Crosslinks for the Next-Generation GPS

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Abstract—The current Global Positioning System (GPS) is a successful civilian and military satellite navigation system, and one that is increasingly depended on by aviation. Use of directional crosslinks on the next-generation GPS—or GPS III—can enhance the reliability and integrity of the satellite constellation. This paper discusses this crosslink network system and its uses for the next-generation civil/military GPS.

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1. INTRODUCTION

GPS is the primary, worldwide navigation service for the United States Department of Defense and civilians alike. Sailors, aviators, car drivers, hikers, and emergency rescue workers rely heavily on GPS capabilities for navigation, accurate time reporting, and position estimation. But what happens when the GPS mission has a greater importance than it does today? What is required, then, is rapid control of the constellation, integrity and notification of a "bad signal," and navigation messaging. There are two network solutions for improving the integrity and control of a large satellite constellation—a proliferation of ground stations spread throughout the world, or the use of intersatellite crosslinks.

The upgrade of GPS II, scheduled to begin in the next 5 years, will improve the quality of the navigation signals. New signals are being added with more modern codes that provide improved performance. A more significant improvement in quality of service, beyond expanding to the new navigation signals on existing frequencies, is the objective of GPS III. GPS III covers timing and navigation accuracy, improved integrity in all areas of the world, anti-jam features for the military, and more coverage with stronger signal power. Many of these improvements need to rely on a network that provides rapid constellation control, fast notification of failures, navigation messaging relays, and possibly robust dissemination of data from sensors (e.g., emergency beacons).

In viewing the potential benefits of a robust worldwide network, one must also weigh the effects of such a system. Which is the right direction to go in a ground-based network or a space-based network? Several areas to be weighed are the following:

1. What is the difference in cost?
2. Is it feasible?
3. Will it be dependable for decades?
4. What is the architecture of the crosslink if it is selected—Ka band, V band, or laser?

GPS III-supported missions that require a network include the following:

1. **Position, Velocity, and Timing (PVT) accuracy improvement** for the signal-in-space.
2. **Integrity**—providing alerts with variable error bounds consistent with various phases of aircraft flights.
3. **Autonomous Navigation**—self-control of the GPS constellation for a limited time if an outage occurs at the ground station, meaning a quality navigation signal continues for a limited period of time.
4. **Growth and Flexibility**—providing the margin and flexibility to accommodate improvements.

[2] The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, the Department of Defense, or the U.S. Government.
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2. PVT Accuracy Improvement

GPS II spacecraft are currently updated by the Control Segment (clock and ephemeris data) twice a day as they pass over existing ground stations. This latency is up to 24 hours and limits PVT accuracy. In GPS III, the robust network could provide updates as often as once every 15 minutes. Therefore, the most significant present source of PVT error can be reduced to a negligible contribution with crosslinks by frequent updates of the ephemeris, constellation clock-drift control, and autoranging.

3. Integrity

GPS III will provide navigation solution integrity by performing outage monitoring, detection, validation, alerting, and the initiation of corrective action. A worldwide network can support this service by enabling improved PVT and ensuring GPS III integrity through monitoring of the signal-in-space trend analysis to detect gradual degradation of spacecraft performance. This also involves anticipating and detecting any sudden shift in clock and ephemeris data.\

4. Autonomous Navigation

Satellite crosslinks enable autonomous navigation by using crosslink-ranging measurements to estimate onboard corrections to the satellite clock and ephemeris. Additional advantages of autonomous navigation are enhanced survivability and a possible reduction in the workload of the master control station. The autonomous navigation function can be the primary means of satellite clock and ephemeris estimation, or a backup in the event of a control segment.

5. Growth and Flexibility

The GPS program is under continual evolution of navigation performance. A reliable space navigation program must also be flexible to meet the navigation needs for the next 30 years. As such, GPS III will be designed with the capability to accommodate product improvements.

