

FASTER THAN FIBER: ADVANTAGES AND CHALLENGES OF LEO COMMUNICATIONS SATELLITE SYSTEMS

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Abstract

Low Earth Orbit (LEO) communications satellite systems are emerging as attractive alternatives to the Geostationary Earth Orbit (GEO) systems. GEO satellites have largely dominated the commercial and government communications satellite systems for telecommunications services since the early 1960's. A principal driver behind the move to LEO satellites is the competition to long propagation delay geostationary orbit satellite systems created by rapid expansion of short propagation delay terrestrial land and undersea fiber optic cable links for national and global connectivity. Communication paths over LEO satellites can have shorter propagation delay than terrestrial fiber. This is because the speed of electromagnetic wave propagation via LEO satellites is 50% greater than that of light in fiber optic cable. This fact eliminates the long propagation delay property that has become synonymous with GEO communications satellite systems. Other drivers are the use of small portable and hand-held earth terminals and the promise of lower launch cost of small satellites to low earth orbits. The paper expands on the properties that promise to make LEO communications satellite systems the choice of the future.

INTRODUCTION

Low earth orbit (LEO) satellites will orbit the earth at altitudes of approximately 800 Km. Because of their low altitude each can see only a relative small portion of the earth at any instant. LEO satellites also travel at high speed relative to the earth, having orbit periods of only 100 minutes. Consequently, a large number of satellites, arrayed in a constellation of multiple satellites in multiple near polar orbits are required to maintain path continuity and to achieve world wide coverage. Paths between the satellite and the earth and between the satellites themselves are dynamic. To maintain path continuity, links must be frequently handed off from one satellite to another.

Because of their low altitude, the path length traversed via the satellites between points on the earth is only slightly longer than the great circle distance between the points. Because the speed of EM wave propagation via LEO satellites is 50% faster than that in fiber light guides, the propagation delay between two points on the earth via the LEO satellites can be shorter than via terrestrial fiber. LEO satellite systems promise to achieve low propagation delay, wireless communications between small portable and handheld earth terminals located anywhere. LEO systems eliminate the long propagation delay encountered by geostationary earth orbit (GEO) satellites. This paper discusses the magnitude of the long propagation over geostationary orbit satellites, the impact that long delay has on human interactive conversational communications and concludes with a discussion of the delay encountered using a constellation of LEO satellites.

GEOSTATIONARY ORBIT COMMUNICATIONS SATELLITES

All of today's commercial communications satellites used for two-way voice conversation, video teleconferencing, data and other interactive services are carried on geostationary earth orbit satellites. These satellites are located in the earth's equatorial plane at an altitude of 35680 Km and at longitudes that are maintained within a tight tolerance to assure the satellites do not drift from their assigned positions on the geostationary orbital arc. The shortest distance between the earth and one of these satellites is 35680 Km to a point directly beneath (the nadir distance). The longest distance is to the earth's edge which is 42560 Km. However, to avoid atmospheric disturbances that can occur on long slant paths, use of elevation angles below 10° is not recommended. The distance between the locus of 10° elevation angles on earth and the satellite is 40496 Km. Consequently, the distance between the geostationary orbit satellite and earth terminals lies between 35680 and 40496 Km. The speed of electromagnetic waves in open space is 3×10^8 m/s, resulting in a propagation time of 120 to 136 ms for a signal to travel between an earth terminal and the satellite and vice versa. The two-way path delay is four times the

propagation delay. Hence, the two-way delay encountered for circuits routed over geostationary satellites between 480 to 544 ms, the actual value being a function of the location and the earth terminals at each end of the satellite link. For earth terminals connecting public switched telephone networks to the satellite system, there are usually long terrestrial paths to the user's telephone set. These terrestrial paths can add 1 ms of two-way delay per 160 Km. In a large country such as the U.S. this added terrestrial delay can be up to 30 ms. In the average European country it can be up to 10 ms. Thus, the total two-way delay encountered over geostationary orbit satellite systems can range from 520 to 584 ms.

HUMAN REACTION TO PROPAGATION DELAY

For interactive human telecommunications such as voice conversation, the propagation delay over the two-way path between conversants influences the perceived quality of service. The delay over geostationary satellite is far more than that normally encountered in conversation and is usually noticed by the customers engaged in conversation over such systems. The delay in itself is a cause of difficulty in conducting conversation to some customers. The deleterious impact on quality of service is greatly exacerbated if echo from the far end is permitted to return to the person talking. Modern echo cancellers, which kill the echo near its origin have virtually eliminated echo as a cause of difficulty but the delay remains.

