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Architecture Study of Space-Based Satellite Networks for NASA Missions

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Summary

Traditional NASA missions, both near Earth and deep space, have been stovepipe in nature and point-to-point in architecture. Recently, NASA and others have conceptualized missions that required space-based networking. The notion of networks in space is a drastic shift in thinking and requires entirely new architectures, radio systems (antennas, modems, and media access), and possibly even new protocols.

A full system engineering approach for some key mission architectures will occur that considers issues such as the science being performed, stationkeeping, antenna size, contact time, data rates, radio-link power requirements, media access techniques, and appropriate networking and transport protocols. This report highlights preliminary architecture concepts and key technologies that will be investigated.

Introduction

Traditional NASA missions, both near Earth and deep space, have been stovepipe in nature and point-to-point in architecture. There was no notion or need to communicate directly with other spacecraft. All communications (command, control, and data) went to a customized ground infrastructure either directly or via NASA's Tracking and Data Relay Satellite System (TDRSS). NASA and others have conceptualized and are beginning to plan missions that require space-based networking. The Earth Science Technology Office sensor web concept is a prime example. The notion of networks in space is a drastic shift in thinking and requires entirely new architectures, radio systems (antennas, modems, and media access), and possibly even new protocols. Space-based networks, like those envisioned for a sensor web, require far greater resources than NASA alone can provide. A number of cooperating entities including NASA, the Department of Defense (DOD), the European Space Agency, the National Space Development Agency and others will provide these systems. Thus, common communication packages need to be developed that allow these space-based systems to interoperate.

NASA Glenn Research Center will be performing an architecture and system engineering study. This study will address space-based satellite networks primarily for NASA missions; however, dual-use capabilities will be considered. This will allow common subsystems to be utilized by other satellite users such as other government agencies (U.S. or otherwise) and commercial entities. A full system engineering approach for some key mission architectures will occur that considers issues such as the science being performed, stationkeeping, antenna size, contact time, data rates, radio-link power requirements, media access techniques, as well as networking and appropriate transport protocols. These space-based network architecture designs will be developed to be evaluated in a preliminary design review with critical systems investigated further.

This report highlights preliminary architecture concepts and key technologies that will be investigated.

Design Philosophy

There are often numerous solutions to a given network design problem. Wherever possible, we wish to develop networks that can be designed with techniques and technologies already in place in the telecommunications and computer information industries. By doing so, we should be able to dramatically reduce the cost, deployment time, and risk.

Architecture Concepts

In order to limit the problem, three main architecture concepts will be considered:

(1) A myriad of loosely coupled ground stations in support of low-Earth-orbit (LEO) spacecraft
(2) A fully meshed sensor web
(3) A formation-flying constellation where the entire constellation performs as one unit

Each architecture has unique problems that must be addressed. Our goal is to see if common solutions exist to these problems. In addition, we would like to determine if there are similar problems that exist in terrestrial systems. If so, there already may be solutions that NASA can use outright or adapt. Likewise, there may be a similar problem existing in the terrestrial communications networks, which has yet to be solved. NASA may be able to provide the additional motivation needed to encourage industry to cooperate and collaborate in solving this problem.

A Myriad of Ground Stations

Traditionally, LEO satellites have been designed to communicate to the ground either directly or via a relay satellite. Those missions that communicate directly to the ground require the satellites and ground stations to be highly scheduled and coordinated. The ground stations are programmed to know exactly when and where to track the satellites. In addition, a rather limited set of ground stations are involved. Often the satellites are in polar orbits and the stations are near the Polar Regions to allow for maximum connection time (refs. 1 and 2). These satellites often utilize techniques whereby the satellite stores data until it has connectivity with the ground, at which time it forwards the data down at a high rate. For such architectures, the longer the satellite is in isolation, the more data it has to store. This, in turn, requires higher transmission rates to offload the data once a connection is achieved. Thus, this architecture results in rather expensive ground stations that are highly scheduled but have a small duty cycle. In addition, the spacecraft costs increase because of the need for added onboard storage and high-rate communications to the ground.

