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A Survey of Transport Protocols for Deep Space Communication Networks

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ABSTRACT
NASA proposes to develop a common infrastructure for all its forthcoming space exploration missions. This infrastructure called the Interplanetary Internet (IPN) will take the Internet of the Earth to outside planets and facilitate in the efficient transfer of the huge amount of scientific data collected by the space probes back to Earth. The development of an efficient transport protocol for the Interplanetary Internet is a major challenge to the research community. In this paper, a survey has been done for all the major transport protocols developed for deep space communication. The paper discusses the infrastructure of the IPN along with the major challenges for deep space communication. Emphasis has been made on the issues of transport protocol design for LEO-GEO based satellite networks and deep space communication networks. The genesis of the work on Interplanetary Internet and the evolution of the concept of Delay Tolerant Networks have been explained. An attempt has been made to discuss all the major transport protocols and conventional approaches used for transport protocol design for deep space networks. The concepts related to IPN, DTN, Bundle Layer, Disruption Tolerant Networks, DTN Convergence Protocols, LTP, Saratoga, DS-TP, DTTP, ARC, TP-Planet, and CCSDS CFDP have been discussed.

General Terms
Protocol, TCP, Survey, Interplanetary Internet, RTT, BER, Deep Space Protocols

Keywords
DTN, LTP, Saratoga, DS-TP, DTTP, ARC, TP-Planet, CFDP

1. INTRODUCTION
The Deep Space remains a matter of mystery to the human mind from ages and the quest of exploring it has always fascinated scientist and technologist worldwide. With the increasing interest in deep space missions, there is a need for an infrastructure in the deep space, to cater to the communicational and navigational requirements of the explorer spacecrafts and orbiters [42]. There is also a need for the delivery of the high volume of scientific data gathered by the deep space probes to Earth. This has to be done in a way that maximizes the throughput and minimizes the power requirements. Considering these factors NASA proposes to develop the next generation deep space network called the Interplanetary Internet as shown in Fig.1 [51]. The Interplanetary Internet [44], [46] will take the terrestrial Internet to outside planets and provide a common infrastructure to all the forthcoming space exploration missions. This will try to reduce the cost enabling better management of the space missions by providing a generic solution than configuring for mission specific requirements. Fig.1 shows an envisaged future configuration of the Interplanetary Internet providing a communication infrastructure connecting all the major entities of space exploration as proposed by V.Cerf et al in [51].

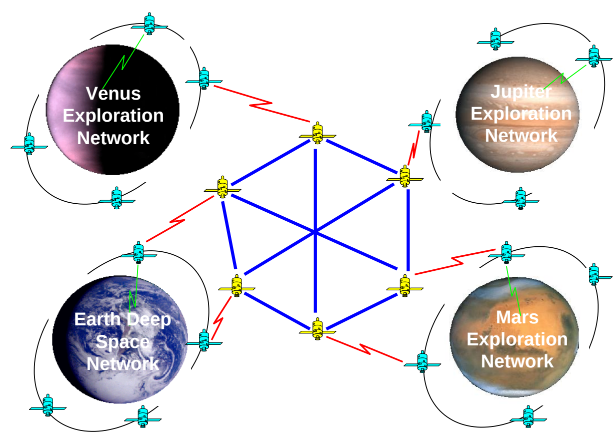

Fig. 1 Future Architecture of Interplanetary Internet

The IPN is a network of regional networks. There are three main architectural components of the IPN namely the Planetary Surface Network, Planetary Satellite Network, and Backbone Network as shown in Fig.2 [42] and proposed by O.B.Akan, et al in [42].

First is the Planetary Surface Network, which consists mainly of two types of entities. The entities belonging to the first category can directly communicate to a satellite and the others with low transmission capability can communicate only among them. Generally, sensors are distributed throughout the surface of the planets to collect scientific information and communicate to each other using ad-hoc networking protocols. Other entities are the landers and the rovers, which collect the data from the sensor nodes and communicate directly to the LEO satellites forming part of the Planetary Satellite Network [42].

