# Protocols for Reliable Data Transport in Space Internet

Ruhai Wang, Tarik Taleb, Abbas Jamalipour, Bo Sun

***Abstract*—A variety of protocols have been proposed for reliable data transport in space Internet and similar network environments. It is necessary to conduct a survey on these protocols to investigate and compare among them. In this article, we present a survey on the protocols proposed for reliable data transport in space Internet, with a focus on the latest developments. The survey includes the following contents: (1) Classification of these protocols into different approaches; (2) Discussions and comments on the design and operation methods of the protocols; and (3) Comparisons and comments on the main techniques and performance of the protocols.**

***Index Terms*—Space Internet, interplanetary Internet, transport protocols, TCP extensions, DTN.**

## I. INTRODUCTION

CONSIDERING the significant success of the terrestrial Internet, the National Aeronautics and Space Administration (NASA) and the military have been working to enable space communications using Internet-type protocols which could be defined as space Internetworking or simply space Internet. Space Internet covers a wide space environment ranging from High-Altitude Platforms (HAP) or Unmanned Airborne Vehicles (UAV) in low-Earth orbit (LEO) through geo-stationary Earth orbit (GEO) to deep space. The Internet in deep-space environments is generally defined as the interplanetary (IPN) Internet [1]. For a literature review of the Internet architectures at the IPN level and the Earth-orbit level, interested readers are referred to [1], [2].

The performance of TCP over satellite communication channels is limited by the unique and challenging characteristics of the very different space environments [1], [3], [4], [5]. A variety of data transport protocols, including congestion control mechanisms, have been proposed for the realization of the Internet in the space and similar operation environments. Surveys on data transport protocols in space Internet are seen in [1], [2], [4]. In [1], Akyildiz *et al.* present a survey of the architectures, algorithms and protocols developed for deep-space networks and IPN Internet. But this survey provides an overview of the interplanetary technologies for each layer, and not the transport protocols for the space Internet in all space environments. In [2], the satellite-based Internet is introduced with discussion on multiple access control, satellite routing and transport issues provided. In [4], various TCP enhancements addressing the performance challenges of TCP/IP in satellite networks are presented. In [5], Jamalipour *et al.* provide a solid review of the future satellite networks and their interoperability with terrestrial wireless and wired networks, and address the impairments of the satellite link and their effects on TCP performance. A large number of new protocols have been proposed at the transport as well as other layers for reliable data transport in space Internet in recent years. It is necessary to conduct a survey to compare and investigate these protocols, especially for these latest developments.

This article summarizes a variety of protocols for reliable data transport in space Internet, and surveys these protocols and mechanisms, focusing on the advanced developments in recent years. The aim of this article is to keep the community updated on the research progress of data transport technologies of the space Internet in an integrated form. The article is organized as follows. The next section reviews the challenges of TCP in satellite communication environments and classifies the various protocols for reliable data transport available for space Internet. Then, a thorough survey of these protocols is presented by discussing their design and operation methods, comparing and commenting on their main techniques and performance. Finally, the article is concluded with a summary.

## II. OVERVIEW OF TCP, OPERATION ENVIRONMENT AND DATA TRANSPORT PROTOCOLS FOR SPACE INTERNET

It is well known that the ubiquitous and long-standing TCP faces many challenges in space communications because its original design philosophy is not very effective in the extreme space communication environments [1], [5]. Several issues of the Internet design are inappropriately addressed by TCP, limiting its performance. One major issue is that TCP is designed to use the window-based transmission control algorithms. With the sliding window flow-control mechanisms, TCP regulates the amount of data a source can send by adjusting the window size relying on the acknowledgement information from the destination. As another major issue, TCP cannot distinguish the data losses caused by network congestion and link errors. The performance impact on TCP by these issues is not very obvious in the terrestrial Internet. However, the problems caused by these issues become obvious and even serious due to the challenging characteristics of space communications. Highly long link delays, noisy channels, asymmetric channel rates, and intermittent contact conspire to adversely degrade the performance of TCP.