How Much Delay Is Tolerable?

Normal face-to-face conversation across a distance of say 11 feet encounters a two-way delay of 20 ms. This delay is caused by the speed of propagation of sound in air which is 1100 ft/s. No one ever notices delay this short. Telephone conversation coast-to-coast across the U. S. encounters a two-way delay typically of 25 to 30 ms. The delay also passes unnoticed in conversation as long as echo is eliminated. Just how much delay can be tolerated before it is sufficient to be noticed assuming echo is eliminated? Tests performed on humans indicate that the time it takes to react to visual, aural or tactual stimulus ranges from 200 to 300 ms, the faster reaction time being for young people. Thus, it can be expected that human perception of delay in conversation will become noticeable at approximately these same values.

Turn-Taking In Conversation Among Humans

Humans are accustomed to conversing over short distances having delays of only a few 10s of ms in face-to-face conversation. They have developed courteous, subtle conversational turn-taking cues in which the party talking indicates the offer to the other party to take their turn at talking. For a range of two-way delays out to 200 to 300 ms, the interpretation of these cues between the parties of a conversation appears to remain relatively unambiguous.

Face to face conversation among humans is a process which is regulated by auditory and visual cues. Turn-taking during conversation is facilitated by components of the speech itself, while additional relevant information is provided by some body movements. In an interactive environment, communications systems, audio and visual or audio only, with delay may modify the temporal interaction patterns of conversation and consequently interfere with its flow and in extreme cases with the intended information content of speech messages (Treurniet 1977).

The exchange of the talking role in telephone conversation, referred to as "turn-yielding", may be signaled by five possible auditory cues (Duncan 1972) : (1) intonation, or a change in voice pitch at particular syntactic locations, (2) drawl on the final syllable or on the stressed syllable of a terminal clause, (3) stereotyped expressions such as "but uh" or "you know", (4) a drop in voice pitch and/or loudness in conjunction with a stereotyped expression, (5) syntax; specifically, the completion of a clause involving a subject-predicate combination.

Other signals identified (Duncan and Niederehe 1974), which might be called "turn-taking", indicate that a listener wishes to shift to the talker state. For example, prior to expressing a turn-taking signal, he may or may not have been participating in back-channel behavior consisting of small units of speech such as "m-hm" or "yeah", but which do not pretend to claim the floor. Other typical "turn-taking" signals are audible inhalation, and paralinguistic overloudness.

Talker switching times refer to the intervals between reversal of talking between pairs of conversants. The distribution of talker switching times has been shown to have a modal value around 200 to 300 msec (Jaffe and Feldstein 1970). Such short switching times imply that responses to turn-yielding signals occur with short delay following emission of the signals. When a turn-yielding signal is given, the speaker has the intention of yielding the

The earth coverage of the satellite is circular, the circle being the locus on the earth where the elevation angle to the satellite is some selected value such as 10°, 20° or 40°. This locus is centered immediately beneath the satellite. The diameters of the earth coverage for 760, 800 and 960 Km altitude satellites at the various elevation angles are given in the following table:

TABLE 2. Diameter of Earth Coverage versus Elevation Angle.

ORBIT ALTITUDE (Km)	@ 10° (Km)	@ 20° (Km)	@ 40° (Km)
760	4095	2874	1515
800	4224	2970	1583
960	4712	3397	1838

In some LEO system designs, the coverage is divided into separate beams. Within the coverage determined by the elevation angle, each beam covers a smaller area which operates as a distinctly separate cell. If the beams are fixed relative to the satellite, they sweep over the earth at the speed of the satellite (approximately 24000 Km/h). Because the cells are moving past the earth terminal, it will have to switch from beam to beam during a satellite pass. As a satellite departs and a new one arrives the earth terminals will also have to switch from the departing to the arriving satellite. In other designs, the satellite beams are pointed to fixed cells on the earth eliminating the need to handoff from cell to cell during a pass. The systems use a sufficient number of satellites in a constellation, comprising a number of orbits and a number of satellites in each orbit, such that a new satellite arrives in the cone of view of an earth terminal before the old one departs. The cone of view has a width determined by the elevation angle to the satellite at which the system is designed to work. The lower the elevation angle the wider the cone of view. The diameter of the cone of view at the altitude of the satellite is tabulated below.