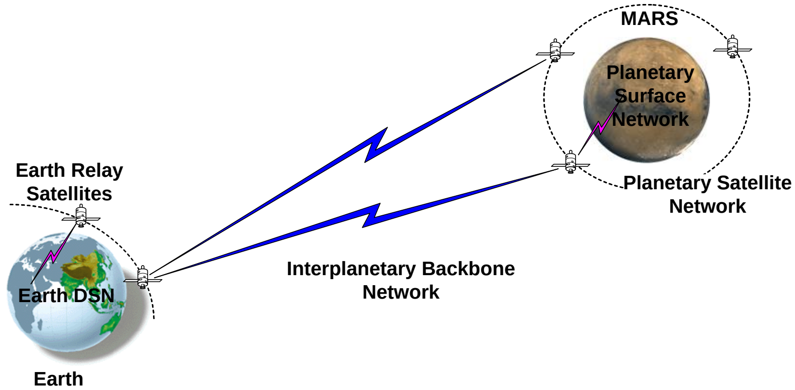

Fig. 2 Deep Space Network Architecture for Mars Exploration Missions

The second entity of the architecture of IPN is the Planetary Satellite Network, which is an access network and is primarily used to provide access to the planetary surface network as shown in Fig. 2. It consists of a constellation of satellites providing the relay and navigational services to the planetary surface network elements. The satellites in the constellation can be organized in a hierarchical way like a combination of LEO and MEO/GEO satellites [34], [45]. This is because the power transmission capability of the elements in the planetary surface network is considered low. The satellites provide the necessary storage requirements to cache the data received and transmit it at the best opportunity.

The third and the most important is the Backbone Network, which consists of satellites that provide the necessary infrastructure for communication of data from one planet to the other. The satellites used can be GEO satellites or satellites placed in gravitationally stable Lagrange points of other planets to provide the necessary relay function [52]. It includes elements of the Earth based Deep Space Network, which can communicate directly over a long haul link to satellites. It also includes the entire single and multiple hops inter satellite links necessary to carry data to the outer planets [44], [46].

However, there are significant challenges posed by the deep space networking paradigm that need to he addressed for this objective as discussed in [42], [45], [47], [51].

The most challenging issue arises from the long distance by which planets are separated which creates very long signal propagation time. This very long round trip time poses major challenges in the designing of suitable protocols for data communication. The RTT experienced in IPN ranges from minutes (Earth to Mars) to even hours considering (Earth-Jupiter) networks. The second important point is the high channel error rates associated with high asymmetry in forward and return link bandwidth. The third most challenging issue is that of intermittent link connectivity because of a lack of fixed infrastructure.

Several researchers and many international research organizations are currently engaged in addressing these issues and developing the required technologies for realization of the challenges posed by IPN Internet [26], [34], [36], [41], [43].

2.0 TRANSPORT PROTOCOLS FOR SATELLITE BASED NETWORKS

TCP has been highly successful in the existing terrestrial internet but when it comes to satellite based networks or in general networks involving long delays and high bandwidth the performance in found to degrade drastically. There is an ongoing research in the area of development of suitable transport protocol, which can circumvent and address all the issues arising in satellite-based networks. In Section 2.1, a short glimpse is provided about the issues for satellite based transport protocols. Section 2.2 provides an overview of transport protocol issues for deep space communication.

2.1 Transport Protocol Issues for Leo-Geo Networks

Several schemes aimed at mitigating the impairments introduced by satellite channel for performance enhancement of satellite-based networks have been proposed and analyzed in [58], [59], [60]. RFC 1323 [62] indicates that the TCP performance does not depend only on the transfer rate but upon the product of the transfer rate and the round-trip delay called the bandwidth-delay product. This measures of the amount of unacknowledged data that TCP must handle in order to exploit the whole channel bandwidth. TCP performance problems arise when the bandwidth-delay product is large. Satellite links [61] which are characterized by high propagation delay makes the acknowledgement arrival slow and the transmission window needs a long time to grow. Another problem of TCP over satellite networks is its reaction to channel errors [40]. It is quite well known that transport protocols are not able to distinguish congestion events from link errors. Even when the cause of loss is not congestion the protocol reduces the transmission window size [56] at each loss independently of the cause, degrading the overall communication performance [3], [5], [9]. The problem of improving TCP over satellite has been widely investigated in the literature [53], [54], [55].