Improved navigation signals, potential growth in navigation-related messaging demands, and the deployment of "smart" navigation technologies (antennas, algorithms, etc.) will make demands on a network that can increase throughput requirements by an order of magnitude. If GPS is used as a host for other sensor or communications payloads, this can also boost throughput demands. Therefore, the worldwide network needs to be flexible in accommodating greater data throughput for GPS III over the next 30 years.

In this report, Section II covers issues and concepts relating to crosslinks and are discussed in terms of (1) function in the GPS constellation, (2) architecture choices for the system, and (3) issues with the design factors of a GPS crosslink system. Three existing satellite systems use crosslinks—Iridium, TDRS, and Silex—and have several years of space heritage with the networking aspect of crosslink constellation management and data routing. The Aerospace Corporation has conducted several studies in conjunction with crosslinks: (1) alternative to crosslinks—ground-based network, (2) autonomous navigation simulations relating to the ranging architecture issues, (3) conceptual spacecraft design and performance of crosslinks, and (4) spectrum-related interference studies. Section III discusses spectrum allocation and unintentional interference sources in detail. The AF GPS JPO is evaluating study contracts with three contractors on GPS III, including crosslink architecture design and performance. Future studies are planned to answer burning performance issues related to communication, navigation, and network issues.

6. Crosslinks for GPS III—Function, Architecture Choices, and Design Factors

At least two types of constellation architectures have been considered for GPS III: the traditional six-plane constellation used in the current GPS system, or a three-plane constellation. The number of satellites under consideration ranges from 27 to 33. Regardless of the final constellation architecture, several design parameters need to be established, such as (1) latency—end-to-end delay, (2) connection—number of connections per spacecraft, (3) continuous vs. "make-before-break" connectivity, (4) network—IP or other packet-based data routing, switch-based routing, throughput rate, data rate, and processor control, (5) link, and (6) payload—weight, power, transmitter power, data rate, frequency, and bit error rate. When considering crosslink parameters, one needs to consider sufficient data rate, bandwidth, ranging chip rate, and an ITU-compliant frequency plan. Finally, crosslink interference issues need to be explored to ensure that navigation and hosted payloads will meet their mission requirements in the presence of other emitters.

7. Flight Heritage

There is flight heritage of satellites with large constellation and sophisticated crosslinks. Iridium has 66 satellites all connected by Ka-band crosslinks and the entire Iridium constellation has been operating for 3 years. TDRS has an IP-based crosslink network established between geosynchronous orbit and low Earth station orbit. Military programs have successfully used 60 GHz crosslinks. Laser crosslinks have been used on the European Silex program between geosynchronous orbit and low Earth orbit. It is obvious that RF intersatellite crosslinks have extensive flight heritage, and optical crosslinks are developing on-orbit experience. For Ka-band crosslinks, the flight heritage of the Iridium constellation shows that a large constellation can handle packet data routing, constellation control, and remote access to spacecraft commanding and telemetry. Optical crosslinks offer an increase in data capability that could fulfill the data needs of GPS over the decades, but they also pose a higher level of development risk.

8. Ground Network Study

The Aerospace Corporation produced a report studied the possibility of a ground-based, worldwide network meeting the future needs of GPS [1]. The purpose of the report was to assess its feasibility of supporting both the military and civilian services of GPS. The missions considered for this study included the following:

- Standard GPS Tracking, Telemetry, and Command (TT&C)
- Navigation Data Uploads
  - Autonomous Navigation and Integrity was not supported in this study.
- Search and Rescue (SAR)—an optional payload
- Blue Force Tracking (BFT)—an optional payload

A proposed search and rescue service of GPS III supports relaying data packets from the 406 MHz emergency beacons currently used with the Search and Rescue Satellite (SARSAT) program sponsor—NASA. This data needs to be routed to NASA and worldwide ground stations at specific ground sites. One of the applications of this service would be in the payload of a rapid-deployment military force called Blue Force Tracking. This organization will be used for post-conflict peace-building situations. A specialized GPS service is envisioned for this force, and a worldwide network is envisioned to support it.