TABLE 3. Diameter of Cone of View versus Elevation Angle

ORBIT ALTITUDE (Km)	@ 10° (Km)	@ 20° (Km)	@ 40° (Km)
760	4581	3214	1694
800	4752	3357	1781
960	5419	3906	2114

The number of satellites in a constellation must be such that the distance between them is sufficiently smaller than the width of the cone of view so that overlap occurs between arrivals and departures. For the systems designed to operate at low elevation angles like 10°, the diameter of the cone of view is approximately 4800 Km. A typical constellation for such a system is that for the IRIDIUM system which uses 6 near polar orbits separated by 30° between their ascending and descending nodes along the earth's equator and 11 satellites per orbit. This results in N-S orbit separations of 3884 Km and E-W orbit separations of 3467 Km near the equator and 2720 Km at latitudes of over the U.S. and Europe. These distances are less than the cone of view diameter and overlap is guaranteed.

For systems designed to operate at high elevation angles of 40°, such as the proposed Teledesic, the constellation may use 21 near polar orbits separated by 9.5° between their ascending and descending nodes along the earth's equator and 40 satellites per orbit. This results in N-S orbit separations of 1005 Km and E-W orbit separations of 1061 Km near the equator and 816 Km at latitudes of over the U.S. and Europe. These distances are less than the cone of view diameter of 1781 Km and overlap is guaranteed.

COMPARISON OF TERRESTRIAL AND LEO LINK PROPAGATION DELAYS

Connections via LEO satellites comprise uplinks and downlinks between an earth terminal and the nearest satellite and intersatellite cross links if more than one satellite is required to reach the destination. All satellite connections are assumed to propagate in free space at the speed of light. All terrestrial connections are assumed to propagate in fiber optic cable at 2/3 the speed of light.

Consider a case in which a single LEO satellite hop is used to cross the U.S. from Washington DC to San Francisco. By terrestrial fiber link, the shortest path length (great circle distance) between these cities is 4000 Km for which the two way propagation delay would be 40 ms. Assuming a single hop via a LEO satellite located halfway between the cities, the shortest path distance would be 4518 Km resulting in a two way propagation delay of 30 ms. The terminals at each end of the satellite link would see the satellite at an elevation angle of 11.52°. If the path were routed via two satellites, one near each end, separated by a cross-link distance of 4000 Km and seen each

floor to someone else. If the implicit offer is not accepted immediately, it may be withdrawn and the speaker may continue. A tardy acceptance of the offer of the floor in excess of 200 to 300 msec, might then result in confusion due to simultaneous speaking.

Such tardiness can result from conditions imposed by telephone circuits with long propagation delay. The round trip delay can be 70 ms on Trans-Atlantic submarine fiber optic cable circuits, 120 ms on Trans-Pacific submarine cable circuits, 200 ms on terrestrial circuits from Europe to the Orient via North America, and 600 ms on geostationary orbit satellite circuits. If the turn-yielding signal is delayed by amounts in excess of 200 to 300 ms, the delay between emission of the signal and the response to that signal is significantly more than that normally expected. A talker unaware of the physical delay due to the circuit, may continue speaking following a period of high probability of a response, resulting in simultaneous speaking. Similarly, delay of a speech signal can also result in confusion if both parties emit such a signal, and the two signals are separated by less than the delay time of the circuit. With short two-way delay, a speech signal can be inhibited if a similar signal is received from the other party. With long two-way delay, a speech signal may be emitted before receiving the signal from the far end possibly causing confusion as to who possesses the floor.

The effect of delay on conversation interaction should be expected to be less when the conversants speak slowly rather than quickly. Slow speech, resulting in longer switching pauses, allows turn-yielding signals and speaker-state signals to be received before utterances are initiated at inappropriate times. It is not uncommon for those who have become conditioned to long propagation delay geostationary satellite circuits to automatically switch to a slow speaking rate when they sense that they are on such a circuit.

Regarding "turn taking" in conversation, long propagation delay occasionally causes the yielding conversant to doubt that the cue has been recognized and may elicit an attempt on his part to attempt to send an additional cue. Often this happens just as the other conversant's delayed response arrives causing a conversation collision which is usually followed by the expenditure of effort on the part of both correspondents to recover the pattern of conversation. Such experiences are recognized by correspondents who frequently use long propagation delay satellite circuits and it is common for them to use conscious discipline to wait a bit longer for responses to turn-taking cues when using such circuits. When this is done, long propagation delay circuits perform satisfactorily. However for two-way delays in excess of this range, confusion in the perception of the turn-taking cues between the participants engaged in a conversation begins to occur and is further exacerbated as the delay increases. The occurrence of echo and poor performance of the echo control measures exacerbates the human factors situation especially when the delay over the path becomes long.