2.2 Transport Protocol Issues for Deep Space Communication Networks

To realize the IPN Internet and meet the communication requirements of deep space missions the challenges posed by the IPN Backbone links need to be addressed [42]. However, in deep space communication networks the existing reliable transport protocols have shown to achieve very poor performance [1]. The extremely high propagation delay in deep space links is the dominant factor in this performance degradation. Transport protocol solutions proposed for satellite links [49], [50], [57] cannot be directly applied to the IPN backbone network, because of the extremely high propagation delay, very high packet error rates, high asymmetry, and blackouts. CCSDS [33] developed the Space Communications Protocol Standards- Transport Protocol (SCPS-TP) [29] that is a set of TCP extensions. SCPS-TP mechanisms are a combination of existing TCP protocols with some modifications and extensions [42]. It addresses the issues of link errors, bandwidth asymmetry, and link outages, which are shown to be inadequate to address the challenges in the IPN backbone network [27]. The CCSDS File Delivery Protocol (CFDP) [25] is developed for reliable file transport over space links. The problems of intermittent connectivity, large and variable delays and high BER is addressed by the bundling approach [22] using a custody-based store-and-forward mechanism. Even though this approach achieves reliable transport over intermittent links, a specifically tailored transport protocol is required for high-performance bundle transport between two IPN Internet nodes. A reliable transport protocol named TP-Planet is proposed in [42] for the IPN backbone network. It uses some novel techniques based on probing the network with low priority dummy packets and rate based AIMD protocol to provide performance enhancements in deep space links. There exist other deep space protocols like Saratoga [8], DS-TP [21], and LTP [15], [16], [17], which are DTN convergence protocols developed for use in deep space missions.

3.0 DEEP SPACE TRANSPORT PROTOCOLS

In the following sections, a brief description of all the transport protocols developed so far, for deep space communication is presented. Emphasis has been given on the concept of Interplanetary Internet and Delay Tolerant Networking along with the relevant protocols, which can be used with DTN to provide a unified solution for the Interplanetary Internet.

3.1 Interplanetary Internet Concept

V.Cerf, et al in [51], first proposed and provided a detail description of the Interplanetary Internet, a communication system to provide Internet like services across planetary system with an objective to support deep space exploration. The basic architecture of the system, along with the points where the deep communication philosophy varies with the traditional ways of communication has been explained. The authors also described the issues, which protocol developers have to keep in mind when designing protocols for deep space communication. The suggestions provided at a macro level in designing deep space transport protocols provided the framework for development of deep space transport protocols. The first suggestion is do not rely upon on the assumption of an end-to-end connectivity while designing transport protocols for deep space communication. It is very probable to have a planet come in the way from the source to the destination. The second implication is to not assume ample bandwidth because of the scarcity of power in deep space scenario along with high bit error rates. One has to keep in mind of the drop in signal strength with the square of the distance and considering interplanetary distances signal attenuation is a major factor. Moreover, protocol developers have to consider the preciousness of deep space links so design protocols keeping the provision of security and confidentiality of the application data.

Considering the huge cost involved in deep space missions, protocols developed also need to be backward compatible as it may not be possible to update the whole network with the latest technology. Another important suggestion provided by V.Cerf, et al is that the transport protocols for deep space should not waste time waiting for Acknowledgements to come for the transmitted packets. It should transmit as much as possible and then wait patiently for the ACKs to return. In a way, it referred to reduce the chattiness of transport protocols as is used in the traditional Internet. A new paradigm of store and forward technique of communication by establishing an overlay network, on top of transport layers of the underlying networks have been proposed. It introduces the Bundle Protocol and discusses how it binds with the IPN Architectural issues and with the techniques used for communication between two nodes of the IPN. The methodologies used for IPN routing and how it differs from traditional routing has been discussed. It also mentions the security related problems that exists in IPN. V.Cerf et al in [51] provided a strong foundation to the concept of Interplanetary Internet and provided the design guidelines for the development of protocols for this type of networks.

3.2 Delay Tolerant Networking

A delay tolerant network in a network designed to operate effectively over extreme distances such as those encountered in space communications or on an interplanetary scale. In such an environment, long latency sometimes measured in hours or days is evitable. The concept of Delay Tolerant Networking the genesis of which has been the work on IPN has been presented in [48] by V.Cerf et al. The basic principles of Delay Tolerant Networks have been explained keeping the context of the Interplanetary Internet. This generalization addresses networks, whose operational characteristics make the conventional networking approaches not feasible or impractical. The DTN Architecture based on message switching has been described in [18]. The concept of DTN Nodes, Regions, and Gateways are discussed along with the issues of addressing the DTN Nodes. The Bundle Layer is proposed in the context of DTN and how the bundle layer terminates the local transport protocols and operates end to end have been explained. The issues related to bundle routing, and the way DTN Routing is different from traditional routing has been described. The way the bundle layer provides the reliability and the concepts of custody transfer has been proposed. It also points the issues, which should be addressed in a DTN environment like the time synchronization. The concepts of DTN convergence layer, which will be used by underlying protocols, have also been proposed in [48]. The practical experience obtained using DTN is space is elaborated in [2], [6] and [19]. Various DTN routing techniques are explained in [4], [39] with routing issues for mobile DTN networks is explained in [7].