To reduce the overall system cost and increase the number of science missions as well as the amount of science performed by each mission, we propose modification of the traditional LEO satellite direct-to-ground architecture. The paradigm shift we attempt to make is to bring the cost of the ground and space infrastructure down significantly by volume production and sharing of network resources. The basic question becomes “Is it technically, economically, and politically feasible to utilize a myriad of loosely coupled, highly adaptive, ground stations located throughout the world to perform a multitude of missions?”

Figure 1 illustrates the concept of a myriad of loosely coupled ground stations. Consider that thousands of ground stations could be situated throughout the world at a variety of locations. These terminals could be located at nearly every major university throughout the world if the costs were reasonable. Assuming that is the case, the ground infrastructure already exists to allow each station to be connected to the Internet. By deploying new networking techniques, any satellite could utilize any ground station that permitted access and could accommodate that satellite’s modulation schemes. Thus, a single ground station can service a multitude of spacecraft and a single spacecraft can utilize a multitude of Earth stations.

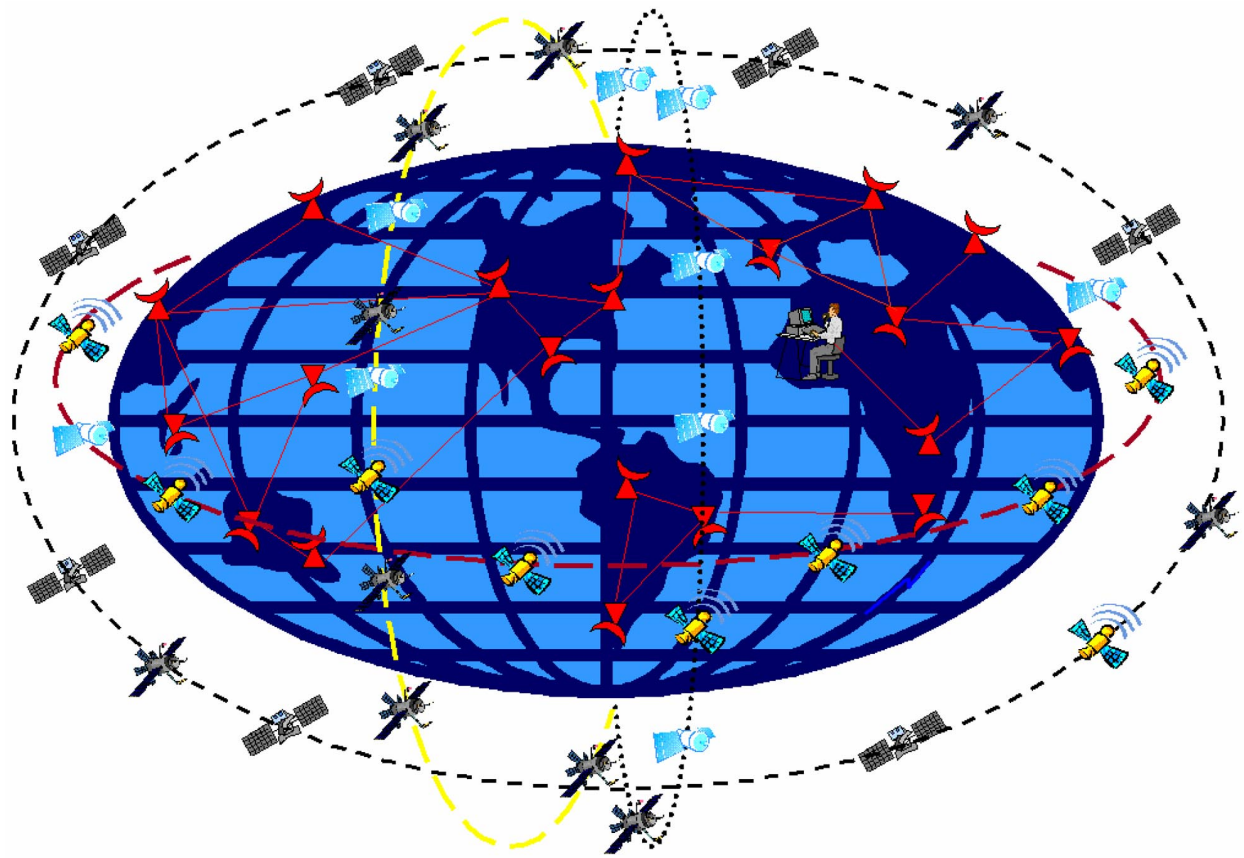

Figure 1.—Myriad of loosely coupled ground stations and many low-Earth-orbit (LEO) spacecraft.

Such a network can evolve and grow. As the network expands, more orbits can readily be served, thereby increasing the amount and types of science missions that can be performed. In addition, the spacecraft may serve other needs such as mobile communications or paging services, thus sharing the satellite resource and offloading some of the system expense to commercial endeavors.

The key is volume production of uniform spacecraft and Earth terminals. Volume and uniformity will reduce system costs.

A paradigm shift in spectrum allocation that allows for a dynamic (on-demand) allocation of spectrum is also required. This will enable better spectrum utilization.

A Fully Meshed Sensor Web

The NASA Earth Science Enterprise is moving toward network centric communications for its missions. Sensor webs, constellations of spacecraft, and LEO missions that communicate with geostationary Earth orbit (GEO) relay satellites, directly to the ground, and with high-flying sensor platforms are all expected to have multiple communications paths. The characteristics of each of these paths will, more often than not, be unknown—particularly with the introduction of software radios. Some links will be shared; others will be dedicated. Manual pre-engineering of these complex networks will no longer be possible.

Figure 2 illustrates the dynamics of a simple sensor web and the necessity for full utilization of network resources. This illustration shows that manual intervention and pre-engineering of the network is not practical.