Space communications, especially those in deep space, generally operate with round-trip delays much longer than

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| **Acronym** | **Definition** |
|---|---|
| 16APSK | 16-Ary Amplitude and Phase Shift Keying |
| 32APSK | 32-Ary Amplitude and Phase Shift Keying |
| 8PSK | Eight-Phase Shift Keying |
| ACK | Acknowledgment |
| ACM | Adaptive Coding and Modulation |
| AIMD | Additive-Increase, Multiplicative-Decrease |
| ARQ | Automatic Repeat-reQuest |
| ATM | Asynchronous Transfer Mode |
| BCH | Bose-Chaudhuri-Hocquenghem |
| BDP | Bandwidth-Delay Product |
| BER | Bit Error Rate |
| BETS | Best Effort Transport Service |
| BP | Bundle Protocol |
| CCSDS | Consultative Committee for Space Data Systems |
| CFDP | CCSDS File Delivery Protocol |
| CLP | Convergence Layer Protocol |
| CWIN | Congestion Window |
| dB | Decibel |
| DTN | Delay-Tolerant Networking |
| DTNRG | DTN Research Group |
| DVB | Digital Video Broadcasting |
| DVB-RCS | Digital Video Broadcasting - Return Channel Via Satellite |
| DVB-S | Digital Video Broadcasting over Satellite |
| ECN | Explicit Congestion Notification |
| FEC | Forward Error Correction |
| GEO | Geo-stationary Earth Orbit |
| HAP | High-Altitude Platforms |
| IP | Internet Protocol |
| I-PEP | Interoperable PEP |
| IPN | Interplanetary Internet |
| IRTF | Internet Research Task Force |
| ISDN | Integrated Services Digital Network |
| LDPC | Low Density Parity Check |
| LEO | Low-Earth Orbit |
| LTL | Lower Transport Layer |
| LTP | Licklider Transmission Protocol |
| NAK | Negative Acknowledgment |
| NASA | National Aeronautics and Space Administration |
| PEP | Performance Enhancing Proxy |
| PETRA | Performance Enhancing Transport Architecture |
| P-XCP | Proportional XCP |
| QPSK | Quaternary Phase-Shift Keying |
| REFWA | Recursive, Explicit and Fair Window Adjustment |
| RTT | Round-Trip Time |
| SACK | Selective Acknowledgment |
| SCPS | Space Communication Protocol Standards |
| SCPS-TP | Space Communication Protocol Standard-Transport Protocol |
| SCTP | Stream Control Transmission Protocol |
| SNACK | Selective Negative Acknowledgment |
| STP | Satellite Transport Protocol |
| TCP | Transmission Control Protocol |
| TCPW | TCP Westwood |
| TP-Planet | Transport Protocol-Planet |
| UAV | Unmanned Airborne Vehicles |
| UDP | User Datagram Protocol |
| UTL | Upper Transport Layer |
| XCP | Explicit Congestion Control |
| XFWA | eXplicit & Fair Window Adjustment |
| XSTP | Extended STP |

the terrestrial Internet. For example, the round-trip times (RTTs) can be up to 40 minutes long for the cis-Martian channel and even over 100 minutes for a channel from the Jupiter to the Earth. Substantially long end-to-end RTTs in space communications hurt TCP interactions between the space Internet node and the ground Internet node. This limits the usefulness of TCP acknowledgment feedback from the remote destination node and influences the effectiveness of TCP transmission control. In comparison with the terrestrial communications, space communications feature much noisier channels resulting in very high bit error rates (BER) with $10^{-5}$ very common and even on the order of $10^{-1}$ in deep space environment [1]. The data loss due to a high channel BER in the space environment has a disproportionately negative effect on TCP performance. This is because TCP makes an erroneous congestion decision which misinterprets any data loss as a congestion loss, as mentioned. Generally speaking, multiplicative-decrease in sending data rate is designed as a response to data loss caused by network congestion. Consequently, the throughput of TCP is decreased, for the data loss caused by bit error corruption instead of real network congestion. Space communications channels are frequently asymmetric in terms of channel bandwidth: the bandwidth of the forward channel (or uplink), from the ground to the spacecraft, is generally much lower than the bandwidth of the return channel (or downlink), from the spacecraft to the ground. The ratio of channel asymmetry can be as low as 1:1000 in Earth-orbit communications and even significantly lower in deep space environment. This channel asymmetry adversely affects the performance of TCP because it is ACK-clocked, relying on the timely feedback of ACKs through the forward channel, to make steady progress of data transmission. However, the forward channel is too slow to handle the effective transmission of returning ACKs, resulting in frequent loss of ACKs and consequential performance degradation of the protocol. These issues of TCP have been fully investigated in the literatures [1], [3], [4], [5], and thus are not discussed in detail here.