3.3 Bundle Protocol

The objectives envisaged to be addressed by Delay Tolerant Networks is achieved by the use of a new layer called the Bundle Layer [22]. This is the layer, which makes DTN Protocol stacks different from conventional TCP/IP protocol stack. The main objective of the Bundle protocol is to address the issue of non-availability of end-to-end path from the source to the destination typically seen in Deep Space Communication. It is an innovative way to handle issues associated with intermittent link connectivity. By dividing the large end-to-end path into shorter hop-by-hop transfer the effect of high bit error rate on packet loss is also handled [48]. At the application layer of the Internet architecture, Bundle Protocol [22] forms a store and forward overlay to provide message oriented transmission and retransmission [18]. It ensures reliability of messages by using the technique of custody based transfer where intermediate nodes accept the custody of bundles received and the ultimate destination confirms the message reception to the source using a return receipt. The Bundle Protocol handles intermittent connectivity, and has the ability to take advantage of scheduled, predicted, and opportunistic connectivity, which are very crucial considering the temporary nature of link connectivity characterizing this type of networks [6]. In fact, the DTN [7] acts as a framework within which different transport protocols suitable for the link coexist, and are glued to the overall operation of the network by the Bundle Layer [7]. The Bundle protocol requires the use of convergence layer protocol (CLP) for its proper operation below it and provide the necessary convergence with Internet Protocols used to send and receive bundles [12], [23] among DTN nodes.

One of the significant characteristic of the Bundle Protocol is the use of secondary storage for bundles compared to the use of primary storage in conventional TCP/IP. In Internet, using TCP the congestion control issue arises from the unavailability of router buffers or primary memory constraints. Using the Bundle Protocols, the congestion control issue for a DTN network ultimately comes to the availability issue of huge amount of secondary storage space. This is more pronounced considering the large delay in interplanetary links and the period of link intermittency spanning from hours to days, which necessitates a huge amount of bundles to be stored. Therefore, using the Bundle Protocol the proper operation of the network calls for the use of appropriate buffer management techniques to be implemented [2], [31], [35]. RFC 5050 [22] gives a detailed specification of the bundle protocol and [14] gives its operation experience from space. A set of issues and limitations of the Bundle Protocol have also been pointed out in [11].

3.4 Disruption Tolerant Networking

In RFC 4838 [28] a description of the architecture of delay and disruption tolerant networking, an evolution of the architecture originally designed for the Interplanetary Internet has been provided. In this RFC [28], the definition of delay tolerant networks which was more oriented towards addressing delay typically seen in the planetary communication networks have been generalized. Moreover, its applicability has been increased to address a wider domain of situations where it can be applied [13]. The concept of disruption tolerant networking has been proposed and it has been suggested for sensor-based networks having scheduled intermittent connectivity [37]. Terrestrial wireless networks that cannot maintain end-to-end connectivity can also use the concepts of disruption tolerant networking [32]. Satellite based networks with periodic connectivity [20] and underwater acoustic networks [30] with moderate delays and frequent interruptions due to environmental factors can use the disruption tolerant networking architecture. It discusses many new issues related to DTN like fragmentation and reassembly, flow control and congestion control issues for DTN and handling priority classes. Mobility modeling and routing issues for disruption tolerant networking is an exciting new research area elaborated in [24].

3.5 Delay Tolerant Convergence Layers

The Delay Tolerant Networking TCP Convergence Layer Protocol is described in [12], which is a TCP based convergence layer for DTN. The architecture of the TCP Convergence Layer (TCPCL) protocol, in terms of its position in the protocol stack, between the Bundle layer and the TCP lower layer has been described. The concepts of TCPCL connections, which comprises of a TCP connection have been explained. A TCPCL connection starts when a bundle node initiates a TCP connection for the purposes of bundle communication and terminates when the TCP connection ends due to the nodes terminating the connection, or due to network errors causing failure of the TCP connection.

3.6 Licklider Transmission Protocol

RFC 5325 [16] explains the motivation for the development of the Licklider Transmission Protocol (LTP) designed to provide retransmission-based reliability over links, characterized by extremely long round-trip times and/or frequent interruptions in connectivity. LTP [15] is primarily developed to support long haul reliable transmission in the interplanetary space but has utility in other environments also. LTP acts as a convergence layer for the Bundle Protocol, acting over the single-hop deep space communication links.

