AN OVERVIEW OF THE IRIDIUM® LOW EARTH ORBIT (LEO) SATELLITE SYSTEM

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ABSTRACT

This paper provides a tutorial overview of the IRIDIUM® low earth orbit (LEO) satellite system. Section I contains an introduction to the IRIDIUM® network as well as the system specifications. Section II discusses the satellite constellation design, orbital parameters, and horizontal pointing angles between satellites. Section III introduces the idea of time dependent connectivity in a mobile network, and analyzes the cycle of network connectivity for IRIDIUM®. Section IV discusses the IRIDIUM® Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) schemes and uses these to calculate the overall system capacity. Section V examines the call processing procedure to include user location and call set up. Finally, Section VI analyzes the network performance in terms of end-to-end delay and hop count.

INTRODUCTION

The IRIDIUM® system is a worldwide, low earth orbit (LEO) satellite communications system designed to support voice, data, facsimile and paging. An international consortium of telecommunications companies, which includes Motorola, Raytheon, Siemens, Telesat and Bechtel, is developing IRIDIUM® [4]. The main components of the IRIDIUM® system are the satellites, gateways, and user handsets. The IRIDIUM® satellites are currently being launched, and the system is expected to be operational in September, 1998. Regional gateways will handle call setup procedures and interface IRIDIUM® with the existing Public Switched Telephone Network (PSTN). A dual mode handset will allow users to access either a compatible cellular telephone network or IRIDIUM® [4]. IRIDIUM® will give the user the capability to receive personal communications worldwide using a single telephone number. It is designed to augment the existing terrestrial and cellular telephone networks. IRIDIUM® is expected to provide cellular like service in areas where terrestrial cellular service is unavailable, or where the PSTN is not well developed. The current estimate for the cost of a user handset is $3000 [5]; use of the system is expected to cost $3 per minute.

CONSTELLATION DESIGN

Existing satellite communications systems primarily use geostationary earth orbit (GEO) satellites with an altitude of approximately 35,800 km [5, 12]. GEO satellite systems allow full earth coverage below 70 degrees latitude with as few as three satellites. The one way propagation delay of a GEO satellite system is approximately 120 ms. The transmit power required to overcome the propagation loss of a 35,800 km path makes handheld user terminals impractical. The first generation of GEO satellite mobile communications began with INMARSAT-A in 1982 [2, 5]. The ship-based user stations had a 40 W transmitter and a 1.2-meter dish antenna [5]. The current version, INMARSAT-M, became operational in 1993 and has suitcase-sized user terminals [2]. The IRIDIUM® system requirements of worldwide coverage with a small, lightweight user handset resulted in a system design using a LEO satellite constellation. The primary advantages associated with LEO satellites are a lower required transmit power, a lower propagation delay, and polar coverage.

The IRIDIUM® satellite constellation consists of six orbital planes with eleven satellites in each plane for a total of 66 LEO satellites. The satellites are arranged using the Adams/Rider circular polar constellation [1, 11]. The satellites are in a circular orbit at an altitude of approximately 780-km and at an inclination of 86.4 degrees. Orbital planes one and six are counter-rotating and are separated by approximately 22 degrees. The remaining orbital planes are co-rotating and are separated by approximately 31.6 degrees [10]. The velocity of a LEO satellite relative to the earth is given by Equation 1 where ω is the earth angular rotation speed, R_g is the GEO satellite orbit radius, and R_l is the LEO satellite orbit radius [7].

$$V_l = \frac{\omega R_g^{3/2}}{\sqrt{R_l}} \tag{1}$$

The angular rotation of the earth is calculated as 0.2618-radians/hour using Equation 2.

$$\omega = \frac{2\pi \, radians}{24 \, hours} = 0.2618 \, radians / hour \tag{2}$$

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The orbital radius of the satellites is calculated by adding the equatorial radius of the earth, 6378-km, to the satellite altitude. This results in values of R_g = *42,178-km* and R_l = *7158-km*. The velocity of a LEO satellite relative to earth is calculated as V_l = *26,804-km/hour* using Equation 2. The IRIDIUM® constellation parameters result in an orbital period of 100.13 minutes [2]. The minimum inclination angle for a user to see a given satellite is 8.2 degrees. At a fixed location on earth, the average in-view time for a satellite is nine minutes and either one or two satellites are visible at a time [5]. The coverage area of a single satellite is given by Equation 3 where R_e is the radius of the earth and θ is the earth central angle [6].