A variety of protocol solutions have been proposed at transport and other layers to address the mentioned problems that TCP faces in the space environment. Most of these solutions are designed as the transport layer protocols by modifying TCP and its operation infrastructure, while some of them are designed as application and link layer protocols but also including data transport functionalities. These protocols can be roughly classified by three categories.

One category involves changes only to the TCP protocol. The changes are generally on the congestion-control and error-control algorithms of TCP. These changes are often done for TCP at the end terminals only, i.e., the data source and/or destination; thus, the rest of the network is considered non-accessible. Furthermore, the changes are transparent to routers, and the end-to-end semantic of TCP remains unchanged. Typical solutions involving only TCP modifications and extensions are: Stream Control Transmission Protocol (SCTP) [6], Satellite transport protocol (STP) [7], extended STP (XSTP) [8], TCP Peach [9], TP-Planet [10], and TCP Westwood (TCPW) [11]. Among these solutions, STP and XSTP involve changes only to error-control algorithms, and SCTP changes both the error-control and congestion-control algorithms, while the rest of the protocols involve changes to only congestion-control algorithms.

The second category involves modifications to the TCP protocol and/or network operation infrastructure and elements. For heterogeneous networks containing one or more satellite links, users and servers can not all be expected to run satellite-optimized TCP protocols on an end-to-end user basis. In this case, it is reasonable to divide the end-to-end TCP connection into multiple transport connections and isolate the satellite link using a proxy agent (or an intermediate gateway) introduced between the terrestrial network and satellite network. Then a satellite-optimized protocol can be run over the space link. By doing this, the long-delayed and lossy satellite link is shielded from the user in a transparent manner. The TCP connection is generally divided either using TCP Spoofing or using TCP Splitting. These two methods have been well discussed in [5], [7], so they are not discussed in detail here. The approach of splitting connection has also been generalized as the so called performance enhancing proxy (PEP) [12], intended to mitigate all link-related performance degradation. The examples of transport protocols that involves modifications to the TCP protocol and/or network operation infrastructure are explicit congestion control (XCP) [13], proportional XCP (P-XCP) [14], recursive, explicit and fair window adjustment (REFWA) [15], REFWA Plus [16], the Consultative Committee for Space Data Systems (CCSDS) Space Communication Protocol Standard (SCPS)-Transport Protocol (SCPS-TP) [17], Interoperable PEP (I-PEP) [18], on-board satellite "split-TCP" proxy [19], and performance enhancing transport architecture (PETRA) [20].

The third category refers to a set of protocols that are designed to provide data transport functionality but operate at the application and link layers. Representative protocols in this category are the Delay-Tolerant Networking (DTN) [21] bundle protocol (BP) [22] and Licklider Transmission Protocol (LTP) [23] produced within the Internet Research Task Forces (IRTFs) DTN Research Group (DTNRG) [24]. BP and LTP sit at the application layer of the DTN architecture. In comparison to the conventional Internet architecture (i.e., TCP/IP architecture), DTN is an end-to-end architecture designed to provide communications in highly stressed space environments, especially over interplanetary space links, using the technique of store&forward message switching. The store&forward message switching is different from the immediate forwarding done by IP. With message switching, the whole message or fragments of such messages are moved from a storage place on one node to a storage place on another node. The store&forward approach for space communications generally means that a router keeps a copy of every data packet sent until at least the next node has sent an ACK confirming the packet has been received successfully or the expiration of the packets time-to-live which is designed to be much longer than the routers time-to-acknowledgment [21]. By this, it ensures that no data packets gets lost en route, even if a router is offline. This type of operation is quite different from the terrestrial Internet in which a router does not keep track of the packets it transmits or of where they will be going beyond the next hop. In addition to the DTN BP and LTP protocols, the CCSDS File Delivery Protocol (CFDP) [25], an application layer file protocol developed under the CCSDS standards process, also belongs to this category.

