InterPlanet Computer Networking: System Architecture for Delay and Disruption Tolerant Networks in Planetary Space

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ABSTRACT

The interplanet internet is a conceived computer network in space, consisting of a set of network nodes that can communicate with each other. These nodes are the planet's orbiters (satellites) and landers (e.g. robots, autonomous machines, etc.) and the earth ground stations, and the data can be routed through Earth's internal internet. In this paper, we propose an interplanetary internet system architecture to operate successfully and achieve good communication with other planets including the Earth. The architecture proposes a suite of means to address delays and solar interference in a disconnected regions of the planetary system to achieve end-to-end communication. We propose relay-satellites on asteroids for delays due to propagation for routing information. Also propose Ethernet set-up for planet Mars network, Recovery switch for release of queued packets, time stamping of incoming messages in a queue and transmitting through other planetary spacecrafts that addresses delays during the periods of solar radiation interference and conjunctions. As it is planetary based architecture outline, the results could not be tested due to unavailability of large scale wireless networks over long distances however, the proposed architecture would be effective in addressing delays and disruption in a planetary communication.

INTRODUCTION

Inter-planetary exploration, be it Lunar habitation, asteroid mining, Mars colonization or planetary science/mapping missions of the solar system, will increase demands for inter-planetary communications. The movement of people and material throughout the solar system will create the economic necessity for an information highway to move data throughout the solar system in support of inter-planetary exploration and exploitation. The communication capabilities of this interplanet information highway need to be designed to offer; 1) continuous data, 2) reliable communications, 3) high bandwidth and 4) accommodate data, voice and video.

The **interplanetary Internet** is a conceived computer network in space, consisting of a set of network nodes that can communicate with each other. These nodes are the planet's orbiters (satellites) and landers (e.g., robots), and the earth ground stations. For example, the orbiters collect the scientific data from the Landers on Mars through near-Mars communication links, transmit the data to Earth through direct links from the Mars orbiters to the Earth ground stations, and finally the data can be routed through Earth's internal internet.

Interplanetary communication is greatly delayed by interplanetary distances, so a new set of protocols and technology that are tolerant to large delays and errors are required. The interplanetary Internet is a store and forward *network of internets* that is often disconnected, has a wireless backbone fraught with error-prone links and delays ranging from tens of minutes to even hours, even when there is a connection.

In the core implementation of Interplanetary Internet, satellites orbiting a planet communicate to other planet's satellites. Simultaneously, these planets revolve around the Sun with long distances, and thus many challenges face the communications. The reasons and the resultant challenges are**:**

The interplanetary communication is greatly delayed due to the interplanet distances and the motion of the planets.

The interplanetary communication also suspends due to the solar conjunction, when the sun's radiation hinders the direct communication between the planets. As such, the communication characterizes lossy links and intermittent link connectivity.

The graph of participating nodes in a specific planet to a specific planet communication, keeps changing over time, due to the constant motion. The routes of the planet-to-planet communication are planned and scheduled rather than being fluctuating.

The Interplanetary Internet design must address these challenges to operate successfully and achieve good communication with other planets. It also must use the few available resources efficiently in the system.

While IP-like SCPS protocols are feasible for short hops, such as ground station to orbiter, robots to lander, lander to orbiter, probe to flyby, and so on, delay-tolerant networking is needed to get information from one region of the Solar System to another. It becomes apparent that the concept of a *region* is a natural architectural factoring of the Interplanetary Internet.

A *region* is an area where the characteristics of communication are the same. Region characteristics include communications, security, and the maintenance of resources, perhaps ownership, and other factors. The Interplanetary Internet is a "network of regional internets".

What is needed then, is a standard way to achieve end-to-end communication through multiple regions in a disconnected, variable-delay environment using a generalized suite of protocols. Examples of regions might include the terrestrial Internet as a region, a region on the surface of the Moon or Mars, or a ground-to-orbit region.

