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AN OPERATIONAL AND PERFORMANCE OVERVIEW OF THE IRIDIUM LOW EARTH ORBIT SATELLITE SYSTEM

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ABSTRACT

Today, both the military and commercial sectors are placing an increased emphasis on global communications. This has prompted the development of several low earth orbit satellite systems that promise worldwide connectivity and real-time voice communications. This article provides a tutorial overview of the IRIDIUM low earth orbit satellite system and performance results obtained via simulation. First, it presents an overview of key IRIDIUM design parameters and features. Then, it examines the issues associated with routing in a dynamic network topology, focusing on network management and routing algorithm selection. Finally, it presents the results of the simulation and demonstrates that the IRIDIUM system is a robust system capable of meeting published specifications.

Private companies are striving to provide truly seamless global communications to the public, making today's personal communication systems (PCS) a proving ground for new technologies. This global approach has sparked the development of several new communication satellite systems, which abandon the traditional use of geostationary earth orbit (GEO) in favor of medium earth orbit (MEO) and low earth orbit (LEO) satellite systems. LEO and MEO satellite networks increase the service regions of their designers, providing services to regions of the world where there is little or no telecommunication infrastructure, such as Asia, Africa, Eastern Europe, South America, and the polar regions [1]. These LEO and MEO satellite networks provide global coverage to their users, which a typical GEO satellite system cannot provide. One such LEO satellite system, Motorola's IRIDIUM system, was completely deployed in May 1998.

IRIDIUM was conceived in 1987, and is the first private global wireless communication system to provide voice, data, fax, and paging services to the world [2]. The original configuration called for 77 satellites, and was named after the atom IRIDIUM, which has 77 orbiting electrons [3]. However, in an effort to maximize satellite coverage and reduce costs, the constellation was optimized, requiring only 66 satellites. The IRIDIUM system orbit is based on a constellation proposed by Adams and Rider [4, 5].

At an altitude of 780 km above the earth, 66 satellites are arranged in six planes, each plane containing 11 satellites (Fig. 1). Planes have a near-circular orbit, with co-rotating planes spaced 31.6 degrees apart and counter-rotating planes (one and six) spaced 22 degrees apart [6]. The minimum elevation angle for an earth station is 8.2 degrees, which maximizes the coverage area of the satellite and improves the link quality compared to lower elevation angles. Lower elevations increase fading due to multipath and have a negative impact on link quality. Average satellite in-view time is approximately 10 minutes [7].

The main components of the IRIDIUM system are the satellites, gateways, and user handsets. The satellites utilize inter-satellite links (ISLs) to route network traffic. 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 [2].

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 street price for a user handset is approximately $3,400 [8]; a monthly access charge of approximately $70 is required.

Use of the system is expected to cost $2 to $3 per minute for outgoing calls within the U.S. and $7 to $8 for outgoing calls in other countries (including all calls originating from an ocean-going vessel); incoming calls are billed to the caller [8].

Constellation Design

Existing satellite communications systems primarily use GEO satellites with an altitude of approximately 35,800 km [7, 9]. 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. Unless very large multi-beam satellite antennas are used, the use of handheld terminals are impractical with GEO satellite systems. The first generation of GEO satellite mobile communications began with INMARSAT-A in 1982 [3, 7]. The ship-based user stations had a 40 W transmitter and a 1.2-meter dish antenna [10]. The current version, INMARSAT-M, became operational in 1993 and has suitcase-sized user terminals [3]. 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 velocity of a LEO satellite relative to the earth is given by Eq. 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 [11].

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

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

$$\omega = \frac{2\pi \text{ radians}}{24 \text{ hours}} = 0.2618 \text{ radians / hour} \quad (2)$$

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/h using Eq. 2. The IRIDIUM constellation parameters result in an orbital period of 100.13 minutes [3]. 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 [7]. The coverage area of a single satellite is given by Eq. 3 where R_e is the radius of the earth and θ is the earth central angle [12].

$$A = 2\pi R_e^2 (1 - \cos\theta) \quad (3)$$

The earth central angle θ is calculated using Eq. 4, where R_e is the radius of the earth, E is the minimum elevation angle, and h is the satellite altitude [12].