Table I summarizes the proposed protocol solutions and roughly classifies them into the three mentioned categories. It is important to note that the above classification of the protocols into three categories is based on their design motivations. The protocols in these three categories are proposed for different applications. Depending on the application, some protocols in one category could be used in the context of another category and vice versa.

## III. A SURVEY OF DATA TRANSPORT PROTOCOLS PROPOSED FOR SPACE INTERNET

In this section, a survey of the data transport protocols available for the space Internet is conducted.

### *A. Protocols Involving Only Changes to TCP*

SCTP — SCTP [6] is a reliable, message-oriented protocol originally designed for Internet applications that have recently been introduced. These new applications, such as IP telephony, telephone signaling, and ISDN over IP, generally need a more sophisticated service than TCP can provide. Besides adoption and modification of some features of TCP, SCTP has some innovative features that help SCTP achieve better performance than standard TCP in satellite communications. The unique features of SCTP include multi-streaming and multi-homing transmission services [6]. Generally speaking, each connection between a TCP client and a TCP server involves one single stream. The problem with one single stream is that a packet loss at any point in the stream blocks the delivery of the rest of data. In comparison, SCTP can have multi-stream service in each connection, which is called association in SCTP terminology. If one of the streams is blocked, the other streams can still deliver their data. The experiment showed that multi-streaming can significantly increase channel goodput over lossy satellite links, when the receivers buffer is limited [26]. With multi-homing service of SCTP, the sender and receiver can define multiple IP addresses in each end for an association. In this case, when one path fails, another interface can be used for data delivery without interruption. This approach can make data transmission highly reliable and fault tolerant. SCTP also uses other techniques to solve the problems of high BER, long delay and distinguishing losses due to link congestion and error corruption.

In comparison to other protocols, SCTP has some unique features and should be considered an absolutely new transport-layer protocol. The multi-homing capability is a good idea but it needs different network paths from one host to another in real use. The multi-streaming idea to reduce overhead is also a good idea, but it is applicable only if data going to a host can be logically separated into different data streams.

STP — STP [7] was developed as a satellite-specific transport layer protocol by modifying an existing ATM-based, reliable link layer protocol. In comparison, STP incorporates many of the features that have been proposed for TCP to improve its performance over stressed satellite links, including:

- Adoption of a selective negative acknowledgment (SNACK) option rather than the positive acknowledgment option of TCP;
- Not using retransmission timer;
- A different way to acknowledge data to overcome the problem of channel asymmetry: The STP sender periodically requests that the receiver acknowledges all data that have been successfully received, and packet losses detected by the receiver are explicitly negatively

Table I. Data Transport Protocols available for Space Internet in Three Different Categories.

| **Solutions Classifications** | **SCTP** | **STP** | **XSTP** | **TCP Peach** | **TP-Planet** | **TCPW** | **XCP** | **P-XCP** | **REFWA** | **REFWA Plus** | **SCPS-TP** | **I-PEP** | **ì Split-TCPî proxy** | **PETRA** | **BP** | **CFDP** | **LTP** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Solutions involving TCP protocol modifications** | ◊ | ◊ | ◊ | ◊ | ◊ | ◊ | | | | | | | | | | | |
| **Solutions involving modifications to TCP and/or network infrastructure** | | | | | | | ◊ | ◊ | ◊ | ◊ | ◊ | ◊ | ◊ | ◊ | | | |
| **DTN and Other Protocols** | | | | | | | | | | | | | | | ◊ | ◊ | ◊ |

acknowledged. A combination of periodic requests of acknowledgments and negative acknowledgments reduces the reliance on acknowledgment channel bandwidth when packet losses are rare. It is also helpful in speedy recovery when packet losses occur;

- Use of rate-based congestion control.

A major problem with STP is that it has no mechanism of differentiating between packet losses caused by network congestion and bit-error corruption.

XSTP — XSTP [8] can simply be considered as an extension to STP. It solves the problem of STP when the packet losses caused by link congestion and bit-error corruption can not be differentiated. The problem is solved by using an end-to-end probing mechanism similar to TCP-probing. The TCP-probing mechanism uses the persistence of the error condition as an indication to the kind of prevailing error in the network. XSTP reuses the acknowledgment polling cycle of STP as a probing mechanism as well as for early error detection, and it uses the SNACK option of STP as a way to detect premature activation. The probing mechanism of XSTP is a sender-only, configurable option which helps XSTP preserve the end-to-end semantics of STP.