Impact Of Long Propagation Delay On Data Communications

Long propagation delay is also detrimental to performance of conventional ARQ protocols used for data communications. Consequently, special provisions for coping with the geostationary orbit propagation delay, not needed for short propagation delay circuits, are necessary

LOW EARTH ORBIT COMMUNICATIONS SATELLITES

Low earth orbit satellites are those located in circular orbits at altitudes typically between of 760 to 960 Km above the earth. Satellites at these altitudes travel around the earth in a near circular orbit every 100.5 to 104.7 minutes. On a zenith pass, the time it takes between satellite rising and setting is 14.9 to 17.2 minutes. However, the satellites are useful for communications only when, relative to an earth terminal, they are above an elevation angle of 10° for systems operating at the L-band frequencies (1.5 to 1.6 GHz) and above an elevation angle of 40° for Ka band frequencies (20 & 30 GHz). This reduces their useful pass time for communications to at most 10.2 and 12.3 minutes for 10° elevation angle and 3.84 and 4.79 minutes for 40° elevation angle. Zenith pass time values are tabulated below. Non-zenith pass times will be shorter.

TABLE 1. Satellite Zenith Pass Times in Minutes versus Elevation Angle.

ORBIT ALTITUDE (Km)	@ 10° (min.)	@ 20° (min.)	@ 40° (min.)
760	10.23	7.18	3.84
800	10.64	7.51	3.98
960	12.27	8.84	4.79

end at an elevation angle of 40° , the total path distance would be 6400 Km resulting in a two-way propagation delay of 43 ms. Thus, the propagation delay over the LEO satellite(s) can be equal to or be less than that of fiber for transcontinental U. S. calls. The delay over a geostationary satellite would be 590 ms. Neither the terrestrial fiber nor LEO satellite delays are sufficient to cause subjectively noticeable delay for CONUS calls.

Consider next a call from Washington DC to London. The great circle distance in this case is 6080 Km resulting in a two-way terrestrial path delay of 61 ms. In this case it would take at a path between two or three satellites to connect via a LEO system. If a two satellite path connection is required, the cross-link path between the satellites would be 4000 Km and at each end, elevation angles of 20° or greater would complete the connection in most cases. For this arrangement, the total path length would be 7520 Km resulting in a two-way propagation delay of 50 ms. If a third satellite were needed, then the elevation angles would be 40° or greater and the path length would be increased to 10240 Km yielding a two-way delay of 68.3 ms. For longer distance calls, say from the west coast of the US to Rome, a great circle terrestrial path distance of 10880 Km, the terrestrial fiber optic cable path two-way propagation delay would be 110 ms. For a three satellite path and assuming a 20° elevation angle at each end, the LEO satellite path distance would be 11520 Km resulting in a two-way propagation delay of 75 ms. For a four satellite path and assuming a 40° elevation angle at each end, the LEO satellite path distance would be 14240 Km resulting in a two-way propagation delay of 96 ms.

For a final case, consider a call from Washington DC to Sidney Australia routed across the Pacific on undersea fiber optic cable via Japan. The great circle distance to Japan is 10400 Km and that from Japan to Australia is 8000 Km yielding a total of 18400 Km and having a round trip propagation delay of 184 ms. A LEO satellite system connection for this distance would involve five or six satellites. Assuming six satellites with an elevation angle of 20° at each end, the total path distance would be 23520 Km resulting in a two-way propagation delay of 157 ms.

In all of the above important trans-Atlantic and trans-Pacific cases, LEO satellites are seen to match or provide shorter delays than achieved by fiber optic cable. Both are far have far less delay than that of geostationary satellite systems.

CONCLUSIONS

Wireless communications via satellite has a significant advantage over terrestrial cable communications because it is unencumbered by the need to route a cable between the users and free from the threat of interdiction by nature or man. For a quarter of a century, wireless satellite communications has been provided by geostationary orbit satellite systems and they have ushered in the era of the fully connected world village. However because of their inherent long propagation delay, geostationary orbit systems have a lower quality of service. LEO satellite systems now promise to provide worldwide wireless communications with propagation delay that is shorter than that of terrestrial fiber optic cable, thus eliminating the major cause of lower quality of service for satellite systems.

Acknowledgments

This paper was prepared under of the auspices of the Center for Satellite and Hybrid Communication Networks at the Institute for Systems Research, University of Maryland, College Park, MD. The Center is sponsored in part by a grant from NASA under its CCDS program. The authors wish to acknowledge the contributions of the Bagel Club.

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