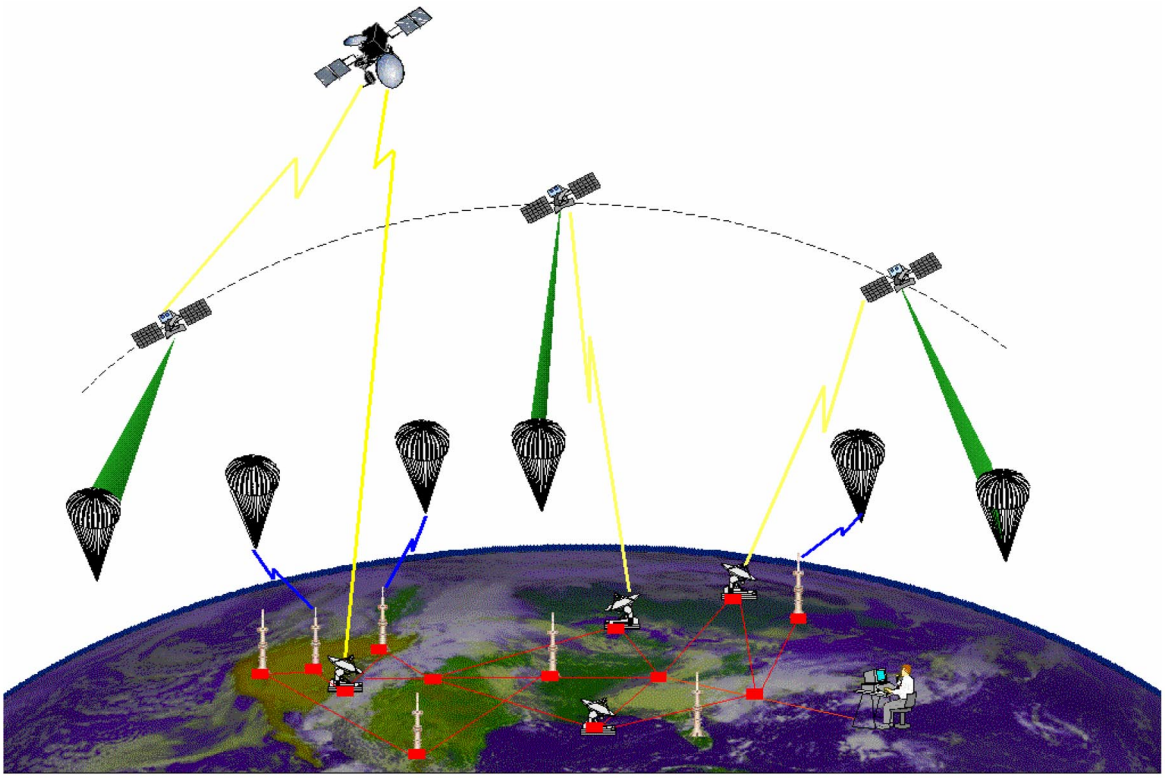

Figure 2.—Fully meshed sensor web.

For this example in this figure, consider that a balloon (or aircraft) is our high-flying sensor and relay platform. The balloon is perhaps one of many balloons that have been launched and will travel the globe until retrieved or lost. In addition to having sensors onboard, the balloon has multiple communications links. One link is a low-rate communication link to terrestrial sensors. Those sensors may reside in the rain forest, on ocean buoys, or near fault lines and volcanoes. The balloon will act as a relay for those low-power sensors and send the sensor information to a LEO or GEO relay satellite. The balloon also has a high-rate communication link to ground. This link is active when the sensor is in sight of various low-cost receiving stations spread throughout the world. Such receiving stations may exist at universities or government installations, or they may be provided by private industry (e.g., teleport providers or Internet service providers). Once in contact with these terrestrial stations, the balloon would transmit any stored data at a high rate and much lower cost (in dollars and power) than using the space relay satellites. Both the availability of terrestrial and space assets is expected to grow as the network evolves. In this instance, all links may be shared with other systems. In addition, one may utilize the relay-satellite link for a portion of the data transmission and complete the transmission directly through the terrestrial station. At one instant, the communications may be via the GEO relay satellite at a very slow rate (kbps) with a moderate-quality and very long delay link. An instant later, communications may be transmitted directly to a terrestrial node with a high-rate and high-quality link.