TCP Peach — TCP Peach [9] addresses the challenges of large bandwidth-delay product (BDP) and high BER over satellite channels. It replaces slow start and fast recovery with sudden start and rapid recovery, in addition to direct adaptation of classical congestion avoidance and fast recovery of TCP. The new mechanisms, sudden start and rapid recovery, use low priority “dummy” packets to probe the availability of network resources. Sudden start addresses the problem of slow pace and long duration of the TCP slow start. Rapid recovery addresses the problem of TCPs misinterpretation of packet corruption as link congestion, whereas on a satellite link packet losses are more likely due to channel-error corruption. Successful acknowledgments of the received dummy packets are interpreted as an indication of bandwidth availability. Dummy packets are differentiated from regular data packets using attached control bits. Because of their low priority, dummy packets are generally the first to be discarded by routers in case of link congestion. The priority information of packets is required by the routers.

TCP Peach is considered an innovative way to address transmission control in TCP. But it needs the capability to support priority drops in the routers, which is presently unavailable. In addition, TCP Peach still allows fluctuation of congestion windows, leading to complicated implementations. Also, it could be potentially unfair if congestion causes many connections to send dummy packets at the same time.

TP-Planet — TP-Planet [10] is designed to address challenges and achieve high throughput performance on deep-space backbone links of the interplanetary network. It deploys a modified rate-based additive-increase, multiplicative-decrease (AIMD) congestion control to avoid throughput degradation. The main contributions of TP-Planet are two novel algorithms, i.e., initial state and steady state. The initial state algorithm replaces the inefficient slow start of TCP and captures available link resources in a fast and controlled manner. The steady state algorithm decouples congestion decisions from single-packet losses in order to avoid erroneous congestion decisions due to a high BER on the channel. To reduce the effects of a blackout situation, TP-Planet also incorporates a blackout state procedure. The SACK mechanism of TCP is modified to delay the acknowledgment in order to solve the problem of channel bandwidth asymmetry.

TCPW — TCPW [11] modifies the TCP congestion control algorithms to improve its performance, especially over lossy wireless links such as satellite links. It only needs a sender-side modification and does not require any inspection and/or interception of TCP packets at routers. The key idea of TCPW is to continuously measure the bandwidth used by the connection at the sender via monitoring the arrival rate of acknowledgements. The bandwidth is estimated by dividing the amount of data (confirmed by an ACK) by the acknowledgment interarrival time. This estimate is smoothed over time using a low-pass filter and then used to compute congestion window (CWIN) size and slow start threshold after a congestion event. In the case of link congestion, TCPW selects a new CWIN size by taking into account the network capacity at the time of congestion, instead of directly halving the CWIN size as TCP does.

TCPW is actually a refinement to TCP. Although evaluation results from the protocol developers show that TCPW outperforms TCP in cases of very high packet error probability, it is probably not an effective transport protocol in space Internet. This is because it does not solve the long propagation delay problem that is the major feature in space Internet.

### *B. Protocols Involving Changes to TCP and/or Network Infrastructure*

XCP — XCP [13] was originally developed to handle the congestion in a communication environment with a large BDP similar to space, but not necessarily for satellite networks. XCP contains protocol designs for both endpoint hosts and routers. Its main contribution is the use of explicit congestion control feedback instead of having the sender probe for network bandwidth resource availability. It controls the dynamics of the aggregate traffic independently from the relative throughput of the individual flows in the aggregate. Congestion is controlled using an analytically tractable approach that matches the aggregate traffic rate to the link capacity, while traffic queue-forming is prevented. The decoupling of congestion control from bandwidth allocation allows XCP to reallocate bandwidth between individual flows without worrying about dropping packet aggressively or utilizing available bandwidth too slowly.

XCP should not be identified as a variant of TCP. The primary difference between XCP and TCP concerns their congestion control techniques. Different from the protocols that use a variety of solutions proposed over time, XCP is developed to use its own congestion control mechanisms, based on explicit congestion notification (ECN) and control theory. XCP considers network congestion a problem at both the network and transport layers and performs congestion control in a way that matches the true transmission control rate for effectiveness. XCP addresses the large BDP problem on satellite channels; however, a high BER and channel asymmetry still deteriorate the performance of XCP.