$$A = 2\pi R_e^2 (1 - \cos\theta) \tag{3}$$

The earth central angle θ is calculated using Equation 4 where R_e is the radius of the earth, E is the minimum elevation angle, and h is the satellite altitude [6].

$$\theta = \left[\cos^{-1}\left(\frac{R_e \cos E}{R_e + h}\right)\right] - E \tag{4}$$

The IRIDIUM® satellite coverage area, as shown in Figure 1, is calculated as 15,299,900-km^2, which equates to a footprint radius of 2209-km.

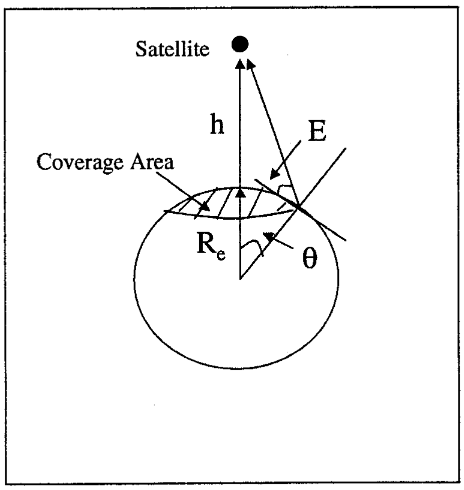

Figure 1: Satellite Coverage Area

The IRIDIUM® satellites weigh approximately 680-kg [4] and have an expected life span of five years [8]. The original design proposal for IRIDIUM® included 77 satellites. The name IRIDIUM® was chosen because a drawing of the 77 satellites in orbit around the earth resembled the model for an atom surrounded by electrons [2].

There are currently two design approaches for connectivity in a LEO satellite network. These approaches depend upon whether the satellites serve as repeaters, or if they have onboard switching technology. Satellites that serve as repeaters are used in a "bent pipe" architecture. A mobile user's transmitted signal is reflected off the satellite to a gateway in the same satellite footprint. The switch used to process the call is located at the gateway. This type of system requires a gateway in each satellite footprint in order to interface mobile users. The GLOBALSTAR system, currently under development by Loral QUALCOMM Satellite Services Inc., utilizes a "bent pipe" architecture [5]. Satellites with onboard switching technology are able to use inter-satellite links (ISLs) to route calls. A mobile user's transmitted signal is routed through several satellites and downlinked to either a regional gateway or another mobile user. This creates a network in the sky and allows the use of large regional gateways instead of gateways in each satellite footprint. The IRIDIUM® network will have satellites with onboard switching technology and ISLs.

The IRIDIUM® network will have up to four ISLs for each satellite. The ISLs will operate in the frequency range of 22.55 to 23.55-GHz at 25-Mbps [5]. Two of these links will be intra-orbital links to the forward and aft adjacent satellites in the same orbital plane. There will also be up to two inter-orbital links, one each to the two adjacent orbital planes. The horizontal pointing angle between two satellites in adjacent orbital planes, using a reference of zero degrees parallel to the equator, varies between approximately ±65 degrees over one orbital period [11, 13]. This angle varies most slowly over the equator where satellites in adjacent orbits are the most separated, and it varies most rapidly over the poles where the orbits cross. The variation in horizontal azimuth between satellites makes steerable antennas necessary to maintain inter-orbital links. Even with steerable antennas, it would be very difficult to maintain inter-orbital links at higher latitudes where the azimuth varies rapidly. An approach to maintaining inter-orbital links is to select a nominal horizontal azimuth close to that between satellites over the equator. Then the antenna is designed to be steerable over a range that allows inter-orbital links at lower latitudes where the horizontal azimuth changes more slowly. A nominal horizontal azimuth of ± 45 to 50 degrees with an antenna steerable over a 30 to 45 degree range is sufficient to maintain inter-orbital links between latitudes of 50 to 60 degrees north and south [11, 13]. Although the actual characteristics of the ISL antennas on IRIDIUM® satellites are not published in open literature, this approach is reasonable since it allows inter-orbital ISLs over the most populated regions of the earth.