The Aerospace Corporation ground network study concluded that there could be a simpler space vehicle because of the lack of directional crosslinks (e.g., no need for precise pointing, etc.). A less complex space vehicle means the potential of reducing the GPS Space Segment cost. The study also concluded that a ground-based network provides no significant improvement in the overall GPS architecture and implementation. However, what the study did find was that there is an increase in overall architecture deployment cost in terms of the initial deployment and life cycle costs. Furthermore, the study did not consider all of the military and civilian missions planned for GPS III. For example, the autonomous navigation service was not provided by this study, and integrity monitoring was not used. An extensive ground-based system may be too expensive to provide rapid constellation commanding. Furthermore, there is an overall complexity increase to the ground system, resulting in the need for overseas stations. Worldwide ground network sites may not be the most secure network for GPS when one considers the conflicts and unrest that exist in the world today and overall system vulnerability.

In view of the constraints on a ground-based network, the needs of GPS III lead to considering a space-based network using intersatellite crosslinks for GPS III.

9. Current Studies

The Air Force GPS Program Office is currently conducting studies with three contractors (Lockheed Martin, Spectrum Astro, and Boeing) on the design and implementation of the GPS III system. The Aerospace Corporation has also conducted three studies of baseline constellations with top-level crosslink performance parameters. These studies are not intended to be used in the design of the GPS III system, but to determine if some of the critical system performance requirements can be met. One study being conducted by The Aerospace Corporation Concept Design Center (CDC) has created a generic GPS III system with crosslinks. Other studies include autonomous navigation simulations, spectrum regulatory and interference studies, and a preliminary laser crosslink simulation.

First, the Concept Design Center considered two GPS constellation configurations: six planes and three planes [2]. The number of satellites in each constellation configuration ranged from 27 to 36. The Aerospace Corporation also conducted a top-level study of the use of laser crosslinks for GPS [3]. The purpose was to determine if laser crosslinks are practical and can provide significantly better navigation performance. Second, a simulation tool has been developed to study onboard autonomous navigation performance. The simulation determines signal-in-space errors, given the constellation definition, clock and ephemeris error models, measurement noise models, crosslink network configuration (number of links and link assignments), and onboard processing algorithm (either the current algorithm, where each satellite estimates only its own clock and ephemeris states, or an enhanced algorithm that effectively implements the current ground filter on board). Preliminary results for both six- and three-plane constellations show that performance is very sensitive to crosslink network configuration if the current estimation algorithm is used.

Third, frequency allocation and interference is one of the main issues of any satellite system. A frequency interference study is summarized in detail in the next section. At this time, only the Ka-band frequency is analyzed. V-band frequency will be completed at a later date.

10. Frequency Allocation and GPS III Crosslinks [4]

In consideration of a crosslink architecture, one needs to first look at the spectrum allocation for intersatellite links for nongeosynchronous satellites. One needs to also review the domestic and international regulatory allocations for the frequencies of interest. According to the International Telecommunication Union (ITU), two frequency bands are allocated and are ideal for intersatellite links: Ka band and V band (approximately 23 GHz and 60 GHz). Iridium and TDRS crosslinks operate at 23 GHz, and this frequency has the most flight experience. Nongeosynchronous satellites (NGSO) are restricted in the 22.55 to 23.55 GHz band. That band is therefore one of several candidate bands being considered for GPS III crosslink operations. The 22.55 to 23.55 GHz band is shared by three different services on a co-primary basis. These are the fixed service, the Mobile service, and the Intersatellite service.