P-XCP — P-XCP [14] is proposed to overcome the left problems of XCP. To solve the high BER problem of XCP, P-XCP maintains the data sending rate when a packet loss is detected. With this modification, an XCP sender depends only on the congestion header to adjust its sending rate. To solve the problem of link underutilization, XCP adjusts the aggregate feedback based on the ratio of the number of rate-limited connections to the total number of connections sharing the link. Similar to XSTP, which is considered a variant of STP, P-XCP is also considered a variant of XCP in this survey.

REFWA — REFWA [15] is proposed to improve TCP efficiency and fairness over multi-hop satellite networks. It was designed by taking advantage of multi-hop satellite constellations to make approximate flow estimates of the RTT and BDP of the link. To control link utilization, REFWA matches the sum of window sizes of all active TCP connections sharing a bottleneck link to the effective network capacity. To obtain optimal efficiency and fairness, REFWA provides all the active connections with feedback proportional to RTT values. The feedback is signaled to the TCP sender through the receivers advertised window field in the header of the TCP acknowledgment packet. This is done without changing the protocol, and thus requires no modification to the TCP implementation at the endpoints. The REFWA scheme is an extension to the initially design XFWA scheme [27]. The major difference between the two schemes consist in the recursive feature of the REFWA scheme that enables it to work properly in more complicated environments where connections traverse multiple bottlenecks and the available bandwidth may vary over the data transmission time. To cope with link errors in wireless environments such as satellite networks, the REFWA scheme is further extended and a new error recovery mechanism is added to its original design [16], [28]. The enhanced version of REFWA is dubbed REFWA Plus. The fundamental challenge in loss recovery consists in distinguishing between congestion induced packet drops from those due to link errors. In the added error recovery mechanism, this distinction is based on comparison of the new and old values of the explicit congestion feedback signaled by the REFWA scheme to TCP senders. Effectively, a packet drop due to network congestion is likely to be preceded by a decrease in the computed feedback, whereas packet drops that are followed by an increased feedback are likely to be due to link errors [28].

SCPS-TP — SCPS-TP [17] is a standardized protocol used to overcome various space channel problems and to provide reliable data transfer in space environments, with a focus on earth-orbit space. SCPS-TP has implemented three capabilities to address the problem of data loss due to bit errors: explicit corruption response, the SNACK option, and a loss-tolerant end-to-end header compression mechanism. SCPS-TP addresses the problem of long RTT by expanding the range of commonly used TCP timers to allow RTT delays of minutes to hours, besides the deployment of the Window Scaling option. It relieves the limitation of satellite channel asymmetry mainly by using the techniques of channel rate-control and acknowledgment frequency reduction. To solve the problem of erroneous congestion decisions, SCPS-TP implements two congestion control mechanisms, SCPS-VJ and SCPS-Vegas, based on the well known TCP-VJ and TCP-Vegas, respectively. SCPS-Vegas has an application option for the user to configure the source of packet loss as either bit-error corruption or link congestion. As a recently developed feature, SCPS-TP is also able to split a TCP connection into different connections, using the technique of SCPS-TP gateway, thus including it in this approach. For a literature review of the SCPS-TP enhancements and gateway, interested readers are referred to [17].

As a set of TCP extensions in space, SCPS-TP is based on existing TCP implementations, with some modifications and extensions to address TCP performance problems. In other words, the capabilities of SCPS-TP are actually a combination of existing TCP algorithms. Some of these algorithms are known to perform poorly in space communications, especially in deep-space environments. As a simple example, SCPS-TP deploys TCP-Vegas to make congestion decisions based on

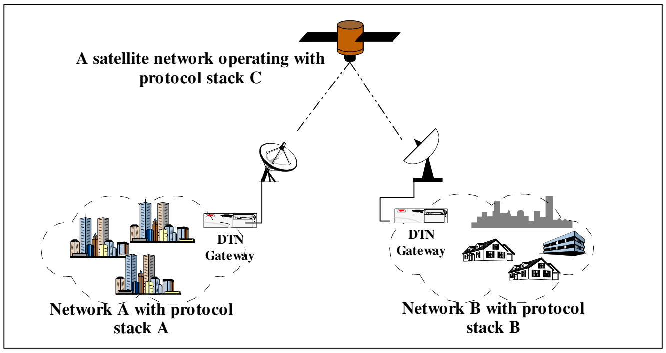

Fig. 1. A satellite networking interconnecting between incompatible networks. DTN gateways perform the interoperability procedure.