This fully meshed architecture is actually an expansion of the prior architecture. The basic idea is the same: utilize standard and uniform spacecraft, communication links, and ground stations to the fullest extent possible, thereby enabling volume production and standard operation to reduce system cost and risk. Thus, missions must be designed to allow for reusable hardware and software and standard integration at all levels of system development including media access, authentication, authorization, and accounting. Some compromises may have to be made regarding optimization of individual science missions for the good of the whole.

A Formation-Flying Constellation

The terms formation-flying spacecraft, spacecraft constellations, and spacecraft clusters have a number of meanings. The Globalstar and Iridium communication satellite networks and the Global Positioning System (GPS) all are spacecraft constellations, and all require moderate positioning relative to one another. However, none of these systems has all the spacecraft operating together as a single unit.

For our study we plan to address communication issues related to a formation-flying constellation where the entire constellation performs as one unit. Sometimes the science cannot be performed any other way. Other times the system might be designed such that several smaller spacecraft and more modest launch vehicles each carrying one unit can cost less than one very large spacecraft and launcher. This provides for a robust mission whereby the risks are distributed over several launches and spacecraft. No single failure would lead to loss of the mission.

The Micro-Arcsecond X-ray Imaging Mission, MAXIM, is a very good example of a formation-flying constellation. Figure 3 depicts a proposed architecture for MAXIM consisting of a fleet of up to 33 optics spacecraft flying in formation. These telescopes will work in unison to simultaneously observe the same distant objects, combining their data and becoming 100 times more powerful than any single x-ray telescope that has previously been used (refs. 3 and 4).

