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A SURVEY ON THE RECENT DEVELOPMENTS IN DELAY TOLERANT NETWORKING AND ITS APPLICATIONS FOR INTERPLANETARY INTERNET

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ABSTRACT

Delay Tolerant Networking is the current hotspot in the area of deep space communication. DTN uses a standard message format called Bundle Protocols (BP) to transfer any data. Till date, very few research works have been done to test the performance of these Bundle Protocols. This survey paper brings out the current architecture of the InterPlaNetary (IPN) Internet, the features of the Bundle Protocols, and a real time scenario describing how these features of the BPs add up resulting in the efficient transmission between two network nodes in terms of packet transfer, security and other parameters. The recent experiments conducted on space DTN is also discussed in this paper. A survey on the current IPN architecture also reveals the necessary improvements that must be made at all the layers of the architecture to make it more reliable, efficient than the present time.

KEYWORDS : Bundle Protocols, Interplanetary Internet, Delay Tolerant Networking, Interplanetary Overlay Network

On Earth, electronic signals zip around at the speed of light with negligible delay and almost no errors because the distances are short and it is easy to provide strong signals. But as one moves farther into space the distances become large and delays and errors are introduced. It would be very difficult to conduct a phone call between Earth and the Moon, where 1.25 seconds is the minimum one way link delay or one way latency. At Mars, where the delay may easily be half an hour, the phone callwould be impossible. The one way signal latency between Earth and different destinations is shown in figure 1 (Mukherjee J., 2012).

The initial phases of communication in space or satellites missions used radio signals shot towards the spacecraft antenna whenever they came in view. This, as expected, resulted in long signal delays and intermittent connectivity in deep space communications. Space craft disappear behind the Sun for days on end, planets rotate, and spacecraft on and around them can only occasionally see Earth. The radio links used were noisy and prone to errors. The whole nature of communication was not same as on Earth no longer chatty, with lots of instant feedback, but far more like the letter writing days of the nineteenth century. (Figure 1)

What was needed then, was a standard way to achieve end- to end communication through multiple regions (A "region" is an area where the characteristics of communication are the same. These characteristics include communications, security, the maintenance of resources, and other factors. The Interplanetary Internet can be visualized as a "network of regional internets") in a disconnected, variable-delay environment using a generalized suite of protocols.

Consequently various networking architectures were developed(Joyeeta M., 2012), to build a standardized suite of protocols for all other future missions, like Delay Tolerant Networking (DTN), Deep Space Networking (DSN), InterPlaNetary Internet (IPN) etc.

The Interplanetary Internet study at NASA's Jet Propulsion Laboratory (JPL) was started by a team of scientists at JPL led by Vinton Cerf and Adrian Hook. Cerf is one of the pioneers of the Internet, and currently holds the position of distinguished visiting scientist at JPL. Adrian Hooke is one of the directors of the CCSDS (CCSDS stands for Consultative Committee for Space Data Systems). Founded in 1982 the Consultative Committee for Space Data Systems (CCSDS) is a multinational forum for the development of communication and data system standards for spaceflights. It is a basically a forum that discusses the problems of the spacecrafts and Earth data systems and generates plans for their operation and development. Here, leading space communication experts collaborate in developing the most well engineered space communication and data handling standards of the world. The resulting CCSDS document library contains recommendations which provide detailed technical guidance to space agencies for developing their data handling systems for various space missions. (Figure 2)