NETWORK CONNECTIVITY

Communication networks are commonly represented by graphs of nodes, representing communication locations, and links, representing communication transmission paths. The IRIDIUM®

network essentially has two planes of nodes, the satellites and the earth stations, that are moving with respect to each other. This has the effect that the links connecting earth stations to satellites change over time. This is similar to the changing connectivity between mobile users and base stations in a typical cellular telephone network. In a cellular network, the user connects to the base station with the strongest signal. As the user moves from the area of one base station to another, his call is handed off to the new base station. In the IRIDIUM® network, a link is established from an earth station to the satellite with the strongest signal. The satellites are moving much faster than the mobile users. Mobile users can be considered stationary with respect to the velocity of the satellites, as even a mobile user in an airplane is travelling much slower than a satellite. As the satellites pass overhead, the link from earth station to satellite is handed off from a satellite leaving the user's area to one entering the user's area.

The connectivity between the plane of earth stations and the plane of satellites is cyclic in nature. The cycle of this network connectivity can be defined as the time it takes for the two planes to line up in the same position and establish the same links between earth stations and satellites. Recall from above that each satellite has an orbital period of 100.13 minutes, so the satellite plane is in the same position every 100.13 minutes. The ground stations are in the same position every 1440 minutes. It seems logical that the cycle of the network connectivity can be found by finding the number of days in which the satellite constellation completes an integer number of orbital periods. The values for several days are summarized in Table 1.

Table 1: Constellation Periods per Day

No. of Days	No. of Minutes	No. of Constellation Periods
1	1440	14.38
2	2880	28.76
3	4320	43.14
4	5760	57.53
5	7200	71.91
6	8640	86.29
7	10080	100.67
8	11520	115.05
9	12960	129.43
10	14400	143.81

Table 1 shows that the satellite constellation does not complete an integer number of periods within ten days. This seems to illustrate that the same connectivity between earth stations and satellites is not established on a cyclic basis. However, the size of the satellite footprint and the ground station's minimum elevation angle must be taken into account to determine connectivity between ground stations and satellites. Even though the relative location of a satellite and ground station may not be precisely the same, the same links may be established. Satellite visibility from an earth station can be easily modeled using the commercial software SATLAB by Cadence Design Systems, Inc. [3].

To test the cyclic network connectivity with SATLAB, Kansas City was selected as an earth station site. At the beginning of the simulation, the fifth satellite in the second orbital plane was visible to Kansas City and was travelling from north to south. The time that the satellite was visible to Kansas City each day is summarized in Table 2.

Table 2: Cyclic Satellite Visibility

Day	In View Times Travelling N-S		In View Times Travelling S-N	
	Pass 1	Pass 2	Pass 1	Pass 2
1		8:00-8:03 AM	7:08-7:18 PM	8:50-8:58 PM
2	5:41-5:47 AM	7:20-7:30 AM	6:36-6:45 PM	8:16-8:26 PM
3	6:47-6:57 AM	8:29-8:36 AM	6:05-6:11 PM	7:43-7:53 PM
4	6:14-6:24 AM	7:55-8:04 AM	7:10-7:20 PM	8:55-9:00 PM
5	6:42-6:50 AM	7:22-7:32 AM	6:37-6:47 PM	8:19-8:28 PM
6	6:49-7:00 AM	8:02-8:05 AM	6:06-6:14 PM	7:45-7:55 PM
7	6:16-6:27 AM	7:59-8:06 AM	5:34-5:38 PM	7:12-7:22 PM

The simulation began at 8:00 AM on day one. The satellite made four passes each day, two in the morning and two in the evening. In the morning the satellite was travelling from north to south and in the evening it was travelling from south to north. The visibility times in Table 2 show that Kansas City could be connected to same satellite, travelling in the same direction, every morning between 5:41 AM and 8:06 AM. The cycle of the network connectivity is therefore approximately 24 hours. Note that even though the same satellite was visible to Kansas City approximately every twelve hours the cycle of network connectivity is 24 hours. This is because all the satellites and earth stations are not in the same position every twelve hours. For example, a satellite that is north of Kansas City at 7:30 AM is actually south of Kansas City at 7:30 PM.