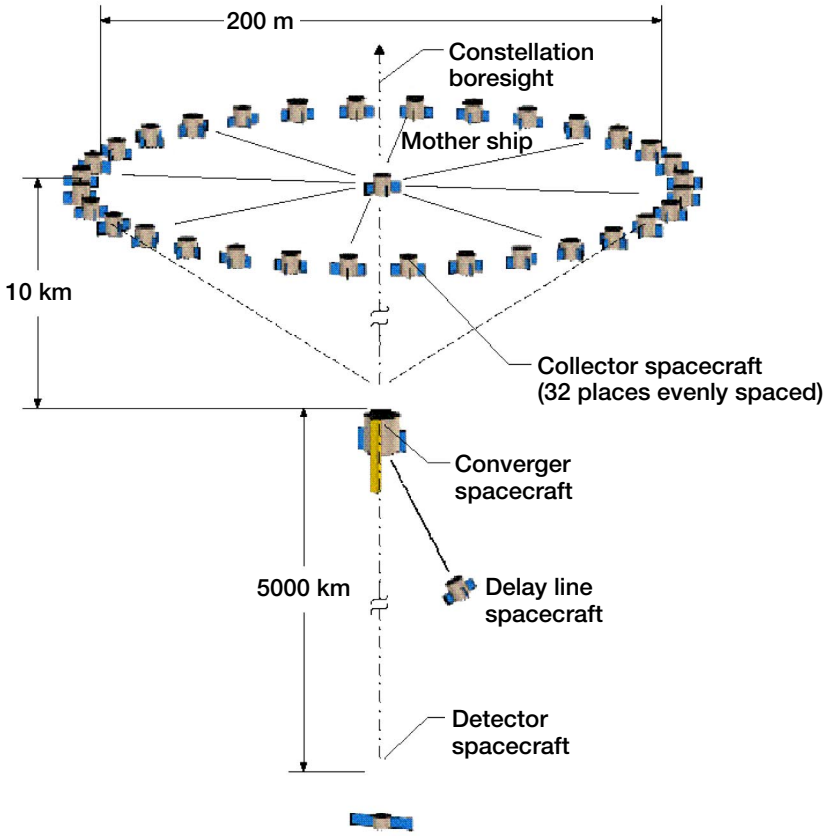

Figure 3.—Proposed architecture of MAXIM Mission (ref. 4).

Numerous technologies are being addressed regarding formation-flying constellations. However, nearly all of these are related either to the instrumentation or to the precision stationkeeping. Few, if any, studies have investigated the exact communications requirements for the science missions. Nonetheless, some communication simulations studies have been conducted to determine if current terrestrial communication technologies may apply (ref. 5).

Technologies and Issues

Both the loosely coupled ground station architecture and the fully meshed sensor web have similar issues and technologies that need to be addressed. The formation-flying constellation architecture has its own issues and problems related to the need for individual spacecraft to perform as one unit. However, if the formation-flying constellation were in a low Earth orbit, the hub spacecraft, also known as the mother ship, could very likely be considered another node on the sensor web. Thus, a formation-flying mother ship may have to deal with those same issues as any spacecraft in a fully meshed sensor web.

The key technologies and areas that need to be studied for the loosely coupled ground station architecture and the fully meshed sensor web architecture are listed below:

(1) A standard media access technique to allow access into the ground station
(2) A programmable modem or software defined radio (SDR) that can accommodate a number of standard modulation and coding formats similar to those defined for the Intelsat terminals (ref. 6)
(3) A standard method for authentication, authorization, and accounting (AAA)
(4) Routing techniques
(5) Secure networking over shared infrastructure

The key issues that need to be addressed regarding communications in a formation-flying constellation include

(1) The overall architecture and distribution of processing
(2) The type of communication that needs to take place among the sensor spacecraft
(3) Timing and synchronization issues
(4) Whether a separate communication channel should be allocated for positioning or if positioning can be performed in-band
(5) The media access required between the mother ship and sensor spacecraft

A generic issue that needs investigation for all the previously identified architectures is the development of auto-tuning reliable transport protocols.