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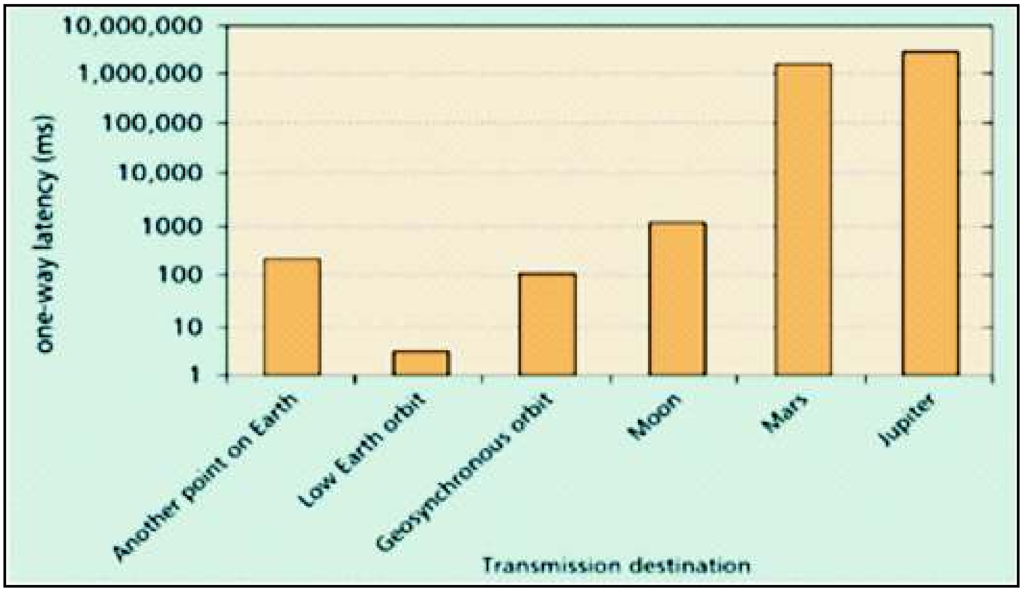

Figure 1 : Comparison of One Way Signal Latency Between Earth and Different Destinations

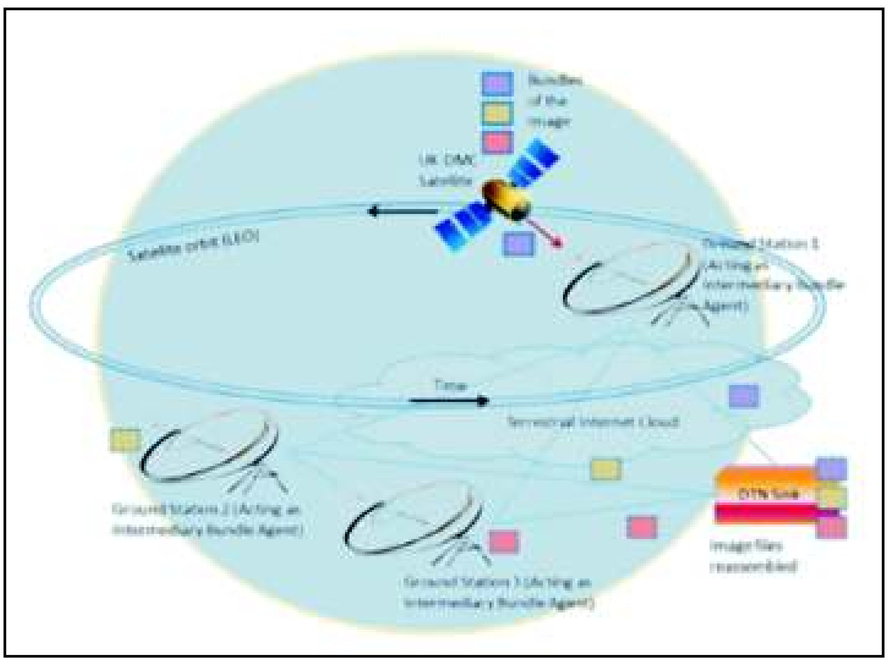

Figure 2 : Use of Bundling and Fragmentation Over A Number of Passes of the Satellite