The cyclic connectivity of the network is relevant when conducting an analysis of the network. A typical analysis would be to determine the effect of a failed link or node on the network performance. In order to analyze the effect of a failed ISL or satellite on all ground stations, the network should be analyzed for a minimum of one cycle. The time changing connectivity is also useful in determining the effect of a failed satellite on a single earth station's connectivity. The satellite visibility times in Table 2 show that a failed satellite will cause an outage in connectivity between a given earth station and satellite for up to 37 minutes every 24 hours. Note that this is a worst case since two satellites are often visible to an earth station. The earth station could therefore establish a link to another satellite during part of the time that the failed satellite is visible.

SYSTEM CAPACITY

The IRIDIUM® system uses a combination of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). The TDMA frame is 90-ms long and it contains four full duplex user channels at a burst data rate of 50-kbps [5, 9, 10]. The four full duplex channels consist of four uplink time slots and four downlink time slots as shown in Figure 2.

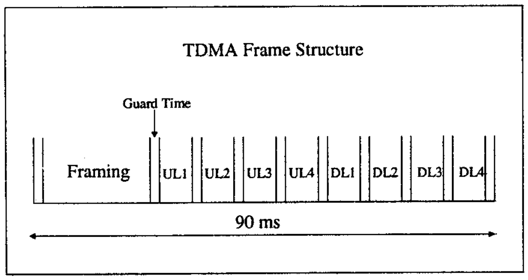

Figure 2: IRIDIUM® TDMA Frame Structure

The IRIDIUM® system will support full-duplex voice channels at 4800-bps and half-duplex data channels at 2400-bps [5]. The specific details of the TDMA frame, such as the number of framing bits and the length of a user time slot, are not published in open literature. In addition, the type of voice encoding that will be used to provide acceptable voice quality at 4800-bps is proprietary and is not published in open literature. However it is not difficult to show that the known TDMA frame length and burst data rate will support a sustained data rate of 4800-bps. Equation 5 shows that each user must transmit 432 bits in a 90-ms frame to achieve a data rate of 4800-bps.

$$4800\,bps \times 90\,ms \quad = \quad 432\,bits \tag{5}$$

Equation 6 shows that a user uplink or downlink time slot with a burst data rate of 50-kbps is 8.64 ms.

$$\frac{432\,bits}{50\,kbps} \quad = \quad 8.64\,ms \tag{6}$$

The eight user time slots take up a total of 69.12-ms, which leaves 20.88-ms of the TDMA frame for framing bits and guard time slots. A possible frame structure is to use a framing time slot twice as long as an individual user time slot. This would result in 864 framing bits taking up 17.28-ms. Subtracting this value from the 20.88-ms remaining in the TDMA frame leaves 3.6-ms for guard time slots. This can be divided into eight 400 microsecond guard time slots between time slots in the frame, and two 200 microsecond guard time slots at each end of the frame. Although the exact frame structure is not published in open literature, this approach is reasonable. It uses 4.6% of the 90-ms frame for guard time, and utilizes 76.8% of the frame for actual data bits.

IRIDIUM® uses frequencies in the L-band of 1616 to 1626.5-MHz for the user's uplink and downlink with the satellites [5, 10]. This gives the system 10.5-MHz of bandwidth. As shown in Figure 3, the IRIDIUM® FDMA scheme divides the available bandwidth into 240 channels of 41.67-kHz for a total of 10-MHz [9]. This leaves 500-kHz of bandwidth for guard bands, which amounts to approximately 2-kHz of guard band between channels.