The Fixed and Mobile services are terrestrial-based systems, and preliminary calculations show that these services should not pose an interference threat to GPS III intersatellite links because of their relatively low transmit power levels. The intersatellite service is used for communication crosslinks between satellites in various orbits. Many different operators have filed for satellite-to-satellite crosslinks, but it appears that only the Iridium system is actively using the band at the present time. It is, however, likely that other systems will occupy this band in the future

A preliminary analysis indicates that the risk of a GPS III crosslink causing unacceptable interference with other systems in this band is not high. Preliminary analysis also indicates that the risk of a GPS III crosslink receiving unacceptable interference from these other systems is not high. However, further analysis using more up-to-date information on link parameters, antenna sidelobe performance, and a more mature GPS III crosslink network topology is recommended in some cases to confirm these findings. Figure 1 summarizes the results of this preliminary analysis.

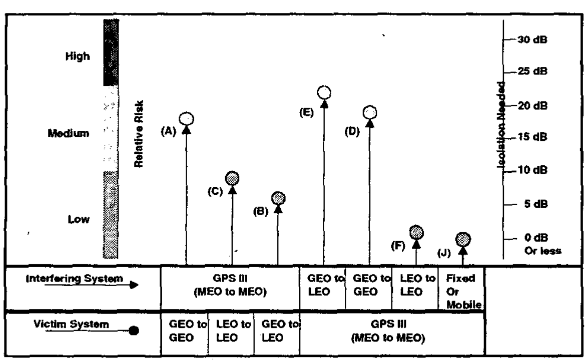

Fig. 1. Comparison of Interference Cases

The two rows across the bottom of Figure 1 illustrate the various interference cases that have been analyzed. The circles above the two rows indicate the relative risk of harmful interference for various combinations of these systems. The evaluation of relative risk is derived from a calculation of the amount of isolation required to meet a given level of interference into the victim system. The required level of isolation is shown by the scale on the right-hand side of the figure. The letters A, B, C, D, E, F, and J identify specific cases that are defined below.

11. Interference Assessment in the 23 GHz Band

A matrix can be drawn to represent all of the various combinations this analysis of one class of users interfering with another class. For the purposes of this discussion, it covers the cases where MEO to MEO systems (GPS III) are involved and use the same frequency as the other system. This matrix is shown in Table 1. The various cases to be discussed further in the document are labeled A through J.

The cases recommended for further study are indicated by heavy borders (Cases A, D, E, and I).

12. Preliminary Evaluation of Interference Potential

Calculations were conducted on the isolation[4] required between an interfering transmit antenna and a victim receive antenna to achieve a wanted carrier-to-interference ratio (C/I) of at least 15 dB for unintentional interference. The threshold value of 15 dB used here as the boundary between acceptable and unacceptable short-term interference levels is arbitrary but useful in this preliminary study. It is assumed that the wanted transmissions are using some form of QPSK modulation, and the strength of the interfering signal as received by the victim receiver will vary significantly over time. Peak interfering signal powers should be very short in duration.

If it can be reasonably assumed that the far side lobes of the crosslink transmit antenna will be at least 30 dB down from the gain peak, then a victim receiver located sufficiently far from the boresight of the GPS III crosslink antenna will benefit from at least 30 dB of isolation from peak signal power. Given this observation, if the isolation value calculated is less than 30 dB, there is a lower risk of interference.

In Case A, GEO-to-GEO crosslinks will clearly cut through the space occupied by the MEO (GPS III) orbits, and thus there is the potential for interference. If the GPS III crosslinks are configured in such a way that there are four crosslinks per GPS III satellite—(for example) with one link established to the leading in-plane GPS III satellite, one link to the trailing in-plane GPS III satellite, and one link to roughly adjacent satellites in the adjacent

[4] In this document, the condition of 0 dB isolation is the condition where the interfering and victim antennas are pointed directly at each other, the carriers are co-frequency, and the antennas use the same polarization sense. If an increased level of isolation is needed to meet a given sharing criterion, then this can be achieved by off-pointing one or both antennas, using different polarization senses, and the like.