Literature Survey

- **UK- Disaster Monitoring Constellation (UK-DMC)**

Perhaps the Bundle Protocol was first tested and demonstrated on board the UK-DMC satellite manufactured by the Surrey Satellite Technology Ltd (SSTL) on August, 2008. In this experiment the proactive fragmentation capabilities of the Bundle Protocols was to be checked which would even allow a large file to be sent over the network during a single contact opportunity to a ground station(Mukherjee J., 2012). Therefore the experimenters didn't provide high propagation delays. There are seven UK-DMC imaging satellites in the Low Earth Orbit (LEO) which have 5 to 14 minutes of contact time during a scheduled pass to a ground station (ground stations are interconnected through terrestrial networks), in its complete 100 minutes orbit. The image taken by the satellite was broken into bundles and required three passes to be transferred to the ground and finally to a “DTN sink” as demonstrated in the figure 2. If the satellite were to transfer it to a single ground station it would take approximately three orbits for a sink to obtain the complete file (considering minimum delays over the terrestrial network). The UK-DMC satellite did it in only one orbit by transferring the image bundles to separate ground stations and then reassembled it over the terrestrial Internet at the sink using the Bundle Protocol of DTN architecture.

- **Experiment on- Board The International Space Station (ISS)**

NASA's Huntsville Operations Support Center (HOSC) has also been testing the DTN technology on the International Space Station (ISS) in collaboration with University of Colorado. It has deployed the bundle protocol in a Bundle Protocol Agent (BPA) to the Commercial-Grade Bioprocessing Apparatus 5 (CGBA5) and carried out a series of tests(Mukherjee J. and Ramamurthy B., 2013). The CGBA5 is primarily an environmental control chamber for life science experiments but along with that it also provides a computational/communicationplatform that has a 1 GHz Intel Celeron processor (32-bit), 1 GB RAM, 4 GB solid-state disk and an operating system Linux 2.6.21. The Rack Interface Computer (RIC) on board the ISS serves as the IP gateway to the ISS payload LAN. We find that the RIC frame size is 96 bytes for uplink and 1248 bytes for downlink. However, the CGBA5 applications can submit data unitsupto the size of 2048 bytes regardless of the RIC frame size. The uplink and downlink bandwidth provided by the channel is 150 and 400,000 bits per second. There's an uplink via S-band and two downlink paths: S- and Kμ-bands. The S-band is viewed as the primary payload uplink and telemetry downlink path with relatively low data and command rate such that the bandwidth and command slots are pre-allocated. On the S-band uplink, the command rate is 8 commands per second,that is driven by an onboard 10 Hertz (Hz) clock. The uplink bandwidth is in turn dynamically allocated, in order to provide the facility with varying size uplinks. This program has helped in establishing a long term, readily accessible communications testbed onboard the ISS. Later deployments has also made CGBA4 a communication computer used for tests that transmit messages between ISS and ground Mission Control Centers. All the data is monitored and controlled by the Payload Operations Control Center (POCC) at the University of Colorado, Boulder. Till now only point-to-point communication takes place between space crafts. Moreover, scheduling transmission time, duration and the destination is done manually. The successful ISS testing have brought another success that will no more require human beings to operate and control transmission jobs, thereby saving a lot of labor cost.

- **Deep Impact Network Experiment (DINET)**

On October and November 2008, NASA performed its first test with DTN in close cooperation with the Epoxiproject. The experiment (mainly performed to simulate a Mars local planet network) was called the Deep Impact Network Experiment (DINET)(Mukherjee J., 2012), and almost 300 images were sent to the spacecraft from various JPL (Jet Propulsion Laboratory) nodes in a duration ofone month. The complete network constituted of 10 nodes: One is the Deep Impact Epoxi spacecraft (that is located at 80 light seconds from Earth and acts as Mars relay orbiter) itself and the other nine are here on Earth at JPL and they simulate Mars landers, orbiters and ground mission-operations centers. The course of the experiment is as follows:

October 18, 2008 - The Interplanetary Overlay Network (Burleigh S., 2007) (Interplanetary Overlay Network (ION) is an implementation of the DTN Bundle Protocol that is intended to be usable for interplanetary communications) DTN software was successfully uploaded on the Epoxi spacecraft and data was sent and received from the DINET Experiment Operations Center.