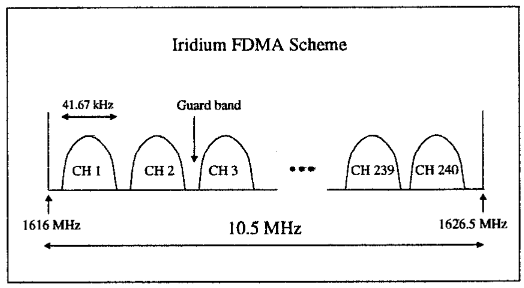

Figure 3: IRIDIUM® FDMA Scheme

The IRIDIUM® network utilizes multiple spot beams on each satellite that divide the satellite footprint into smaller cells. Each IRIDIUM® satellite has three phased array antennas with 16 spot beams for a total of 48 spot beams on the satellite [5, 10]. A spot beam, like a cell in a typical cellular network, is assigned a fraction of the available frequency channels. Frequency channels can be reused throughout the network by assigning them to cells that are far enough apart to minimize co-channel interference. The IRIDIUM® network uses a frequency reuse factor of 12 , which means there are 12 cells in each cluster [10]. Equation 7 shows that this equates to 20 frequency channels per cell.

$$\frac{240\,channels}{12\,cells} \quad = \quad 20\,channels\ per\ cell \tag{7}$$

The frequency reuse factor is described by Equation 8 where I and J are integers.

$$N \quad = \quad I^2 + I \cdot J + J^2 \tag{8}$$

Cells that use the same frequency channels are found by starting in the center of a cell, moving I cells across cell sides, turning 60 degrees, and moving J cells. This is illustrated in the Figure 4 where cells with the same letter use the same frequency channels.

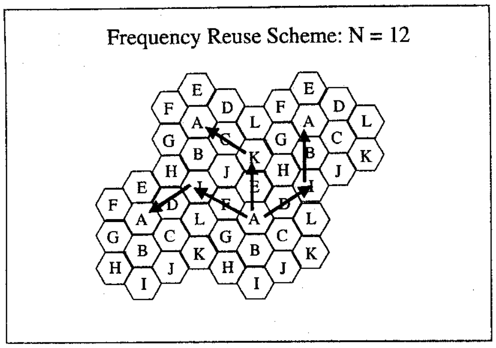

Figure 4: IRIDIUM® Frequency Reuse Scheme

The capacity of the IRIDIUM® network can be calculated by multiplying the number of possible users per cell by the number of active cells in the network. Each cell has four TDMA channels on 20 frequencies for a total of 80 possible simultaneous users. The IRIDIUM® network has 48 cells on each of the 66 satellites for a total of 3168 cells. Since some of the spot beams will overlap, especially near the poles, only 2150 of the possible 3168 cells will be active at once [10]. The remaining spot beams will be turned off to conserve power. The network has 80 simultaneous users in 2150 active cells for a total network capacity of 172,000 simultaneous users.

CALL PROCESSING

The IRIDIUM® system will allow users to roam worldwide and still utilize a single subscriber number. To accomplish this, each user will have a home gateway that normally provides his service. The gateways in this system will be regional and will support large geographical areas. For example, a single gateway will service North America. The gateways serve as the interface to the Public Switched Telephone Network (PSTN). They also perform the functions of call setup, call location and billing. The gateway must maintain a database of subscriber profiles as well as subscriber locations. This register is called the home location register (HLR).

An IRIDIUM® subscriber is uniquely identified by three numbers, the Mobile Subscriber Integrated Services Digital Network Number (MSISDN), the Temporary Mobile Subscriber Identification (TMSI), and the IRIDIUM® Mobile Subscriber Identity (IMSI) [10]. The MSISDN is the telephone number of an IRIDIUM® subscriber. The MSISDN is five digits long, and makes up part of the twelve digit number dialed to reach a subscriber. The first field of the twelve digit number is the four digit country code. This is similar to the country codes used now with the PSTN. The IRIDIUM® network will have its own country code and is currently assigned the codes 8816 and 8817 [10]. The second field of the number is a three digit geographical code. This code will be used to identify a user's home country in regions where one gateway services more than one country. The third and final field of the number is the MSISDN. The TMSI is a temporary number that is transmitted over the network during call setup. This number is changed periodically to protect subscriber confidentiality [10]. The IMSI is a permanent number stored on a credit card sized module that the subscriber inserts into the mobile phone unit. This number contains information that allows a gateway to uniquely identify a user and determine his home gateway.