SYSTEM DESIGN

The overall communication system architecture for the planetary information highway between earth and mars and also between earth and moon is given below in Figure 1 however, for all practical purposes we will consider network between earth and mars as communication delays between earth and our moon are minimal because of shorter distance compared to the planet mars.

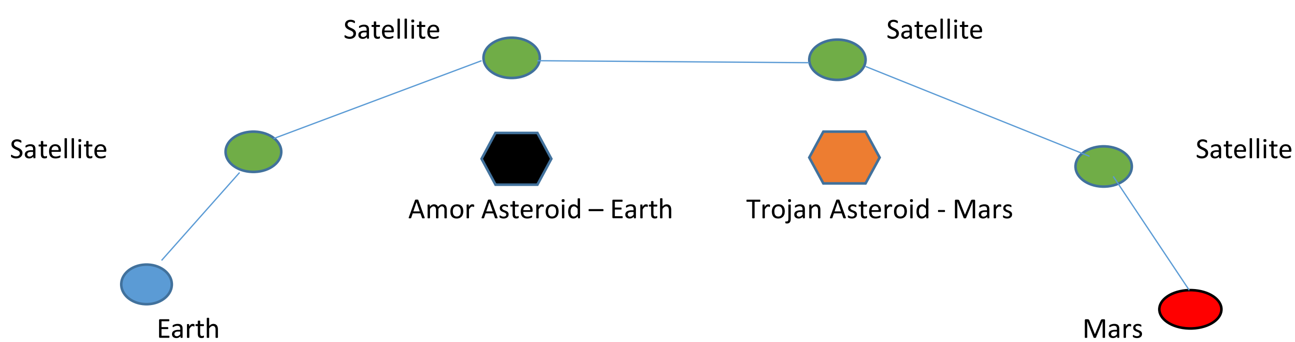

Fig. 1 Planetary Satellite Link

Since the earth already has a substantiate internet infrastructure suitable to transfer video, voice and data, we tum our attention to the communications subsystem of the proposed satellites that would orbit the mars. These satellites could communicate with the existing earth infrastructure and would act as satellite-to-satellite relays, also known as satellite cross-links, to relay signals to their intended receiver located in space. The destination could be personnel transports in route to Mars, for example, or a satellite cross-link in orbit around Mars. This is depicted in Figure 1. For the purpose of analysis, the satellite cross-links are assumed to have the same characteristics in both directions.

Currently, satellite communications are based on the electromagnetic radiation of signals in the RF region and also laser beams to transfer information nearly error-free in the gigabit per second range. The advantage of laser cross-links is its resistance to interference in the microwave region. The current explosion in network technology offers additional areas of interest. ATM switching and routing features is very much applicable to a satellite based relay system. The methods used in the wireless communication industry to transfer calls between cells are also applicable to the proposed satellite relay concept.

DELAY COMPONENTS IN A NETWORK

All communication between Mars and Earth goes through satellites. Because of the distance, there is a substantial delay. As communication signals travel at the speed of light, this means that it can take between 3 and 22 minutes for the information to reach the other end, so a phone call would not be practical. Moving safely from rock to rock or location to location is a major challenge because of the communication time delay between Earth and Mars, which is about 20 minutes on average. Similarly, Propagation time to the Moon and back ranges from 2.4 to 2.7 seconds, with an average of 2.56 seconds and the distance from Earth to the Moon is 384,400 km.

There are different **delay** components in a communication network and these are processing **delays**, transmission **delays**, propagation **delays**, and queuing **delays**. All of these **delays** are fixed, except for the **queuing delays**, which are **variable.**

QUEUING DELAYS

Since the capacity of **Gateway Router**.is limited, there is a possibility that incoming requests exceed router queue capacity and user requested packets may get lost due to queuing delays. These variable delays due to queuing can be addressed with addition of Recovery Switch with same capacity as Router with virtual expandable capacity. This Switch will be configured to router only to manage excess request of Queues in the event of solar or other disruptions to manage queues of packets to avoid the loss of information carrying packets. This Switch will get activated only when router exceeds its capacity and virtually expands to manage building of request queues.