October 20, 2008 - Images were sent to the Epoxi spacecraft and 3 hours later the same images were transmitted and successfully received at JPL exhibiting one of the first examples of the Interplanetary Internet.

October 22, 2008 - During pass 2 of the experiment 264046 bytes (five images) were successfully delivered

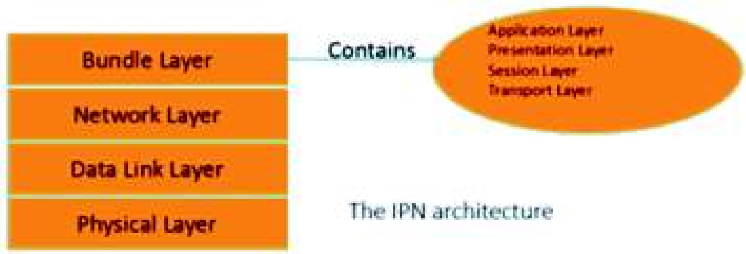

Figure 3 : The Interplanetary Internet Architecture

making 97.6% (approximate) link utilization.

November 3, 2008 - On the 5th DSN tracking pass an additional 1587420 bytes (35 image files) were delivered via the IPN to image reception software in the DINET Experiment Operations Center.

Delay Tolerant Networking

Delay-tolerant networking (DTN) was designed to enable standardized communications over long distances and through time delays. It has something called as Bundle Protocol(Burleigh S. and Scott K., 2007), or BP, as its core element, which is similar to the Internet Protocol, or IP, as the core element of Internet here on Earth. The big di□erence between the regular Internet Protocol (IP) and the Bundle Protocol is that IP works assuming a continuous end-to-end data path, while BP is built to account for errors and disconnectionswhich is very much common in deep space communication. To understand the application of this delay tolerantnetworking in space communications we must look into the Open Systems Interconnection model (OSI) which is a conceptual model that characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers.

OSI Model

In this model the communication functions are partitioned into hierarchical set of layers(Stallings W., 2003). Each layer performs a related subset of the complete process required to communicate with another system. The different layers of the OSI model are: Application, Presentation, Session, Transport, Network, Data Link, and Physical. It is the Application layer which provides access to the OSI model to the users. To enable the current IPs to work with the features of Delay Tolerant Networking, Bundle Protocols (BP) have been definedwhich sits in the Application layer of the current internet model forming a store- and- forward overlay network(Burleigh S., 2007). This newlayer formed (also known as the Bundle Layer(Romano P., Schrotter P., Koudelka O., and Wittig M., 2009)) comprises transport and application layer functionalities. The transport of data packets between IPN nodes is handled by the bundle protocol, while the provision of end-to-end connectivity between source and destination node is handled by application layer functionalities. The final architecture formed is known as the Interplanetary Internet. Since in interplanetary network environments continuous end-to-end connectivity cannot be assumed, the bundle layer must have the capability of storing data bundles as well as their address and route to their final destination until they can be forwarded to the next hop and so on.

The BP interacts with lower layers of the OSI through "Convergence Layer Adapters" (CLAs)(Caini C., Fiore V., 2012). Various CLAs have been defined; the most common are those for TCP, UDP and the Licklider Transmission Protocol (LTP)(Caini C., Fiore V., 2012), (Apollonio P., Caini C., Fiore V., 2013), which is particularly suited to space links including cislunar ones. In the DTN architecture, transport protocol end-to-end features are confined to one DTN hop, while end-to-end communication through multiple DTN hops is provided by the bundle layer, which acts as a store-and-forward overlay; DTN overlay and storage and other DTN features.

The final architecture of the Interplanetary Internet can be given as in figure 3.

Capabilities of Bundle Protocols

- Custody-based retransmission(Apollonio P., Caini C., Fiore V., 2013)
- Ability to cope with intermittent connectivity
- Ability to take advantage of scheduled, predicted,

and opportunistic connectivity in addition to continuous connectivity.