The IRIDIUM® Network must track a user's location as he roams in order to set up calls. When a subscriber turns on his mobile phone unit, it transmits a "ready to receive" signal to the nearest gateway. The signal is uplinked from the user to the satellite directly overhead. If the user is not in the same satellite footprint as the gateway, the signal traverses ISLs until it reaches the satellite that is above the gateway. The signal is then downlinked to the gateway. If the user is not in his home gateway region, the gateway that receives the "ready to receive" signal will recognize that the user is a visiting subscriber. The gateway determines the subscriber's location and enters the information in the visited location register (VLR). The visited gateway also sends information via ISLs to the subscriber's home gateway and requests both a subscriber profile and permission to set up calls for the subscriber. The home gateway sends clearance to the visited gateway and updates the user's location in the HLR.

The gateways perform call setup in the IRIDIUM® network. When a phone call is placed to an IRIDIUM® user, it is routed to the user's home gateway. This call can be placed from the PSTN or from another IRIDIUM® user. The user's home gateway determines the user location by looking up the subscriber in the HLR. The gateway then uplinks a ring signal that travels via ISL to the satellite directly above the user. The signal is downlinked to the mobile unit and it rings. When the user goes off hook, the mobile unit uplinks an off hook signal that travels via ISL to the gateway. The gateway then routes the voice packets over the IRIDIUM® network to the subscriber. Note that the voice packets do not have to be routed through the gateway. If the call is from a mobile user to a mobile user, the actual voice packets can travel completely over the IRIDIUM® ISLs. The call setup information goes through the gateway, but the gateway drops out after call setup. The scenario is slightly different if the user is in a visited gateway region. In this case, the home gateway will send a signal to the visited gateway to ring the subscriber. The visited gateway determines the user location by looking in the VLR and uplinks a ring signal that goes to the satellite over the user. When the user goes off hook, the off hook signal is sent to the visited gateway, and then forwarded to the home gateway. Finally, the home gateway routes the voice packets via the

IRIDIUM® ISLs to the satellite directly above the user. The methods used for call setup in IRIDIUM® are very similar to those used by the Advanced Mobile Phone System (AMPS) cellular telephone system [10].

NETWORK PERFORMANCE

The IRIDIUM® network performance can be measured in terms of end-to-end delay. The typical maximum end-to-end delay for real time voice is 400 ms. The average end-to-end packet delay is described by Equation 9.

$$T_{Packet} = T_{access} + T_{uplink} + (N-1) \cdot T_{cross} + N \cdot T_{sat} + T_{downlink} \quad (9)$$

T_{access} is the access delay associated with the multiple access technique. T_{uplink}, T_{cross}, and $T_{downlink}$ are the propagation delays for the respective links. T_{sat} is the average processing and queuing delay a packet experiences at a satellite node, and N is the number of satellite nodes in the path. The technique for calculating T_{access} for an FDMA or TDMA system is well known and the equations are widely published. The FDMA access is calculated using Equation 10.

$$T_{FDMA} = \frac{Number\ of\ Bits\ per\ Packet}{Channel\ Transmission\ Rate\ (bps)} \quad (10)$$

The TDMA access delay depends on both the packet transmission time and the average waiting time for a TDMA slot. Under the assumption that each TDMA slot is large enough to transmit one packet, the packet transmission time is simply the TDMA slot time. The average time a user has to wait for a TDMA time slot is one half of the TDMA frame length. The TDMA access delay is described by Equation 11 where *Tf* is the TDMA frame length and *Tslot* is the TDMA slot time.