PROPAGATION DELAYS

Large propagation delays, due to the size of the planetary system, cannot be avoided. This clearly precludes real-time interactive voice or video sessions outside the earth to lunar or mars regions. Yet, the need for continuous, uninterrupted services of data, voice and video is important. Anyone monitoring the health and status of a space vehicle desires the ability to have continuous monitoring of spacecraft systems and positions allows for quicker response to react to onboard anomalies. This means that service interruptions caused by planetary and solar interference need to be minimized if not totally eliminated.

Using the estimated distances, one can estimate the range of propagation delays between planets. A simplified model of propagation delays considers only two types of delay. These are: 1) free space delay (which is distance d times the speed of light c) and 2) planetary delay. The sum of these delays yields an estimate of total delay. TotDly = Planet1dly + Planet2dly. A large contribution to propagation delay is a result of free space delay. The distances in the solar system make real-time interactive sessions impractical in certain situations. The range of propagation delays that could be expected throughout the planetary system based on distances and delays in the relay satellites do exist but are so small and constant that they can be ignored. Relay delay is simply a result of the repeater/router functions. Based upon current switch and router technology these delays range from .2 to 20 milliseconds. Planetary delays can be treated as a constant and are estimated as the average delay between a orbiting satellite network and its terminal location.

DESIGN CRITERIA – Relay Satellites on Asteroids

There are numerous theoretically possible satellite configurations that can meet the objective of uninterrupted communications. To select from these choices, the number of satellites required in the system and their locations must be analyzed. The main criterion for assessment is fault tolerance and transmission lag time.

While this analysis focuses on the location of the relay satellites used to bounce a signal from Earth to Mars and back, it is important to consider the necessity of satellites in Mars orbit. Mars-orbiting satellites allow for communication with a Mars base when it's in line-of-sight to the relay satellites.

We next consider designs using the Earth-Mars and intermediate points. The first system is a satellite at the Earth-Mars orientation point. This satellite arrangement would have communication with Earth about 94.5% of the time (the same as Mars direct communication since it lies on Mars' orbit). The remainder of the time the satellites at Mars would be the only source of line-of-sight communication. Unfortunately, this setup has several disadvantages. First, it is fairly far away from Mars. Although the signal transmission from Earth to the relay satellite, can be most effective by the use of the large Earth network, but if there is a long transmission distance from the relay satellite to Mars, the effect of the large communication setup on Earth is partially negated. So, large asteroids (called Amor and Trojan asteroids) have been found at both outer orbit of Earth and Mars. These asteroids require the relay satellite to either have an in-plane orbit around the asteroid, be located some distance away, or sit on an asteroid. While this options require significantly more station-keeping, placing a satellite on an asteroid has the potential of adding more relaying power that benefit to the scenario in reducing propagation delays significantly. With these considerations, we choose to place the satellite in-plane, away from asteroids with the station-keeping feature. Finally, because there is only one satellite in a non-Mars orbit, that satellite is occasionally blocked by the sun. While this creates a layer of redundancy (allowing the Martian satellites to have line-of-sight communication with Earth 94.5% of the time), therefore it is more beneficial to have a satellites outside of the Mars orbit, allowing us to keep the Mars satellites' direct communication and this scenario, involves identical satellites at both Amor and Trojan asteroids. This setup means that the Mars satellites only have to communicate with the Trojan/Amor satellites, not all the way to Earth, thereby significantly reducing propagation delays in communication.

PACKET SWITCHING

We propose network architecture with Ethernet Setup with datagram broadcast and socket programming interface for the Planet Mars as in same manner as presently existing in internal Internet of Earth. The objective here is to achieve a networks that grow with usage and last a long time and essentially involve variable length packet format and structured addressing, use of port numbers and client-server interaction.