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

The IRIDIUM satellite coverage area, as shown in Fig. 2, is calculated as 15,299,900 km^2, which equates to a footprint radius of 2209 km. The IRIDIUM satellites weigh approximately 680 kg [2] and have an expected life span of five years [1].

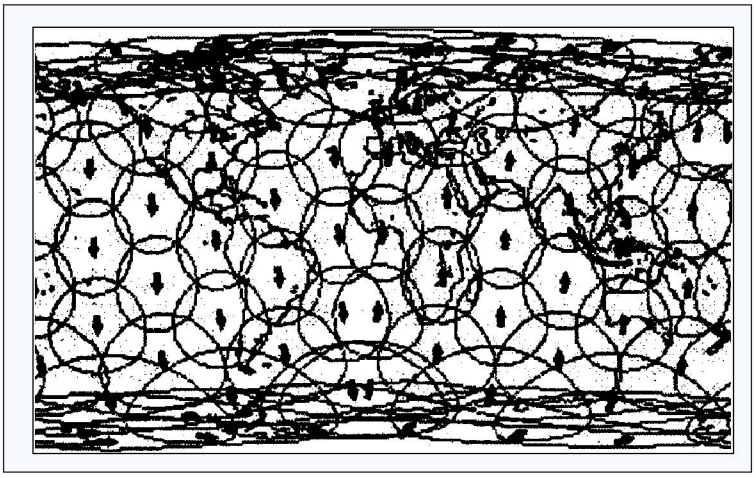

Figure 1. *Depiction of IRIDIUM constellation.*

There are currently two design approaches for connectivity between satellites in the network. These approaches depend upon whether the satellites serve as repeaters, or if they have on-board 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 [7]. Satellites with on-board 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. Until recently, the technological complexity of utilizing inter-satellite links to perform network routing was limited to military applications. The designers of the IRIDIUM network have overcome these hurdles. Consequently, the IRIDIUM network utilizes satellites with on-board switching technology and ISLs.

Inter-Satellite Links

Each IRIDIUM satellite maintains up to four ISLs each. ISLs are links established between satellites in the same plane (intra-plane) and between satellites in adjacent planes (inter-plane). Intra-plane links are maintained permanently, with each satellite having forward and aft connectivity with the satellites directly in front and behind. Inter-plane links are dynamically established and terminated as the satellite transcends its orbital path. Except for the satellites in counter-rotating planes one and six, each satellite has four ISLs. The satellites located within planes one and six maintain only three ISLs each, two of which are intra-plane. Satellites in these planes are not allowed to establish ISLs between each other due to the rapid angular change that occurs between satellites in counter-rotating planes [1].