- Late binding of overlay network endpoint identifiers to constituent internet addresses.

Features of Bundle Protocols

- **Custody Transfer**

Bundle Protocol can add a layer of reliability by using an optional service called custody transfer(Zhou D., Yang M., 2012). Custody transfer requests a node with capable storage to store the bundle if it has storage capacity. The node that accepts custody of a bundle will transmit a custody signal to the node that previously had custody of the bundle. On reception of the custody signal, the previous custodian will delete the bundle from its storage and retransmission buffer. This previous custodian is not required to wait until the bundle reaches the destination to delete the bundle from its storage thus allowing maximum utilization of the limited memory at the nodes. The responsibility of reliably transferring the bundle to the destination lies with the last node that accepted custody of the bundle. Therefore, if the bundle is lost or corrupted at some point of time, the user need not resend the bundle, rather the node that last accepted the custody of the bundle automatically resends the bundle upon the expiration of the TTL (Time to Live i.e. the time for which the bundle remains alive).

Experimental observations at the Communication Research Center, Harbin Institute of Technology, China (Zhou D., Yang M., 2012)shows that when the packet loss rate is less and the link disruption rates are also low, then the throughput in case of without custody is much higher than the throughput in case of with custody. This result can be explained on the basis of the extra time required for the transmission and reception of the custody signal in custody enabled method. But when the packet loss rates are high (say 2%) then the throughput in case of without custody is much higher than that in case of with custody at all link disruption rates. Thus, the feature of custody transfer will definitely help in deep space exploration where the hindrances in terms of packet loss rates and the link disruption rates are very high.

- **Installation of BP As Intermediate Nodes**

By installing the BP in end-points and some intermediate nodes, the end-to-end path is divided into multiple DTN hops(Caini C., Fiore V., 2012). In a heterogeneous network region, e.g. a network that encompasses both terrestrial and space links, the intermediate DTN nodes are usually chosen at the border of each homogeneous network region. In this way on each DTN hop it is possible to use the transport protocol which is best suited for that region.

- **Contact Graph Routing (CGR)**

Contact Graph Routing (CGR) (Caini C., Fiore V., 2012) is a dynamic routing algorithm designed to cope with intermittent scheduled connectivity. In the space environment, communications between DTN nodes are active for only limited intervals of time, called "contact windows" in DTN terminology. Each contact offers the opportunity to transfer no more data than the "contact volume", given by the product of the link speed (in bit/s) and the contact window. Contact periods and contact volumes are assumed to be known beforehand because they are dependent on either DTN node motion or scheduled bandwidth allocation of space links. CGR exploits the knowledge of contacts windows and volumes to find the most suitable path from source to destination, following a complex algorithm, which is fully described in ION (Interplanetary Overlay Network) documentation(Burleigh S., 2007).

Situations may arise where a contact between two nodes does not occur for a long time period during which the bundle TTL (Time To Live) expires or a bundle cannot be transmitted within the set contact period of the two communicating nodes. For both the cases the bundle is removed from its outbound transmission queue and the CGR is re-applied to the bundle so that an alternate route can be computed.

The key point in the CGR algorithm(Caini C., Fiore V., 2012) are the following:

- Each node implementing CGR has a global knowledge of contacts (ie. which nodes it has to transmit the bundles because a "contact plan" has been provided to space nodes by a control centre)

- The route is recomputed at each node implementing CGR.
- Routes are always recomputed for each new bundle, to cope with network dynamics.
- The criteria for "best" route selection may vary. According to the ION releases 2.5.x the "best" path is that which provides the shortest "expected delivery time".