Table 1. Interference Matrix

Interfering System	Victim System				
	GEO to GEO (Spaceway)	**GEO to LEO (ATDRSS)**	**LEO to LEO (Iridium)**	**MEO to MEO (GPS III)**	**MEO to MEO (other)**
GEO to GEO	—	—	—	(D) GPS III secondary	—
GEO to LEO	—	—	—	(E) GPS III secondary (?)	—
LEO to LEO	—	—	—	(F) GPS III defers to Iridium	—
MEO to MEO (GPS III)	(A) GPS III secondary	(B) GPS III secondary (?)	(C) GPS III defers to Iridium	—	(G) Depends on filing order
MEO to MEO (other)	—	—	—	(H) Depends on filing order	—
Intentional Jammer	—	—	—	(I) Vulnerability risk	—
Fixed or Mobile (Terrestrial Based)				(J) Co-primary services	

planes—then it will be rare for a GPS III crosslink to be either contained within the equatorial plane or within a few degrees of the equatorial plane. This network topology is very similar to that used in the Iridium satellite constellation, and seems to be a good starting point for a GPS III network topology. As such, the cone angle between the interfering GPS III transmit antenna boresight axis and the victim receiver should be sufficiently large that an isolation at least 19 dB is achievable, and the risk of significantly interfering with a GEO-to-GEO crosslink should be low.

In Case B, GEO-to-LEO crosslinks will clearly cut through the space occupied by MEO orbits, and thus there is the potential for interference. In addition, the GEO satellites used in these systems (for example, TDRS) do not typically require tight north-south station-keeping, and thus can have significant inclination angles relative to the equatorial plane. This increases the risk for interference. If the cone angle between the MEO satellite transmit antenna boresight axis and the victim receiver is greater than even a few degrees, then this level of isolation is easily achieved. In another case, if the minimum cone angle from the boresight of a transmitting GPS crosslink antenna to the vicinity of LEO orbits can be maintained at some nominal angle (10 degrees, for example), then there should be sufficient isolation to ensure that LEO systems do not receive unacceptable levels of interference. If this condition can be met with the topology of the GPS crosslink network, then no further study is needed for Case B.

In Case A, GEO-to-GEO crosslinks will clearly cut through the space occupied by the MEO (GPS III) orbits, and thus there is the potential for interference. If the GPS III crosslinks are configured in such a way that there are four crosslinks per GPS III satellite—(for example) with one link established to the leading in-plane GPS III satellite, one link to the trailing in-plane GPS III satellite, and one link to roughly adjacent satellites in the adjacent

planes—then it will be rare for a GPS III crosslink to be either contained within the equatorial plane or within a few degrees of the equatorial plane. This network topology is very similar to that used in the Iridium satellite constellation, and seems to be a good starting point for a GPS III network topology. As such, the cone angle between the interfering GPS III transmit antenna boresight axis and the victim receiver should be sufficiently large that an isolation at least 19 dB is achievable, and the risk of significantly interfering with a GEO-to-GEO crosslink should be low.

In Case B, GEO-to-LEO crosslinks will clearly cut through the space occupied by MEO orbits, and thus there is the potential for interference. In addition, the GEO satellites used in these systems (for example, TDRS) do not typically require tight north-south station-keeping, and thus can have significant inclination angles relative to the equatorial plane. This increases the risk for interference. If the cone angle between the MEO satellite transmit antenna boresight axis and the victim receiver is greater than even a few degrees, then this level of isolation is easily achieved. In another case, if the minimum cone angle from the boresight of a transmitting GPS crosslink antenna to the vicinity of LEO orbits can be maintained at some nominal angle (10 degrees, for example), then there should be sufficient isolation to ensure that LEO systems do not receive unacceptable levels of interference. If this condition can be met with the topology of the GPS crosslink network, then no further study is needed for Case B.

In Case C, LEO orbits are well inside GPS orbits. If the GEO crosslinks are set up such that they do not pass near the limb of the Earth, then there is essentially no risk of interfering with a LEO-to-LEO crosslink. If the GPS III crosslink topology is similar to that described in Case A, then this condition should be satisfied.