Media Access

A standard media access technique requires significant consideration because all communication begins with media access. The problem with media access is that one needs to perform some form of communication between the satellite and Earth station or between spacecraft in order to set up the communication links. Traditionally, this is where scheduling occurs. However, the scheduling of a diverse, complex, and evolving network is not scalable. One possible solution to media access is to have a very low-rate omnidirectional beaconing system whereby ephemeris data or spacecraft identification (ID) is provided to the ground station or neighboring spacecraft to enable antenna tracking. In addition, modulation, coding, and data rates could be identified, negotiated, or stored in a standard database referenced by spacecraft ID. Authentication and authorization may also occur at

this time. Once the link is established and conditions are negotiated, communication over primary radiofrequency (RF) links may commence. This communication scenario can occur for each ground station or spacecraft that can receive the beacon communication with adequate capacity.

Media access between the mother ship and sensor spacecraft needs to be defined and will be determined by the requirements of the constellation. A new media access technique may be required depending on the type of timing, the synchronization, and the criticality of the data being transmitted between sensor spacecraft and the mother ship. However, it is highly desirable to develop communication solutions and a constellation design that will allow for use of existing media access techniques such as the IEEE 802.11 wireless Ethernet standards.

Reconfigurable Radios

A programmable modem is a necessity in these architectures to allow various diverse entities to communicate with each other. In some cases, a spacecraft may be power limited and only be able to communicate at low data rates using simple modulation and coding schemes in order to close the link. Other times, entities may be quite close or have tremendous communication capability and highly directional antennas. These entities may be capable of closing the communication path while transmitting at very high rates using spectrally efficient modulation schemes. Thus, the deployment of software configurable modulation and coding devices is highly desirable.

The ideal software-defined radio would have infinite bandwidth and infinite data-rate capabilities. However, the reality is that the greater the bandwidth and data-rate requirements, the quicker one moves from a software digital signal processing reconfigurable radio to a hardware reconfigurable radio (ref. 7). Thus, it is imperative that thorough system and network engineering studies are performed to identify the parameter space in which these radios need to operate.

Reconfigurable radios are probably not required for the formation-flying constellation, which will be well defined prior to launch.

Authentication, Authorization, and Accounting

In order for this architecture to become viable, it is necessary to share infrastructure—particularly the ground infrastructure—with various spacecraft from a variety of organizations with diverse ownership. For sensor webs, it is also highly desirable to share space resources to utilize another's communication paths. Consequently, a common method of authentication, authorization, and accounting (AAA) must be agreed upon. Authentication is the ability to identify an entity beyond all reasonable doubt. Authorization is the ability to grant or deny an identified entity access to specified resources. Accounting is the ability to monitor the entity's use of the allocated resources. This is often done for billing purposes. AAA techniques currently exist and have been standardized by the Internet Engineering Task Force (IETF) for use in various communication networks (refs. 8 to 10). Additional work is ongoing within the Internet Research Task Force (IRTF) regarding new AAA architecture concepts that support AAA services interoperating across organizational boundaries, enable a concept of an AAA transaction spanning many stakeholders, and are scalable to the size of the global Internet (ref. 11).

Many current AAA techniques are directly applicable to space-ground access—particularly involving the use of AAA servers. However, some modifications may be necessary for space-to-space access since continuous connectivity with AAA servers may not be practical or possible.

Use of AAA may or may not be an issue for the constellation of spacecraft, depending on their function and the degree of protection required relative to the perceived threat. Constellations of spacecraft will be well defined in both mission and system communication requirements. It is highly unlikely that an undesirable, foreign entity would try to act as a sensor spacecraft for space-based science missions. However, this must be considered if the constellation is being used for other space-based applications such as reconnaissance.

Routing Technologies

All of the architectures identified in this report represent networks of spacecraft. In particular, the loosely coupled ground station architecture and the fully meshed sensor web are highly dynamic, consisting of both stationary and mobile networks.

Mobile IP (Internet Protocol) and mobile networking protocols have a very good potential to solve the networking and routing problems for the loosely coupled ground terminal architecture (ref. 12). Mobile IP is designed to allow single hosts or entire networks roam off their home networks. It does not stress the RF link and very little information is exchanged to set up the connections. In addition, it has been shown that one can easily secure the mobile network (ref. 13).

