed by the earth (Table 7). During these periods in darkness, all electric systems must be powered by on-board batteries. When the satellite emerges in the sunlight following an eclipse, the solar panels must supply energy to re-charge the batteries. Refer to [14] for a thorough analysis of satellite power sizing.

Table 8 displays the transmission power consumption per user and the corresponding battery and solar power requirements for a LEOS system with space based routing. In the computations, crosslink pattern B was used and the switching time per satellite was set to 5 ms. The crosslink antennas were shut off at an angular velocity of $0.05°/s$. It was also assumed that the same antenna size and technology is used at all altitudes. Under these assumptions, the table shows that the power consumption per user is increasing with satellite altitude, as expected. However, the power consumption per user is completely dominated by the downlink component, which constitutes more than 99% of the total consumption at all satellite altitudes. This result is surprising since crosslink power consumption per channel increases with the square of the distance between satellites. But, the increased power consumption per channel at higher satellite altitudes is offset by a reduced demand for crosslink traffic. Given the user-to-user traffic demand pattern used in these calculations, two factors play

Satellite altitude (km)	Number of satellites	Users per satellite	System user capacity
500	135	21,174	2,858,540
600	105	15,214	1,597,497
700	88	11,527	1,014,362
800	77	9,080	699,159
900	66	7,354	485,365
1,000	60	6,084	365,026
1,200	48	4,399	211,136
1,500	40	2,960	118,386
2,000	28	1,778	49,777
2,500	24	1,196	28,694
3,000	21	865	18,159
3,500	18	658	11,838
4,000	15	518	7,764
5,000	15	347	5,198

Table 9: *Capacity of a LEOS communication system with a transmission power system weight budget of 400 kg for different altitudes.*

a role in the reduction in crosslink traffic. First, as satellite altitude increases, the area covered by a single satellite grows. The larger satellite coverage area results in an increased likelihood that two communicating parties are covered by the same satellite and therefore require no crosslink traffic. Second, at higher satellite altitudes, fewer satellites are needed in a full coverage constellation, so that crosslink traffic requires on average fewer intermediary satellites for the same end user to end user pair.

Table 9 shows the average number of users a satellite can serve, as well as the total system capacity. The table is based on a weight budget of 400 kg for on-board batteries, solar panels for charging the batteries and identical antenna and transmission technologies used on both systems. From the table it is clear that a LEOS system with satellites in high orbits has a significantly lower capacity than a system with satellites in low orbits. One reason is that the system with higher orbits requires fewer satellites to provide the same coverage of the ground. However, this factor is minor compared to the increase in power per channel needed at higher altitudes. The power increase leads to an increase in the battery and solar panel weights per user and hence limits the communication capacity of the satellites.

The same calculations were carried out for all four crosslink patterns, different crosslink antenna shut-off angular velocities and different cross-seam antenna shut-off angular velocities. There was no significant difference in the average power consumption per user for any combination of parameters. Also, using equal weights for all communicating pairs rather than the demand based weights gave practically identical results. The conclusion of this is that the choice of crosslink antenna pattern and antenna technology does not have a significant impact on satellite power consumption, nor does it have an impact on system capacity. An interesting consequence is that a LEOS system with ground based routing does not have higher capacity than a system with the same satellite constellation and space based routing unless the weight budget for batteries and solar panels can be increased. This result is counter to common intuition. However, when not using inter-satellite antennas, there is no need for much of the on-board processing equipment required to control the antennas and the signal routing. Hence, there will be a reduction in satellite payload which can be used to increase power system capacity. Alternatively, reduced satellite weight can be used to lower satellite launch cost, thereby lowering overall system operating cost.

8 Conclusions

This paper investigated the effects of crosslink architecture on the performance of LEOS communication systems. It was found that the choice of crosslink patterns has a noticeable effect on average user-to-user delay and a profound effect on worst-case user-to-user delay. Hence, this aspect of quality of service can be improved without any expenses simply by choosing the best crosslink pattern.

Further, it was found that improvement of antenna technology to provide satellite crosslinks at higher latitudes has only a moderate impact on user-to-user delay. For the demand weighted measure, the user-to-user delay reduction was less than 16%, and in some cases only a few percent. Reduction in worst-case user-to-user delay was less than 20%, and in some cases even zero.

The ability to provide cross-seam links can reduce demand weighted average user-to-user delay by up to 14% and worst-case delay by up to 19%. For optical transmission, the required improvements in steering device technology to provide cross-seam communication as compared to crosslink communication might be too large, and may not be justified by the performance gains. For radio frequency based inter-satellite communication, the trade-off is not as clear since there is not one single factor limiting crosslink communication. However, providing RF based cross-seam antennas will increase complexity of antenna equipment and on-board processing requirements and, thereby, cause an increase in overall satellite complexity, weight and cost.

The small relative gain in average user-to-user delay from provision of cross-seam antennas is explained by the fact that with the given demand pattern, only a very small fraction of the point-to-point communication would experience a significant reduction in delay in the presence of such antennas. Hence, they will have to be subsidized by the large number of users that do not gain significantly from cross-seam antenna technologies.