The core design ideas of LTP have been inherited from CFDP [25]. LTP can be run over both TCP and UDP in an Internet. Using the selective repeat ARQ mechanism it performs retransmission based recovery of lost data. Thus, both TCP-like and UDP-like functionality can be provided by LTP concurrently in a single session. LTP data flows are unidirectional and do not perform any handshakes, flow or congestion control as compared to TCP. LTP can transfer unnamed blocks of data and introduces the concept of partial reliability. It divides each block of data into two parts, the reliable red part, and the unreliable green part.

Delivery of the unreliable green part need not be acknowledged while the red part generally carrying important information needs to be acknowledged by the receiver. This is a novel innovative idea proposed in LTP by which prioritization of data services are possible. Considering the high price paid by retransmissions LTP allows the flexibility of only very important information to be used as the red part. Therefore, laconic acknowledgments are sent only upon encountering explicit solicitations for reception reports called checkpoints, in the sequence of incoming data segments of the red part of the block. Deferred transmission is possible as well, in case the communication link is not available. This drastically improves the performance of the protocol in deep space links.

RFC 5326 [15] gives a detailed description of the LTP protocol with all the details about the segment headers and the internal procedures. RFC 5327 [17] describes the way security is handled in LTP using a set of security extensions.

3.7 Saratoga

Saratoga is described in [8], which was originally developed to transfer remote-sensing imagery from a low-Earth-orbiting satellite constellation [23], but is useful for many other scenarios including ad-hoc peer-to-peer communications, delay-tolerant networking, and grid computing. Saratoga is a simple, lightweight, content dissemination protocol that uses UDP [63]. It is intended for communication between peers that may have only sporadic or intermittent connectivity. It is capable of transferring very large amounts of data reliably under adverse conditions. Saratoga can support fully unidirectional data transfer if required, and is specially designed to cope with highly asymmetric link or path capacity between peers. In scenarios with dedicated links, Saratoga focuses on high link utilization. In order to make the most of limited connectivity times, it leaves the use of standard congestion control mechanisms, for operation over shared links. Loss recovery is implemented via a simple negative-ack ARQ mechanism. Saratoga [8] uses an algorithm where the transmission of packets happen in rounds with lost packets being retransmitted after the end of each round called a hole filling mechanism.

The problem with this approach is the increasing number of rounds, needed to complete the delivery. Moreover, as the RTT is very large, the application at the receiver gets the data after a long time, especially when the error rate is very high, which leads to more retransmissions and an increased number of rounds.

3.8 Deep Space TCP (DS-TP)

In [21] Deep-Space Transport Protocol (DS-TP), a new reliable protocol for deep-space communication links is proposed. Many of the techniques used in the earlier deep space protocols are used by DS-TP and it concentrates mainly on the Double Automatic Retransmission strategy. The main advantage of DS-TP is its ability to complete file transfers faster than conventional TCP, SCPS-TP [29], and Saratoga [8] thereby becoming more important for missions with small connectivity time. Deep space communication links are characterized by long propagation delays, high BER, intermittent connectivity, and bandwidth asymmetries. DS-TP has inherited some of the approaches like rate-based transmission and the SNACK and focus on the optimization of the rest. Specially, it modifies and attempts to provide enhancement to the retransmission strategy of the transport protocol to deal with high BER or blackouts. Precisely, DS-TP includes the Double Automatic Retransmission (DAR) technique, which sends each packet twice importing some intentional delay between the original transmission and the retransmission. Using this strategy in the presence of errors or blackouts, the lost packets will eventually be replaced by the original packets that arrive after a fixed delay. The problem with DS-TP is that, since the redundancy is added to the entire transmitted packets it is not efficient in terms of bandwidth utilization.

3.9 DTTP

In [10], Delay-Tolerant Transport Protocol for Space Internet works (DTTP) is proposed, which uses many of the features as prescribed for DTN and close to DS-TP design philosophy. DTTP introduces a new concept like parallel data transfer in which, the transmitted data is divided into separate blocks and transmitted through different paths. It also proposes a new concept of application oriented transmission behavior. In this technique, redundancy is added to those packets that are time sensitive and thereby the reliability of data transfer is enhanced at the cost of bandwidth. For those applications, which are not time sensitive the hole filling type of algorithm as used in Saratoga [8] is adopted.