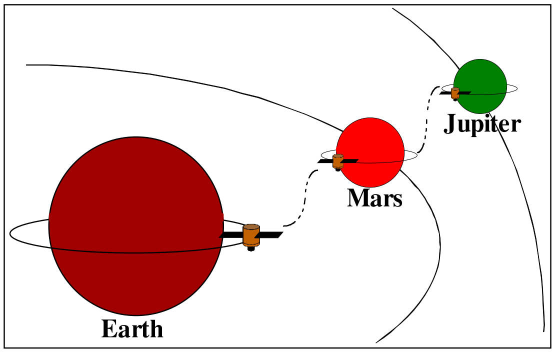

Fig. 2. An outer space network with instantaneous disruption in the interplanetary communication links.

an estimation of RTT. However, an accurate RTT estimation may not be possible over satellite channels because a long and highly varying latency, as well as intermittent connectivity, are generally involved.

I-PEP — Built on top of TCP, recent TCP extensions, and SCPS-TP, the I-PEP protocol [18] is proposed for satellite communication via DVB-RCS by allowing the use of different interoperable PEP products in the client side and server side. Designed as an optimized, open standards over SCPS-TP, the I-PEP removes and modifies those options of the available SCPS-TP capabilities that are not meaningful for reliable communications via DVB-RCS, e.g, elimination of UDP datagram option and the best effort transport service (BETS), adaption of some congestion control mechanisms, and changes of several parameters and options. Functions that are deemed useful for satellite communications but not included in SCPS-TP are also included. The I-PEP protocol is divided into a mandatory transport protocol and an optional session protocol [18]. The transport protocol is derived from TCP, and optimized based on SCPS-TP to provide reliable, flow-controlled and congestion-controlled transmission service. In comparison, the session protocol, as a minimal control protocol, offers several supportive functions to provide session related service between I-PEP clients and I-PEP servers, e.g., informing I-PEP clients about the availability and capabilities of I-PEP servers and negotiating session parameters.

On-board satellite "split-TCP" proxy — The solution of an on-board satellite "split-TCP" proxy [19] is based on the classical split-TCP concept, but the splitting occurs on board of satellites. A proxy agent on the satellite maintains two separate connections for each endpoint of the TCP sessions. Similar to classical splitting, on-board splitting makes use of gateways on the ground. But each gateway operates separate TCP connections with the satellite instead of with each other, and the satellite forwards data between connections. In other words, the satellite itself acts as another application-level gateway between two TCP endpoints [19].

PETRA — PETRA [20] divides the end-to-end connection into different segments using the split-TCP policy, where a different transport protocol can be deployed in each network segment. As a result, satellite-optimized protocols can be used over satellite links while classical TCP should be applied over terrestrial links. The objective of PETRA is to optimize both the throughput performance and the efficient utilization of network resources in space environments. PETRA preserves the end-to-end connection reliability and semantics by dividing the transport layer into two sublayers:

- Lower Transport Layer (LTL): Responsible for data transport and error recovery with each communication segment;
- Upper Transport Layer (UTL): Responsible for maintaining the end-to-end reliability and semantics.

### *C. Delay Tolerant Networking (DTN) and other Protocols*

Before delving into details about protocols tailored for DTN networks, there is first a brief description of how satellites can be part of DTN networks. Figures 1 and 2 depict two different scenarios. In Figure 1, a satellite network interconnects between incompatible networks, each using a different protocol stack. The satellite network, itself, uses a different protocol stack, and provides only periodic connectivity due to the motion of its satellites. The communication between the networks passes through the DTN gateways located at the edge of each network. The DTN gateways are responsible for accommodating data and interoperating among the different network protocol stacks and the addressing families. In Figure 2, an outer space network is shown. In this network, instantaneous disruptions in the inter-planetary communication links occur due to the different motion patterns of planets. In such scenario, satellites act as DTN gateways; store data and forward it whenever the communication link becomes available. Different protocols have been proposed for DTN networks.