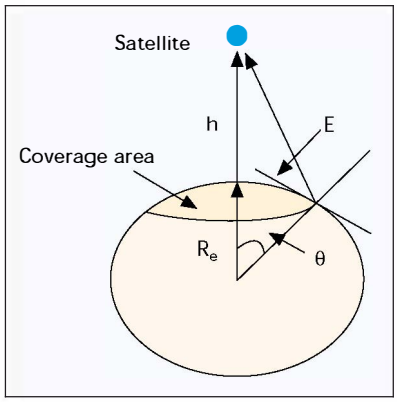

Figure 2. *Satellite coverage area.*

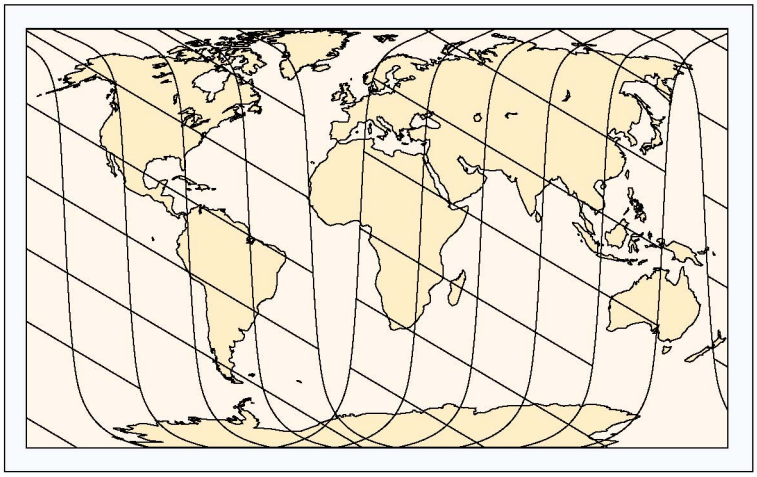

Figure 3. *Depiction of IRIDIUM inter-satellite links.*

The ISLs operate in the frequency range of 22.55 to 23.55 GHz at 25 Mb/s [7]. 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 [5, 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 between orbital planes one and six at the higher latitudes where the azimuth varies rapidly. An approach used to maintain 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 [5, 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. A depiction of these ISLs is shown in Fig. 3, where each intersection represents the position of an active satellite.

ISLs provide the network with a greater level of autonomy when compared to GEO satellite networks. Fewer terrestrial gateways are needed because the routing of calls takes place via these ISLs. As such, IRIDIUM does not depend on the services provided by other organizations such as regional telephone companies [1], which translates into greater profits for the company since fees for terrestrial connectivity are reduced [13].

The complexity of the IRIDIUM satellites is due to the onboard processing capabilities required to manage and support the ISLs and connectivity of the network [6]. Efficient link assignment and routing algorithms can optimize network delay and decrease overhead. These algorithms quickly converge to a routing solution with little overhead, directly impacting the performance of the network and the PCS. Their importance cannot be trivialized and will be discussed further in this article.

NETWORK CONNECTIVITY

Communication networks are commonly represented by graphs of nodes, which represent communication locations, and links, which represent communication transmission paths. The IRIDIUM network essentially has two planes of nodes, the satellites and the earth stations, which are moving with respect to each other. As a result, 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. Based on these values, however, 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. [14].

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 traveling from north to south. The time that the satellite was visible to Kansas City each day is summarized in Table 1.

The simulation began at 8:00 a.m. 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 traveling from south to north. The visibility times in Table 1 show that Kansas City could be connected to same satellite, traveling in the same direction, every morning between 5:41 a.m. and 8:06 a.m. 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 a.m. is actually south of Kansas City at 7:30 p.m.

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 1 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 scenario 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.

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

Table 1. *Cyclic satellite visiblity.*

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 kb/s [6, 7, 15]. The four full-duplex channels consist of four uplink time slots and four downlink time slots, as shown in Fig. 4.

The IRIDIUM system will support full-duplex voice channels at 4800 b/s (2400 b/s according to [16]) and half-duplex data channels at 2400 b/s [7]. 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 2400 b/s is proprietary [16] and is not published in open literature. For purposes of analysis, 4800 b/s full-duplex channels are assumed. If one chose to use a 2400 b/s value for the voice channel, Eqs. 5 and 6 below could be adjusted accordingly along with the following analysis. It is not difficult to show that the known TDMA frame length and burst data rate will support a sustained data rate of 4800 b/s. Eq. 5 shows that each user must transmit 432 bits in a 90 ms frame to achieve a data rate of 4800 b/s.

$$4800 \text{ b/s} \times 90 \text{ ms} = 432 \text{ bits} \tag{5}$$

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

$$\frac{432 \text{ bits}}{50 \text{ kb/s}} = 8.64 \text{ ms} \tag{6}$$

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 percent of the 90 ms frame for guard time, and utilizes 76.8 percent of the frame for actual data bits.