Mobile networks can be nested. Therefore, Mobile IP can therefore be used for fully meshed sensor webs with one mobile network nested in another one. Here, one spacecraft may wish to use a second spacecraft owned and operated by another organization as a communication conduit.

Current Mobile IP techniques do have issues related to route optimization, nesting of mobile networks, and security. Mobile IP and the associated security tend to require multiple levels of tunneling[1] which reduce bandwidth efficiency. Security requirements may also completely eliminate the ability to perform route optimization. These issues are currently being considered for possible improvement by the IETF Networks in Motion (NEMO) working group (ref. 14).

Ad hoc routing protocols may also be appropriate for the fully meshed or loosely coupled ground terminal networks. The idea behind ad hoc networking is to have all entities in the network participate in the routing (whenever possible) and to be completely self-configuring and dynamically reconfigurable. Ad hoc routing protocols can be rather "chatty" if applied inappropriately and may use valuable bandwidth while communicating route updates and status. Also, since orbits are predictable, many satellite-based networks are not truly ad hoc in nature. Maybe of greatest importance is the fact that ad hoc networks have yet to be secured with regard to sharing network infrastructure. However, research is ongoing regarding ad hoc networks for both terrestrial and space networks (refs. 15 and 16). Thus, there is potential to apply such routing algorithms in future space-based networks.

For the constellation of spacecraft, the network is relatively simple—at least locally—and may not require any routing protocols with the exception of the mother ship. The mother ship could easily be represented as just another node in a fully meshed sensor web.

Securing Mobile Networks Over Shared Infrastructure

Having entire networks change their point of attachment within other networks is extremely new technology with very limited deployment. Having entire mobile networks owned by one entity connecting to and having information pass through another entity's network in a secure manner has only recently been accomplished (refs. 13 and 17).

Securing mobile networks over shared infrastructure requires both media access (as previously described in the section Media Access) and encryption. Encryption can be performed using techniques such as IP security (IPSec), virtual private networks (VPNs) or government- and military-approved encryption such as the National Security Agency's High-Assurance Internet Protocol Encryption (HAIPE).

[1]Tunneling is a term used when one packet is encapsulated in another packet. Tunneling is very useful for security in order to hide and encrypt information and to cross dissimilar networks.

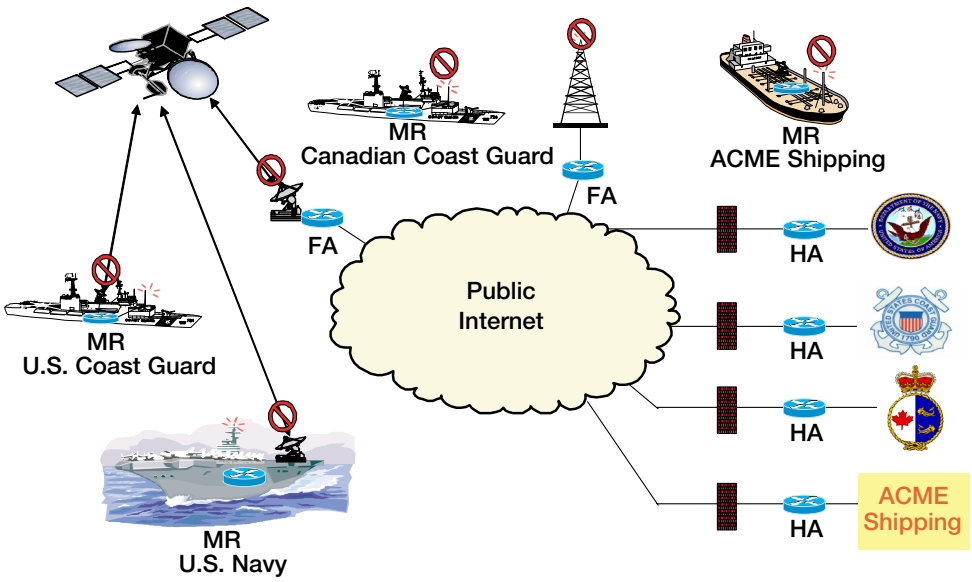

Figure 4.—Encrypting radiofrequency (RF) links makes it very difficult to share infrastructure. MR is mobile router; FA, foreign agent; and HA, home agent.