$$T_{TDMA} = \frac{Tf}{2} + Tslot \quad (11)$$

The method for calculating access delay in a system like IRIDIUM® that uses both TDMA and FDMA is not widely published. However, an analysis of the call setup procedure indicates that the IRIDIUM® access delay is simply the TDMA access delay. As previously discussed, each cell in the IRIDIUM® system has 20 frequency channels with four TDMA users per frequency channel. When a subscriber unit goes off hook, it will receive a dial tone after a slight delay similar to that experienced with a common cordless telephone. This delay is caused by the time necessary to assign the user a frequency channel and it does not contribute to the end-to-end packet delay. It is logical to assume that the user is assigned both a frequency channel and a full duplex TDMA time slot when he receives dial tone. If a TDMA time slot is not available to assign to the user, the frequency channel could not be assigned. At this point, the user can be considered one of four users sharing a TDMA channel and the access delay can be calculated as TDMA access delay. Recall from above that the IRIDIUM® TDMA frame length is 90 ms, and the slot time is 8.64-ms. T_{access} is calculated as 53.64-ms using Equation 11. The propagation delays T_{uplink} and $T_{downlink}$ are calculated as approximately 2-ms using Equation 12.

$$\frac{Satellite\ Altitude}{Speed\ of\ Light} = \frac{780\,km}{3\,x\,10^8\ m/s} = 2.05\,ms \quad (12)$$

The propagation delay T_{cross} varies because the distance between satellites in adjacent orbits changes at different latitudes. Below latitudes of 60 degrees, where ISLs can be maintained between adjacent orbital planes, the distance between satellites varies between 3270 and 4480-km [13]. The distance between satellites in the same orbital plane is 4030-km [13]. Using an average distance of 4000-km between satellites in Equation 13 results in an average T_{cross} of 13.33-ms.

$$\frac{Crosslink\ Distance}{Speed\ of\ Light} = \frac{4000\,km}{3\,x\,10^8\ m/s} = 13.33\,ms \quad (13)$$

The satellite processing and queuing delay T_{sat} is not published for IRIDIUM®, but a reasonable value for current packet switching technology is 100-μs. Using these values, the average end-to-end delay for various numbers of satellites in the path is calculated and summarized in Table 3. These values do not include queuing delay.

Table 3 : Average End-to-End Delay

No. of Satellites in Path	2	3	4	5	6	7	8
End to End Delay (sec)	0.071	0.085	0.098	0.112	0.125	0.138	0.152

The number of satellites in the path between two earth locations depends on a number of parameters, which include satellite look angle, horizontal pointing angles between satellites and routing algorithm. An analysis of the IRIDIUM® network was conducted using the commercial software packages SATLAB and DESIGNER by Cadence Design Systems, Inc. [3] to determine the number of hops between various locations. A look angle of 8.2 degrees was used with a horizontal pointing angle between satellites in adjacent orbital planes of 50 degrees steerable over a range of 45 degrees, and a shortest path routing algorithm. The number of satellites in the path between earth stations varied between five and seven, and is summarized in Table 4. A comparison of Table 3 and Table 4 shows that the average end-to-end delay for the IRIDIUM® system is on the order of 110 to 140-ms. This is well below the required 400-ms delay for real time voice applications which indicates that IRIDIUM® is capable of providing worldwide voice service. As mentioned earlier, the delay values in Table 3 do not include queuing delay which could result from system loading. However, the delay with seven satellites in the path is approximately 138-ms. This leaves over 250-ms of delay that could be added by queuing before the end-to-end delay exceeds 400-ms.

Table 4: Number of Satellites in Path

Source	Destination	No. of Satellites
Kansas City	Madrid	5
Kansas City	New Dehli	5
Kansas City	Cape Town	7
Kansas City	Beijing	5
Kansas City	Berlin	6
Kansas City	Dhahran	5
Kansas City	Rio de Janero	5
Kansas City	Melboune	7

CONCLUSIONS

This paper has presented a comprehensive overview of the IRIDIUM® system. The analysis in several of the sections demonstrated that the IRIDIUM® design is capable of meeting the published specifications. The analysis of the TDMA frame illustrated that IRIDIUM® can provide the published 4800-bps data rate for voice communications. The system capacity calculations demonstrated that IRIDIUM® could support 80 simultaneous users per cell and 172,000 simultaneous users system wide. The end-to-end delay analysis showed that the system is easily able to meet the standard minimum of 400 ms end-to-end delay. It appears that the IRIDIUM® system will provide a dramatic improvement in the current capabilities of both worldwide communications and personal communications systems.

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