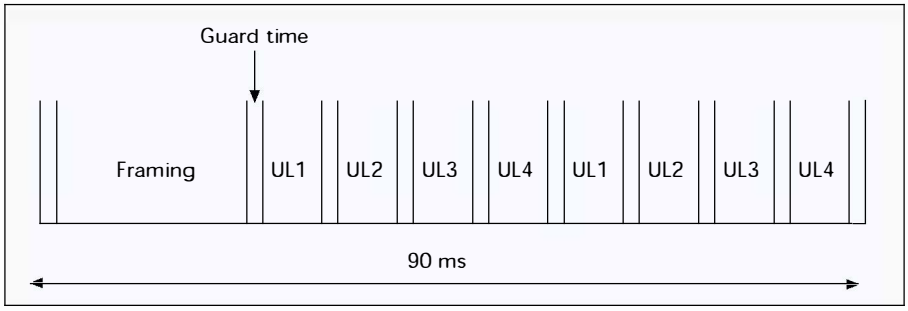

Figure 4. *IRIDIUM TDMA frame structure.*

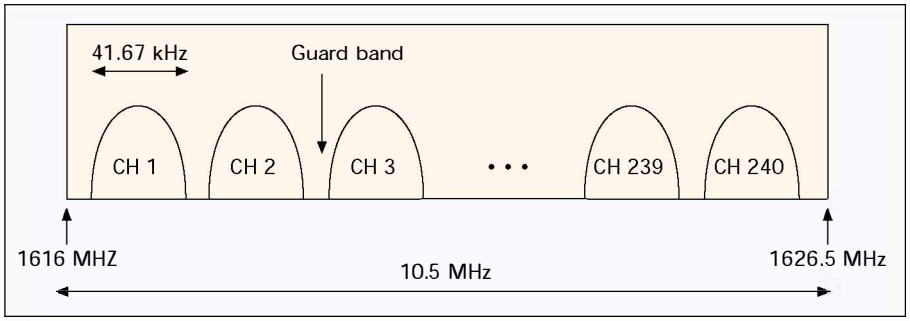

Figure 5. *IRIDIUM FDMA scheme.*

IRIDIUM uses frequencies in the L-band of 1616 MHz to 1626.5 MHz for the user's uplink and downlink with the satellites [6, 7]. This gives the system 10.5 MHz of bandwidth. As shown in Fig. 5, the IRIDIUM FDMA scheme divides the available bandwidth into 240 channels of 41.67 kHz for a total of 10 MHz [15]. This leaves 500 kHz of bandwidth for guard bands, which amounts to approximately 2 kHz of guard band between channels.

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 [6, 7]. 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.

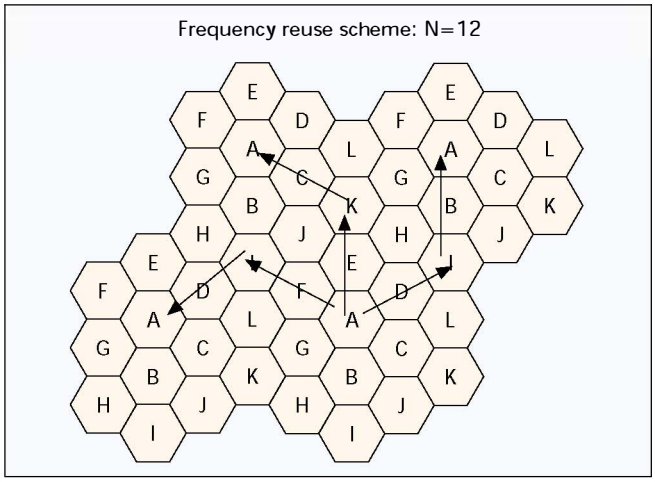

Figure 6. *IRIDIUM frequency reuse scheme.*

The IRIDIUM network uses a frequency reuse factor of 12 , which means there are 12 cells in each cluster [6]. Equation 7 shows that this equates to 20 frequency channels per cell.

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

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

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

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 Fig. 6, where cells with the same letter use the same frequency channels.