- **Fragmentation**

An interesting feature of DTN bundle protocol is the possibility of fragmenting bundles(Apollonio P., Caini C., Fiore V., 2013). There are two types of fragmentation: Proactive and Reactive fragmentation. Proactive Fragmentation is particularly useful feature in the presence of intermittent periodic connectivity, where there may be a strict constraint on the maximum amount of data that can be transferred (contact volume) between two successive DTN nodes at each availability of contact time. In this case, proactive fragmentation automatically subdivides large bundles into multiple fragments of a predetermined size whenever the maximum contact volume is known prior.

Reactive fragmentation works when there is a relatively long disruption of the channel, which forces the DTN bundle protocol to close the connection at Transport layer during a bundle transfer. In order not to retransmit successfully received data, the bundle which is partially transmitted is split into two "fragments". The first consists of data which has already been sent, the second is its complement. When the bundle protocol succeeds in re-opening the disrupted connection, it will send just the second fragment. These fragments are reassembled before delivery to the application.

- **Bundle Security**

Security is one of the most complex and important aspects to be considered in DTN, essentially because challenged network impairments, and in particular long delays make the usual security solutions impractical(Caini C., Fiore V., 2012). To implement security, the Bundle Security Protocol (BSP) has been defined(Symington S., Farrell S., Weiss H., Lovell P., May, 2011). The BSP takes care of both end to end and hop by hop security. It adds the following 4 blocks(Symington S., Farrell S., Weiss H., Lovell P., May, 2011) in the bundle layer of the IPN architecture.

Bundle Authentication Block (BAB), Payload Integrity Block (PIB), Payload Confidentiality Block (PCB) and Extension Security Block (ESB)

BAB is used for authentication at every hop. PIB is used to provide authentication for multiple hops at a time. PCB provides payload(Burleigh S. and Scott K., 2007) (the data that is carried on behalf of an application) confidentiality between source and destination. Finally, ESB provides security (both confidentiality and integrity are recommended in the RFC) for non-payload blocks(Burleigh S. and Scott K., 2007).

The different security threats in transmission of Bundles can be summarized as follows:

- **Direct Asses to Space Assets (Masquerading)**

Space assets are precious and thus must be carefully protected against any form of attack. For this reason only nodes in full control of the space agencies must be authorized to access them. Any attempt to send bundles destined to the relay or to the Lander by the non-institutional user, pretending to be an authorized node, is easily rejected by BAB checking at relay satellite. By contrast, direct transfer in the opposite direction, from the relay orbiters or from the destination to the user (on the source) must be obviously possible(Caini C., Fiore V., 2012).

- **Direct Asses to Space Assets (Denial of Service Attacks (DoS)**

Instead of trying to send bundle accepted, an attacker could try to exhaust the storage resources of space assets, to carry out a Denial of Service attack(Caini C., Fiore V., 2012) (bundle need to be stored at intermediate nodes, and the attacker can exhaust the limited memory present at a DTN node by sending unauthorized bundles). For this reason it is essential that bundles that fail the BAB verification rule be eliminated as soon as possible.

- **Tampering and Eavesdropping**

Unauthorized bundle payload modification (tampering at the source or any node) or reading (eavesdropping)(Caini C., Fiore V., 2012) can be counteracted by an appropriate use of PIB and PCB(Symington S., Farrell S., Weiss H., Lovell P., May, 2011).