Figure 2 summarizes the isolation needed for the three cases of a MEO-to-MEO system (GPS III) interfering with the crosslinks of other systems. The risk of interference increases as the needed isolation approaches 30 dB. Case A was recommended for further study.

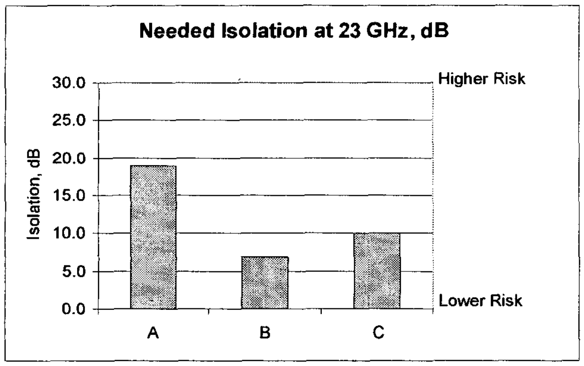

Fig. 2. Cases of MEO-to-MEO Systems as Interference Sources

Case D analyzed the potential for a GEO-to-GEO crosslink to interfere with a GPS III crosslink. An antenna isolation of 20 dB is needed to maintain a C/I level of 15 dB. The geometry is the same as that analyzed for Case A, and for the same reasons given for Case A, the risk is relatively low that a GEO-to-GEO crosslink would cause interference into a GPS III crosslink, provided that the GPS III crosslink topology is similar to that described in Case A.

Case E analyzes the potential for GEO-to-LEO crosslink interference with a GPS III crosslink. An antenna isolation of about 23 dB is needed to maintain a C/I level of 15 dB. However, it is recommended that this geometry and the potential for interference be studied further, using a more mature GPS III crosslink topology and more accurate link parameters to ensure that sufficient angular separation can be maintained between an interfering transmitter and the victim GPS receiver. As before, a statistical analysis can then be performed of the equivalent power flux density (epfd) seen by the victim GPS III crosslink receivers.

Case F analyzes the potential for LEO-to-LEO crosslink interference with a GPS III crosslink. Results shows that an antenna isolation of only about 2 to 3 dB is needed to maintain a C/I level of 15 dB. As seen in Case C, the LEO orbits are well contained within the MEO or GPS III constellation. If the GPS III crosslinks are set up such that they do not pass near the limb of the Earth, then a minimum of 2 to 3 dB of antenna isolation should be easily achieved, and there is essentially no risk of receiving interference from a LEO-to-LEO crosslink.

In Case J, both fixed (microwave tower to microwave tower) and mobile services are allocated as co-primary services in this band. A link budget for a hypothetical fixed or mobile service was calculated. It was assumed for this budget that the service would be used for a 20 km path along the surface of the Earth, carrying 100 Mbps of data. Even with a rain fade budget of 20 dB, the required EIRP is quite low. The required isolation is negative, meaning that a GPS III crosslink antenna could be aimed directly at such a source (not a likely scenario) and still not receive appreciable interfering energy. Thus, interference from either the fixed or mobile services in this band should not be a problem.

Figure 3 summarizes the isolation needed for the three cases of a MEO-to-MEO system (GPS III) receiving interference from the crosslinks of other systems. As the needed isolation approaches 30 dB, the risk of interference increases. Cases D and E were recommended for further study.