3.10 ARC (Adaptive Rate Control) Protocol

In [38] a congestion control algorithm for the deep space Internet in proposed. The Adaptive Rate Control (ARC) algorithm consists mainly of two phases: a probing phase and a shrinking phase. In the probing phase, the congestion window is increased and shrinking phase reduces the sending rate when a congestion episode happens indicating the network capacity has been hit. The probing phase it further divided into a gentle probing phase where the congestion window is increased by one every 100ms, and in the quick probing phase the window doubles every 100ms. The shrinking phase reduces the congestion window using an equation, combining the bandwidth and the RTT.

3.11 TP-Planet

TP-Planet as proposed in [42] provides a reliable transport protocol to be used for the Interplanetary Backbone links. It has come up with a couple of new concepts specially for handling the large RTT initiated degradation of throughput. The main proposition, on which TP-Planet was developed, is based on an assumption of a priority based routing capability to be supported by the network. The entire protocol is based on the capability of the intermediate routers to discard low priority packets during a congestion event. The protocol uses a probing based approach to determine the available capacity in the network. The long RTT is divided into much shorter intervals to reduce the effect of RTT on the performance using a novel emulated slow start method. TP-Planet consists of two novel algorithms namely Initial state and Steady state. The inefficient slow start process of conventional TCP is replaced by the Initial-State algorithm, which captures available link resources in a fast and controlled manner. The Steady-State algorithm attempts to decouple congestion decisions from single-packet losses in order to avoid erroneous congestion decisions due to a high BER on the channel. Rate adjustment decision is taken considering a ratio of the received high priority and low priority packets. This is also used to differentiate losses due to congestion and channel error. A blackout state procedure is used by TP-Planet to reduce the effects of a blackout situation. Channel asymmetry is solved by the introduction of delayed SACK.

Though TP-Planet has proposed some novel approaches for communication under very high delay links it has certain drawbacks. One of the major problems with TP-Planet is that it needs a special capability of low priority packet discard capability in the routers used in the intermediate link. Moreover, it depends on the ACK of the high and low priority packets to determine the transmission rate. So it gets dependent on the high RTT of the connection. Another very important point, which TP-Planet does not consider is that the information it uses for setting its transmission rate is old by the RTT of the connection.

3.12 CCSDS CFDP

CCSDS recommended the CFDP [25], an application layer protocol for automatic, reliable file transfer between a source and a destination which has been used for near earth orbit communication to deep space links. The specialty of CFDP is that is tries to provide transport layer functionality in the application layer. CFDP has the provision to work with both reliable and unreliable services. It can work well with UDP or TCP based transport layer and even can be used directly over data link protocols.

In the extended file delivery mode of CFDP operation, DTN like functionality may be achieved using a similar store and forward approach. The CFDP provides optional file transfer service that operates in either unreliable-service or reliable-service mode. When used as an unreliable service, the CFDP protocol at the application layer is not responsible for reliable data delivery. Instead, the transmission reliability is provided by the underlying transport layer protocol, which is TCP in most cases.

When used in reliable mode UDP like unreliable service is used in the transport layer in order to get a fast data transfer and get away with the RTT initiated degradation of throughput. The data reliability of transmitted data is handled totally in the application layer. One of the significant novel approaches of CFDP is the use of different types of selectable negative acknowledgment types. Theses ACK types provide the necessary flexibility of operation considering the high RTT in deep space scenario. Four types of selectable negative acknowledgment (NAK) modes are supported namely the deferred NAK mode, immediate NAK mode, prompted NAK mode, and asynchronous NAK mode [27].

4. CONCLUSION

Development of transport protocol for deep space communication is a highly challenging task. The research challenges and issues related to this field have been brought out in this paper. The new field of Delay Tolerant Networks and its wide applicability even outside the area of deep space communication has been explained. An attempt has been made to crystallize the relevant ongoing research among the international community in the filed of Interplanetary Internet and Delay Tolerant Networks. Authors have tried to bring out the problems related to the design of transport protocols for deep space networks and IPN. It has been shown how the different transport protocols discussed have handled these issues. The concepts related to IPN, DTN, Bundle Layer, Disruption Tolerant Networks, DTN Convergence Protocols, LTP, Saratoga, DS-TP, DTTP, ARC, TP-Planet, and CCSDS CFDP have been discussed. All these protocols have handled the issues of deep space communication with each bringing a new concept, which helps, in the evolution of the technology. However, it has been seen that even with the presence of many approaches for deep space transport protocols, the research area remains open and none of the existing protocols handle all the issues relevant in IPN. This paper may help researches to start work in the field of transport protocol design for deep space communication and delay tolerant networks along with providing them with a comprehensive list of the existing literature available in this area.

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