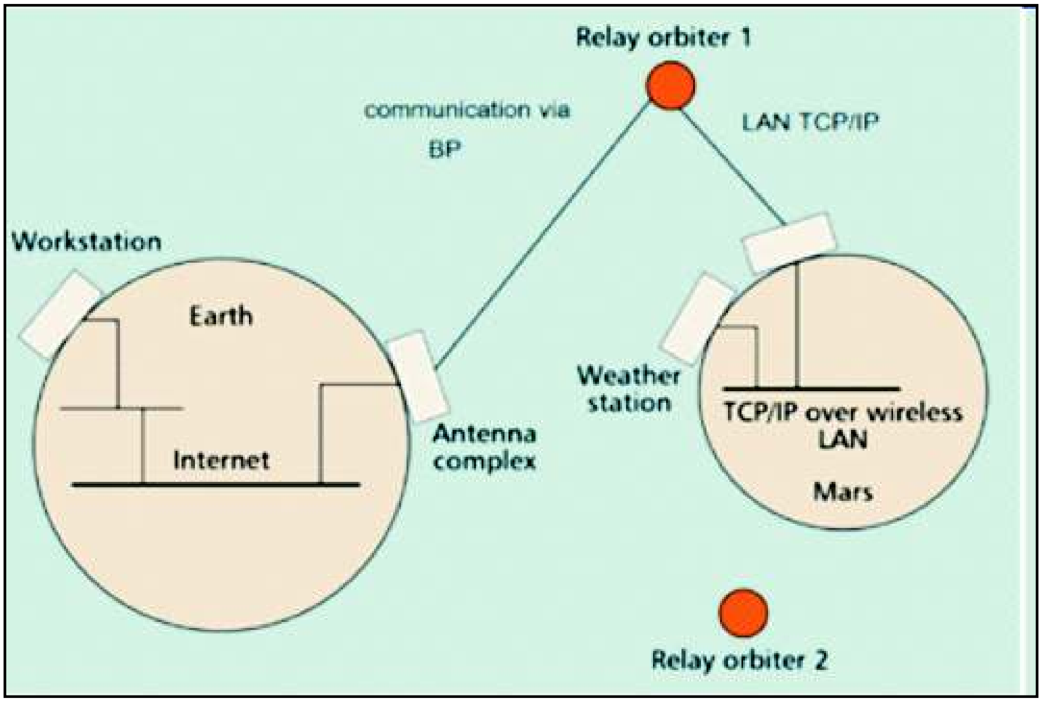

Figure 4 : Diagram Showing File Transfer From Workstation on Earth to Weather Station on Mars

- **Efficient Use of Bandwidth**

The Bundle Protocol tries to use as minimum bandwidth as possible while transmission. This has been accomplished with the help of Self- Delimiting Numeric Values (SDNV) encoding technique. SDNVs were developed for use in these types of fields, to avoid sending more bytes than needed. In this technique any positive numeric value is encoded into N octets, the Most Significant Bit (MSB) of the last octet is set to 0 while all the other octets have their MSBs as 1. The other 7 bits of every octet contain relevant information. An example of the encoding scheme can be of 1 (decimal). It represented by the bitstring "0000001" and encoded as the single byte 0x01 (in hexadecimal). 128 is represented by the bitstring "10000001 00000000" and encoded as the bytes 0x81 followed by 0x00.

A Real Time Scenario

To get a more real visualization of the working of Bundle Protocols for IPN architecture, consider the example of file being transferred from theworkstation of some space agency to a weather station on Mars(Burleigh S., Hooke A., Torgerson L., Fall K., Cerf V., Durst R., Scott K. and Weiss H., 2003). The module must be transmitted first from the workstation to a deep space antenna complex, then from the antenna complex to a constellation of relay satellites in low Mars orbit (no one of which is visible from Earth long enough on any single orbit to receive the entire module, thus disqualifying the conventional RF signals from the options and mentioning the need for a relay orbiter. The other use of the relay orbiter is that it is designed to achieve store-and-forward relay operation(Caini C., Fiore V., 2012) when the link between the relay and the other node is unavailable due to limited direct connection or some other reasons.), and finally from the relay satellites to the weather station. The first leg, i.e. from the workstation to the deep space antennae complex, of this journey would typically be completed using the TCP/IP protocol suite over the Internet. For the next leg of the journey from the antennae complex to the relay orbiter, the IP/TCP suite won't work satisfactorily because of their drawbacks mentioned in the above section. Thus we need a new set of protocols and this is where the IPN (which uses bundle protocols) comes into picture. The Payload Confidentiality Block(Symington S., Farrell S., Weiss H., Lovell P., May, 2011) authenticates the payload and then gives it a consent for the onward journey. The bundle may be transported in single hop or multiple hops(in case of more than one relay satellites) along with optional fragmentation choice depending on the network connectivity. Authentication is done at each hop. The CGR (Caini C., Fiore V., 2012) sets to work every time a node receives the bundle to find the best route (in case of multiple relay satellites). The relay orbiters can eitheraccept the bundle with custody or without custody(Apollonio P., Caini C., Fiore V., 2013) depending on the link disruption rates and packet loss rates.