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 [6]. The remaining spot beams will be turned off to conserve power. The network has 80 simultaneous users in each of 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 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) [6]. 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 [6]. 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 [6]. 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.

In order to set up calls, the IRIDIUM network must track a user's location as he roams. 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 [6].

ROUTING IN A DYNAMIC NETWORK TOPOLOGY

One of the critical drawbacks of LEOS systems is the constellation's time-varying geometry and its evolving coverage caused by satellites' increased orbital speed at lower altitudes [17]. Consequently, the maximum in-view time of a satellite with respect to a fixed point on the earth is approximately 10 to

20 minutes, causing frequent handovers between satellites [17, 18]. These handovers force a mobile call to be handed off multiple times via inter-satellite links in order to avoid a forced call termination. Crosslink hardware in LEO satellites increases the complexity of the satellite since links must be established dynamically to account for changes in network topology [10]. The net result is that the ISLs and the traffic traversing them must be managed and maintained with efficient algorithms. An algorithm's ability to converge to a routing solution rapidly and without a great amount of overhead is used as an indicator for both algorithm and network performance.

The performance of the routing algorithm directly impacts the performance of the system [18], so it is imperative that the routing algorithm converge to a solution quickly without producing a large amount of network overhead. It is therefore important to review algorithms developed specifically for use in LEOS communication networks and those that are adaptable to these networks.

Although the literature contains many articles, studies, and papers on conventional terrestrial routing algorithms, little is available on dynamic routing algorithms, their application, and performance in LEO satellite networks. Since the performance of the routing algorithm directly impacts the performance of the system [18], it is imperative that the routing algorithm converge to a solution quickly without producing a large amount of network overhead. It is therefore necessary to review routing algorithms and how they impact the performance of LEOS communication networks.

Selecting the Right Routing Algorithm

The primary attributes used to characterize routing protocols are complexity, loop-free[1] routing, convergence, storage overhead, computational overhead, and transmission overhead [20]. In a network where the topology is dynamic, these parameters are especially important, since faster convergence to a new route after a topology change insures quick delivery of the data.

Loops increase the time required for a data packet to reach its final destination and introduce overhead, having a negative impact on network performance. In the presence of node or link failures, loops can cause destinations to be unreachable. As a result, loop-free protocols reduce overhead and decrease convergence time. These factors are key for any LEOS routing algorithm.

Many LEO networks use dynamic link assignment to establish connections between themselves and any visible neighbors. The primary goal of link assignment algorithms is to concentrate on connectivity of the network, rather than maximization of network performance [10].

The use of conventional routing algorithms in a dynamic network topology introduces a great deal of overhead. These algorithms use one of two methods to insure proper message routing: synchronizing the network so that each node has the same view of the network's connectivity, or flooding[2] the network with duplicate message packets to overcome the dynamics of the network. Both methods, however, introduce overhead into a system and ultimately have a negative impact on performance [21]. In addition, this overhead results in extra link resource requirements in order to implement these conventional routing algorithms.

IRIDIUM uses a proprietary algorithm for link assignment and routing. Since direct study is impossible, it was necessary to review the literature to find routing and link assignment protocols that were suitable for use in a LEOS system so that the performance of each can be determined via modeling and simulation. Two algorithms stand out in literature as possible candidates for LEO satellite communication systems: Extended Bellman-Ford and Darting.

Extended Bellman-Ford

In [22], the authors present the Extended Bellman-Ford (EXBF) algorithm. This algorithm is based on the conventional Bellman-Ford (BF) algorithm, which solves the single-source shortest-paths problem. The authors of [22], however, present several enhancements to overcome the problems that restricted BFs use in dynamic networks.

One problem is the potential for loops to exist in the connectivity matrix maintained by each node. In the presence of link or node failures, loops cause the BF algorithm to take an extended period of time before converging to a solution. In fact, under these circumstances, the BF algorithm may not converge to a solution at all [22]. To have an acceptable convergence time, loops within the distance tables must be minimized or eliminated so packets do not "bounce" between nodes. The removal of loops is especially critical in networks with dynamic topologies. If loops are not removed, the algorithm may not converge to a solution. Changes in connectivity are more likely to increase loop probability and may result in the changes not being propagated throughout the entire network.