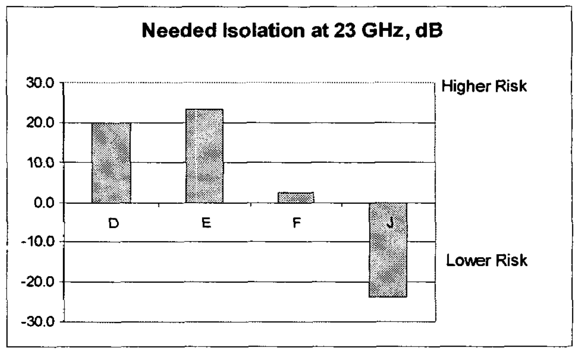

Fig. 3. Cases of MEO-to-MEO Systems as Victims of Interference

13. Future Studies—Network Architecture and Combined Communication and Navigation Performance

Future studies on GPS will cover some of the main risk areas associated with crosslinks. Spectrum and interference issues will be expanded to cover other frequency bands allocated for intersatellite crosslinks, and associated interference potential. However, the main focus of future crosslink network studies will be in terms of understanding the performance drivers, types of network routing, and throughput/latency behaviors. The autonomous navigation simulation, mentioned earlier in the text, is expected to be used in concert with simulations analyzing the communication crosslink network. Therefore, navigation and communication analyses are intertwined.

Although the Concept Design Center baselined the crosslink architecture, other studies are needed for an understanding of blending the navigation, communication, and data routing missions of GPS III. Several questions need to be answered:

1. Which concept offers the optimum connectivity—or the most difficult—for a constellation connected with intersatellite links?
2. Should GPS use circuit switching or be an IP-based packet-switched network?
3. Which protocol should be used to guarantee that packets will not be dropped?
4. What is the reliability of this protocol?
5. What is the flight heritage, if any, of this type of crosslink?

Packet-switched networking in space has been demonstrated on Iridium. Also, IP networking has been experimented with on the TDRS system. Standards are being created by public and government forums for space-related IP networking. Future studies in combining the communication, ranging, and navigation needs will generically identify the following:

1. The type of network—robust with line-of-sight and continuous communication, or "make and break" or scheduled contacts.
2. An efficient way to get the information around the constellation.
3. More characteristics of latency and performance
4. Design for full constellation connectivity but modeled for failures.
5. Data rates needed, how much onboard processing is needed, network configuration and control.

The Aerospace Corporation has developed a General Satellite Network Emulator (GSNE) [5]. In a real crosslink system, one satellite will have two to four (average) connections to other satellites and will be routed to one or more satellites in the network. Therefore, two or more data streams will be processed. GSNE simulates this satellite system by one-to-one mapping between real-to-emulation systems and implementing traffic input parameters. Then, the data is routed through an emulation processor consisting of a gigabit Ethernet switch and several Linux processors. This processor simulates an emulated data block (packet or circuit-switched system) to one real system block by using parallel emulation architecture. The GSNE uses a Beowulf cluster that comprises 80 processors. This allows emulation of up to 80 nodes, simulating satellite or ground stations. It also uses an industry standard message-passing interface (MPI). From this simulation, system performance parameters can be estimated to get a top-level feel of network performance.

14. Conclusion

The achievements of the Iridium, TDRS, and Silex crosslink systems are proof that reliable intersatellite links can be used on a daily basis. However, these satellite systems do not have the extensive utility-quality service and demand for reliability that is placed on GPS. Several studies have been conducted, by The Aerospace Corporation, for concept design of spacecraft crosslinks as well as studies on ranging and interference issues. Spectrum allocation of Ka-band crosslinks is available, but additional satellite systems are expected to file for this frequency. The competing status of operational priority of such crosslinks is an open issue. Other frequencies are also available for crosslink use. Ground-based interference for terrestrial communications that share the Ka band should not be a source of interference to GPS III crosslinks, but further study is needed for some satellite systems' possible interference with GPS III crosslinks. It has been concluded that a ground-based network has several problems meeting mission requirements, and the decision has been made to use a space-based crosslink network system. Because GPS requires a highly reliable system, the crosslinks have to perform at a high reliability rate. This means that the system availability and any down time has to be minimized and not affect the overall navigation functions and services. Future studies will determine the performance of GPS crosslinks, as well as the implementation of the GPS III crosslink designs

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