For the final delivery of the module from the relay orbiters to the weather station on its wireless LAN, TCP/IP might again be the best choice. But now TCP/IP would be running over wireless link protocols. As in interplanetary space, and in contrast to the wired Internet, data rates on these links are likely to be fairly low, but since potential for congestion will be low for the expected future communications, this choice would perhaps be the best in the currently available networking architecture. The entire process can be summarized as shown in figure 4.

Necessary Improvements in the IPN Architecture

IPN research work is currently focused at the bundle layer in the previously introduced IPN architecture. This is because efficient data transport issues in store-and-forward chains are one of the key problems faced in the Bundle Layer. But apart from these issues, there are catches at all OSI layers which need to be considered.

- **Improvement in the Bundle Layer**

The current specifications (Burleigh S. and Scott K., 2007) of the Bundle Protocols does not include error detection mechanisms of bundles. It opens the doors to the employment of coding in the application layer of the Bundle Layers of the current IPN architecture.

- **Enhancements at the Physical Layer**

In order to obtain high transmission efficiency over the long communication links, communication sessions must be scheduled. IPN backbone nodes must calculate communication opportunities with neighbouring nodes in advance to optimize transmission resources(Romano P., Schrotter P., Koudelka O., and Wittig M., 2009).

- **Data Link Layer Issues**

Multiple access schemes (Romano P., Schrotter P., Koudelka O., and Wittig M., 2009) will play an important role in the context of deployed internets for providing connectivity from orbiting planetary spacecraft to multiple surface elements simultaneously.

- **Improvements in the Network Layer**

The network layer plays a major role for data transfer purposes. Planetary networks represent highly mobile scenarios in the network topology. Network layer protocols must be able to cope with mobility requirements, since mobile surface elements need to maintain connectivity while going out of the coverage of one relay orbiter, requiring transfer or handoffs to the next relay satellites.

- **Standardization at the Transport Layer**

Since a lot of research work for IPN has already been performed, issues at the transport layer is mainly standardization. It would be desirable to agree on one common standard for each planetary network, even if the standard may differ from implementations on different missions. For example, the standard for Mars may differ from the standard for Jupiter, but all missions to Mars must implement the same standard. The gateways must be capable to translate data packets from the planetary standard to the standards used for the IPN backbone.

CONCLUSION

This paper discusses about the Bundle Protocols used in Delay Tolerant Networking, specifically for space communication purposes under Interplanetary Internet. It explains the architecture of the current Interplanetary Internet, capabilities of the BPs and their features which help in reliable transport of packets between network nodes in extremely variant environments. Although research on this topic has been continuing since 25 years, There are still many environments, factors which stand to be analyzed. The architecture has to be made even more robust which is easily reflected from the limitations of the BPs in the last part of the paper. Also as the IPN becomes more robust and needs to exchange more data in future, it will be unacceptable to have separate networks namely the terrestrial internet and the interplanetary internet. Therefore the two networks needs to be merged with one another in the near future which may require more layers in the current IPN architecture. This merger will make both the networks act as one connected web.

With a more efficient IPN of the future, BP would serve as the best option in deep space exploration in where communication is lost with some of the satellites like Pioneer10 (at 12.3billion km from Sun). The feasibility of this technology would enable everyone to directly access telemetric data from distant planets and satellites. And lastly if humanity ever decides to expand homes to extrasolar planets (such as Gliese 581g at about 20 light years away from the Earth) the IPN could become a standard communications protocol.

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