It is imperative that encryption be performed at the proper location to facilitate sharing infrastructure between various entities (i.e., countries, corporations, and universities). Protecting the mobile LAN (local area network) and everything behind that LAN while allowing access to the media is key. However, if one encrypts at the RF layer, sharing the infrastructure becomes extremely difficult. Figure 4 illustrates this for a terrestrial mobile network. In this example, encrypting the wireless links precludes the U.S. Coast Guard, the Canadian Coast Guard, the U.S. Navy, and the commercial shipping industry from sharing infrastructure unless the encryption keys are coordinated. Usually, coordination of encryption keys between various entities is not allowed for obvious security reasons. The same concept applies to space. Furthermore, (as of December 2002) there are incompatibilities when operating layer three encryption at mobile router roaming interfaces because of the specification that the time-to-live (TTL) field should be decremented when tunneled. This needs to be resolved within the IETF because changes are needed in the tunneling specification, the IPSec specification, or the mobile routing specification.

Timing and Synchronization

For space networks, onboard timing and clock synchronization are critical. Timing and synchronization information will be used to time-stamp science and telemetry data for later correlation with other independent data sources. Also, the timing and synchronization information will be used to coordinate and schedule transmissions with neighboring nodes in the space-based network.

Depending on the precision that is required and the overall network connectivity that is available, timing and synchronization can be relatively straightforward or quite complex. For general network timing, where network connectivity is readily available, existing techniques such as the Network Timing Protocol (NTP) have been shown to work quite well for LEO systems (refs. 18 to 20). The GPS can also be used to obtain timing information. It is anticipated that many LEO spacecraft will be equipped with GPS receivers in the future for timing and location information since space-qualified GPS receivers are flying today. Other technologies and techniques will have to be deployed for the timing and synchronization of the Internet in deep space and between planets. This may also be the case for formation-flying constellations, where each unit is acting together as a

single instrument. New technologies and research into areas such as quantum physics may provide solutions.

Autotuning Reliable Transport Protocols

There is a need to address efficient, reliable data delivery for highly dynamic, space-based and terrestrial networks (mobile networks, ad hoc networks, evolving networks, etc.). New algorithms need to be developed that can be incorporated into existing reliable transport protocols which enable them to automatically adapt to changing network conditions (autotuning). This is particularly necessary in mobile environments where bandwidth, delay, and link quality may change instantaneously. Autotuning transport protocols will enable full and efficient utilization of the communication link and network—be it shared or unshared. Thus, fairness and quality of service also should be consideration.

Concluding Remarks

Traditionally NASA communication needs consisted of point-to-point communications and single spacecraft mission. NASA and the DOD are moving toward a concept of space networks. Overall, these networks are far more complex and powerful than current systems. However, it may be possible that individual spacecraft can be far less expensive yet far more capable by applying design principles that enable usage of existing terrestrial technologies and practices. Our goal is to develop design concepts that will take full advantage of techniques and technologies already in place in the telecommunications and computer information industries. By doing so, we expect to dramatically reduce the cost, deployment time, and risk. We plan to develop each design concept presented in this report that will be evaluated in a preliminary design review to identify the key issues and problems that must be solved.

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13. ABSTRACT ***(Maximum 200 words)***

Traditional NASA missions, both near Earth and deep space, have been stovepipe in nature and point-to-point in architecture. Recently, NASA and others have conceptualized missions that required space-based networking. The notion of networks in space is a drastic shift in thinking and requires entirely new architectures, radio systems (antennas, modems, and media access), and possibly even new protocols. A full system engineering approach for some key mission architectures will occur that considers issues such as the science being performed, stationkeeping, antenna size, contact time, data rates, radio-link power requirements, media access techniques, and appropriate networking and transport protocols. This report highlights preliminary architecture concepts and key technologies that will be investigated.

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