The choice of crosslink pattern and crosslink antenna technology was shown to have no impact on satellite power consumption and overall system capacity. This result is explained by the very low power consumption of crosslink communication compared to the downlink transmission power requirements. Thus, crosslink power consumption can be ignored in calculations of satellite power sizing and communication capacity. An interesting consequence of this result is that the use of ground based routing cannot increase system capacity unless the weight budget for batteries and solar panels can be increased. However, not relying on space based routing implies that satellite design can be simplified and the reduced payload can be substituted with more battery and solar panel capacity. The main advantage of space based routing appears to be the independence it provides from ground based entities which can control the routing resources needed for ground based routing.

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References

[1] W. S. Adams and L. Rider. Circular polar constellation providing continuous single or multiple coverage above a specified latitude, *The Journal of the Astronautical Sciences* 35, 155–192 (1987).

[2] A. H. Ballard. Rosette constellations of earth satellites, *IEEE Transactions on Aerospace and Electronic Systems* 16, 656–673 (Sep. 1980).

[3] D. C. Beste. Design of satellite constellations for optimal continuous coverage, *IEEE Transactions on Aerospace and Electronic Systems* 14, 466–473 (May 1978).

[4] A. Böttcher, A. Jahn, E. Lutz and M. Werner. Analysis of basic system parameters of communication networks based on low earth orbit satellites, *International Journal on Satellite Communications* 12, 85–94 (1994).

[5] O. Chakraborty. Survivable communication concept via multiple low earth–orbiting satellites, *IEEE Transactions on Aerospace and Electronic Systems* 25, 879–889 (Nov. 1989).

[6] D. B. Crosbie. The new space race: Satellite mobile communications, *IEE Review* 39, 111–114 (May 1993).

[7] J. Fischer and E. Löcherbach. Optical data communication for earth observation satellite systems, in *Proceedings Second European Conference on Satellite Communications*, vol. ESA SP–322, pp. 405–414, Liège (Oct. 1991), ESA.

[8] R. W. Floyd. Algorithm 97: Shortest path, *Communications of the ACM* 5, 345 (1962).

[9] B. Gavish. LEOS – research issues, or, Mozart from the sky?, in *Proceedings of the Second Workshop on Protocols for Multimedia Systems*, pp. 179–202, Salzburg. Austria (1995).

[10] B. Gavish. Telecommunications – a revolution in progress, *Operations Research* 43, 29–32 (1995).

[11] B. Gavish. LEOS – low earth orbit satellite based communication systems research opportunities, *the European Journal of Operational Research* (in print).

[12] B. Gavish and J. Kalvenes. Altitude considerations in LEOS systems, in *Proceedings of the 3rd International Conference on Telecommunication Systems – Modeling and Analysis*, pp. 416–425, Nashville, TN (1995).

[13] B. Gavish and J. Kalvenes. Height considerations in low earth orbit satellite systems, in *Proceedings of the 4th Industrial Engineering Research Conference*, pp. 1047–1056, Nashville, TN (1995).

[14] B. Gavish and J. Kalvenes. The impact of satellite altitude on the performace of LEOS based communication systems, *Wireless Networks* (in print).

[15] B. Gavish and J. Kalvenes. LEOS – optimal satellite launch policies: The dynamic case, Under review in *Operations Research*.

[16] B. Gavish and J. Kalvenes. LEOS – optimal satellite launch policies: The static case, *Management Science* (in print).

[17] E. Hess. Project 21: LEO, MEO or GEO?, *Satellite Communications* pp. 42–46 (1993).

[18] J. Kaniyil, J. Takei, S. Shimamoto, T. Usui, I. Oka and T. Kawabata. A global network employing low earth–orbiting satellites, *IEEE Journal on Selected Areas in Communications* 10, 418–427 (Feb. 1992).

[19] S. G. Lambert, G. W. Ulrich, T. R. Chenoweth, T. R. Morris and W. L. Casey. Short-range multi-terminal satellite crosslink communications, in *MILCOM '92 'Communications — Fusing Command, Control and Intelligence.' Conference Record*, vol. 3, pp. 1170–1174, New York (Oct. 1992), IEEE.

[20] R. J. Leopold. Low-earth orbit global cellular communications network, in *Proceedings of the 13th Aerospace Testing Seminar*, pp. 59–65, Mount Prospect, IL (Oct. 1991), Institute of Environmental Science.

[21] G. Maral, J.-J. de Ridder, B. G. Evans and M. Richharia. Low earth orbit satellite systems for communications, *International Journal of Satellite Communications* 9, 209–225 (1991).

[22] M. Nohara, Y. Arimoto, W. Chujo and M. Fujise. A link study of a low-earth orbit satellite communications system using optical intersatellite links, *IEICE Transactions on Communications* E76-B, 536–543 (1993).

[23] R. J. Rusch. Odyssey, an optimized personal communications satellite system, *Space Communications* 11, 275–286 (1993).

[24] R. J. Rusch. Odyssey, an optimized personal communications satellite system, in *Proceedings of the AIAA 16th International Communications Satellite Systems Conference CP961*, pp. paper 96–1068 (1996).

[25] C. M. Rush. How WARC '92 will affect mobile services, *IEEE Communications Magazine* pp. 90–96 (1992).

[26] S. Sugawara. Satellite network seeks to link remote areas, *Washington Post* (1994).

[27] J. G. Walker. Satellite constellations, *Journal of the British Interplanetary Society* 37, 559–571 (1984).

[28] C.-J. Wang. Delivery time analysis of a low earth orbit satellite network for seamless PCS, *IEEE Journal on Selected Areas in Communications* 13, 389–396 (1995).