To overcome the loop problem, Cheng *et al.* [22] maintain only the simple paths[3] to nodes, and only update the paths to selected neighbors of the current node. This approach eliminates the long convergence time experienced in the presence of loops. In addition, maintaining only simple paths to a node eliminates the failure of the BF algorithm to converge to a solution in certain cases. While not eliminating loops, the approach recommended in [22] is one solution to the problems they create. In order to be totally loop-free, the algorithm utilizes inter-neighbor coordination [23].

Elimination of lengthy convergence times and convergence failure are necessary for EXBF to be considered for use in a LEOS network. Raines et al. [24] evaluated the performance of the EXBF algorithm in low-load, LEOS network simulation trials. Although the use of inter-neighbor coordination was not implemented in these simulation trials, results indicated the EXBF had a significant performance advantage over another algorithm, Darting, to be discussed next. EXBF converged to a solution faster and with less overhead when compared to Darting.

Darting

Darting is another algorithm that has been proposed as suitable for use in LEO networks [21]. This particular algorithm attempts to reduce the message overhead introduced by

[1] *"Loop-free" implies that the path from one node to another does not traverse the same node twice.*

[2] *"Flooding" is a methodology used by conventional algorithms to insure a given packet reaches its destination. A node will broadcast the data packet to all of its neighbors, whom in turn broadcast it to all of their neighbors except for the one that initially sent the packet. This continues until the packet reaches its destination, which occurs only if the destination is connected to the source of the data packet.*

[3] *A "simple path" is a sequence of nodes with no node being repeated more than once, i.e., a loop free path.*

conventional flooding algorithms. The algorithm delays the sending of network "update" messages until absolutely necessary. Darting uses two different methods for updating the network's connectivity routing tables.

First, updates are accomplished by each node encapsulating their local topology changes into the data packets. Nodes that receive the data packets incorporate these updates locally, then add their own updates and pass the data packet along. The process is repeated until the packet reaches its destination. The second method updates all nodes in a data packet's route already visited by the packet. These updates occur when a discrepancy is found between the connectivity data encapsulated in the data packet just sent and the present node's local view of connectivity. Darting creates an update packet that is sent back to the predecessor nodes; these nodes then incorporate any necessary updates. Both methods are triggered only when a data message is present, so a node's view of the network's connectivity remains unchanged in the absence of data messages.

The authors [21] performed low-load simulation trials that compared Darting to conventional routing algorithms. The scope of these trials was limited and did not attempt to model and analyze performance characteristics of traffic traveling between terrestrial earth stations. The results from these preliminary simulations indicated a cost-saving potential for implementation into LEOS communication networks. Raines et al. [24] conducted additional simulations with Darting and EXBF to characterize their performance in a simulated IRIDIUM network. Although these trials modeled traffic between terrestrial earth stations, only low loading levels were attained. The low-load results indicated that the Darting algorithm required as much as 72 percent more overhead when compared to the EXBF algorithm. The additional overhead was a result of a weakness in the Darting algorithm, which manifests itself when routing packets under non-uniform traffic loads. The authors found that encapsulation of updates into the data packets severely handicapped the algorithm, which diminished the overhead savings that resulted from the algorithm's selective update methodology. In summary, it was recommended that modifications be made to Darting's link weight function and to its update frequency to improve the performance of the algorithm and that simulation trials be conducted at higher loading levels.

NETWORK PERFORMANCE

As previously stated, the performance of the routing algorithm directly impacts the performance of the system. The IRIDIUM network performance can be measured in terms of end-to-end delay, percent packet rejection, and overhead. The acceptable maximum end-to-end delay for real-time voice is 400 ms. The average end-to-end packet delay is described by Eq. 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 Eq. 10.