SOLAR RADIATION INTERFERENCE and CONJUNCTIONS

Solar conjunction occurs when a planet or other solar system object is on the opposite side of the Sun from the Earth. From an Earth reference, the Sun will pass between the Earth and the object. **Mars** Solar **conjunction** is a period that occurs when the **Mars** and Earth in their eternal march around the Sun, are opposite from each other by the fiery orb of the Sun itself. Sun emits hot, ionized gas from its corona, which stretches out far into space. **During** this time, the Sun can interrupt radio transmissions to spacecraft on and around the Red Planet and during **solar conjunction**, the emitted gas can interfere with radio signals when engineers try to **communicate** with spacecraft at Mars, corrupting commands and resulting in unexpected behavior from our deep **space** explorers. During that time, all spacecraft have become virtually incommunicado for about two weeks every two years. The reason is **solar conjunction**. During Solar Conjunction, radio signals transmitted by the Deep Space Network to the Mars Reconnaissance spacecraft (and vice versa) must pass through the solar corona. Due to signal interference, the measurements that the Navigation team use for orbit determination become very noisy.

Since the Sun is a strong source of electromagnetic energy, it causes significant interference to communications. As the Sun moves between two inter-planetary objects (planets or spacecraft) the ability to maintain communication degrades until it is no longer possible to operate. These periods of interference are also called conjunctions.

Even though the apparent diameter of the Sun from the Earth is 0.48 degrees, the diameter of solar radiation interference ranges from roughly 6 degrees (+ 3 degrees from center) for a quiet sun and as high as 14 degrees (+ 7 degrees from center) for an active sun. Using this, one can construct a sphere, centered in the middle of the solar system that is used to estimate periods of conjunctions.

In addition, the sun acts a white noise jammer of ground surface terminals when the Sun is aligned with the downlink terminal beam. This alignment happens twice a year around the equinoxes for geosync satellites. During this period, around the equinox, the ground terminal's receiving system is saturated with the sun's radio signal for short periods each day. The period of disruption is also based upon solar activity. Worst case outages for a quiet sun can be as long as 23 minutes and for an active sun it can be as high as 55 minutes. Assuming 10 hours a year of outages due to this type of conjunction yields an overall availability contribution of 0.998859.

Here we propose two options for addressing solar radiation interference and conjunctions:-

1. The first option is to transmit signals through existing other planet spacecrafts or satellites orbiting in planetary space which do not come under the influence of solar interference as we can accurately estimate the periods and extent of solar conjunctions before the event accurance. However, there could be propagation delays in communication due to diversion of signals in comparison to direct link through relay satellites.
2. As we can estimate the periods of solar conjunctions beforehand, the recover switch gets activated which is connected to gateway router and essentially designed to manage and process queue of incoming packets in virtually expandable capacity in the event of solar disturbances and this setup gets activated simultaneously on either side of Earth and Mars. Here in Recover Switch, each message received will be time-stamped in order they arrive and send it to gateway router by releasing the queued messages in first-in first-out manner as the planet communication gets revived through relay satellites.

CONCLUSION

The interplanetary computer network in space is a set of computer nodes that can communicate with each other. We proposed a network architecture with planet's orbiters, landers (robots, etc.), and the earth ground stations and linked through Earth's internal internet, and consisted of relay-satellites on asteroids to address propagation delay. Also proposed Ethernet set-up for Planet Mars network, Recovery switch for release of queued packets, time-stamping of incoming messages in a queue and transmitting through other planetary spacecrafts that addresses delays during the periods of solar radiation interference and conjunctions. As it is planetary based architecture outline, the proposed architecture would be effective in addressing delays and disruption in a planetary communication among disconnected regions of the planetary system to achieve end-to-end communication through multiple regions. . Examples of regions might include the terrestrial Internet as a region, a region on the surface of the Moon or Mars, or a ground-to-orbit region.

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