No. of Satellites in Path	2	4	6	8	10	12	14
End to End Delay (sec)	0.071	0.098	0.125	0.152	0.179	0.206	0.232

Table 2. *Average end-to-end delay.*

$$T_{FDMA} = \frac{\text{Number of bits per packet}}{\text{Channel transmission rate (b/s)}} \quad (10)$$

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 Eq. 11, where Tf is the TDMA frame length and $Tslot$ is the TDMA slot time.

$$T_{TDMA} = \frac{Tf}{2} + T\text{slot} \quad (11)$$

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 Fig. 4 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 Eq. 11. The propagation delays T_{uplink} and $T_{downlink}$ are calculated as approximately 2 ms using Eq. 12.

$$\frac{\text{Satellite altitude}}{\text{Speed of light}} = \frac{780 \text{ km}}{3 \times 10^8 \text{ m/s}} = 2.05 \text{ ms} \quad (12)$$

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 Eq. 13 results in an average T_{cross} of 13.33 ms.

$$\frac{\text{Crosslink distance}}{\text{Speed of light}} = \frac{4000 \text{ km}}{3 \times 10^8 \text{ m/s}} = 13.33 \text{ ms} \quad (13)$$

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 2. These values do not include queuing delay.

The number of satellites in the path between two earth locations depends on a number of parameters, including satellite look angle, horizontal pointing angles between satellites, network load, load-balancing mechanisms, and routing algorithm. An analysis of the IRIDIUM network was conducted using the commercial software packages SATLAB and

DESIGNER by Cadence Design Systems, Inc. [14] 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. A load-balancing mechanism was used in conjunction with either the Extended Bellman-Ford or Darting routing algorithms. The load-balancing algorithm was critical in balancing the traffic load across the network and minimizing queuing delay.

The number of satellites in the path between earth stations averaged between four and twelve satellites for packets that were not rejected. A look-up of these values in Table 2 shows that the average end-to-end delay for the IRIDIUM system would be on the order of 100 ms to 210 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 1 do not include queuing delay which could result from system loading. However, the delay with twelve satellites in the path is approximately 206 ms. This leaves more than 194 ms of delay that could be added by queuing before the end-to-end delay exceeds 400 ms.

During simulation, the load-balancing mechanism kept queuing delay in check and resulted in a 0 percent rejection rate during its use. Without load balancing, the rejection rate of packets varied from 1.38 percent to 8.12 percent at high loads using a uniform traffic distribution, and 3.03 percent to 28.81 percent at medium and high loads using a non-uniform traffic distribution. This fact alone validates the need for a load-balancing mechanism in this type of communication system in order for it to meet real-time voice communication constraints.

Overhead introduced into the system by each algorithm contributed to network traffic and queuing delay. Overhead is the total number of update packets introduced into the network to facilitate connectivity updates to individual nodes. The more update packets generated the greater the possibility of congestion in the network. Overhead is calculated by dividing the total network traffic into the total number of update packets generated by the algorithm. In general, lower overhead indicates better performance. Darting generated a significantly lower amount of overhead traffic than Extended Bellman-Ford. Overhead averaged 1.57 percent to 5.36 percent and 20.12 percent to 37.17 percent for the Darting and Extended Bellman-Ford algorithms, respectively.

CONCLUSIONS

This article 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 b/s 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 able to meet the standard minimum of 400 ms end-to-end delay provided an efficient routing algorithm and load-balancing mechanism is utilized. It appears that the IRIDIUM system will provide a dramatic improvement in the current capabilities of both worldwide communications and personal communications systems.

In the future, PCS users will become more dependent on LEOS systems, as evidenced by the recent advent and use of these systems in both the commercial and military sectors. One system currently being deployed is Globalstar. Another system, currently in development, is Teledesic. Both hope to capitalize on the growing PCS market and the increasing demand for seamless global communications. The success of these systems is largely dependent on their routing algorithms and their ability to efficiently route traffic throughout the network.

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