BP — BP [22] was designed to overcome performance problems associated mainly with large and/or variable delays, intermittent link connectivity and high BERs for the exchange of messages (bundles) in the DTN networks [21]. BP, at the application layer of the Internet architecture, forms a store&forward overlay to provide custody-based, message-oriented transmission and retransmission. The major capabilities of BP include the ability to cope with intermittent connectivity and the ability to take advantage of scheduled, predicted, and opportunistic connectivity. Its capabilities also include hop-by-hop reliable message delivery and optional end-to-end acknowledgment. With store&forward service, BP incorporates automatic retransmission requests and congestion control mechanisms to perform congestion control and provide reliable transmission via local retransmission on a regional basis. The operation of BP requires the services of a convergence layer protocol (CLP) below it to send and receive bundles using the underlying internet protocols. Main CLPs that are currently available are TCP-based, UDP-based, or LTP [23]-based.

The overlay network formed by BP employs persistent storage for its store&forward function as well as to help combat link interruption. Thus, it requires a large buffer at intermediate routers to store data packets, especially in the case of extremely long interplanetary links. This results in a need of an efficient buffer management mechanism to prevent data transmission from being affected by the store&forward operation [21], [22]. A BP reference implementation called DTN-2 is recently available and is currently under evaluation.

CFDP — CFDP [25] was built for automatic, reliable file transfer between a source and a destination, from LEO to complex arrangements of interplanetary space links. Similar to DTN BP, CFDP is considered monolithic, including both reliable transport and application functionality in a single protocol. It can be configured to run over reliable TCP, unreliable UDP, or directly over data link protocols. When configured in the extended file delivery mode, CFDP can operate as a DTN protocol [25] following a store&forward approach. The CFDP provides optional file-transfer service that operates in either unreliable-service or reliable-service mode. With 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. With reliable-service, CFDP takes responsibility of complete and reliable data delivery at the application layer. In this case, a connectionless, unreliable transport protocol such as UDP is recommended at the transport layer. UDP resembles the send&forget characteristics, where a UDP sender bears no responsibility for the transmitted packets. The intrinsic features of UDP make of UDP a better alternative where the fast and timely delivery of data is preferred over reliable and complete data transmission. The reliable file transfer of CFDP offers four selectable negative acknowledgment (NAK) modes: deferred NAK mode, immediate NAK mode, prompted NAK mode, and asynchronous NAK mode [25]. The store&forward operating approach and selectable NAK acknowledgment modes should be helpful for CFDPs performance in stressed space environments.

LTP — As a convergence layer protocol in DTN architecture, the LTP scheme [23] was designed to operate over point-to-point, long-haul, deep-space radio frequency links or similar links characterized by an extremely long transmission delay and/or frequent interruptions in connectivity. It is principally intended to serve as a reliable convergence layer protocol, underlying BP designed for interplanetary space. LTP inherits core design ideas from CFDP. It can be run over both TCP and UDP in an internet. It performs retransmission-based recovery of lost data with the selective repeat ARQ mechanism. LTP recognizes each block of data as having two parts: a "red-part", whose delivery must be assured by acknowledgment and retransmission, followed by a "green-part", whose delivery is attempted, but not assured. The length of either part may be zero; that is, any given block may be designated entirely red or entirely green. Thus, LTP can provide both TCP-like and UDP-like functionality concurrently in a single session. In comparison to TCP, LTP flows data uni-directionally, and does not perform any handshakes, flow or congestion control. Similar to CFDP, LTP also implements immediate and deferred retransmission. The LTP reference implementation is available and currently under evaluation.

Reliability in DVB networks — The first generation (DVB-S/DVB-RCS) as well as the second generation (DVB-S2/DVB-RCS) of the DVB satellite network acquire a robust physical layer which supports different types of modulation and code rates based on Forward Error Correction (FEC) mechanisms and the use of packets interleaving. This feature allows the satellite physical layer to be robust and largely reduces the probability of consecutive packet losses, mainly with the use of the new satellite standard that enhances the coding technique by introducing the Low Density Parity Check (LDPC) codes as well as the Bose-Chaudhuri-Hocquenghem (BCH) codes. Indeed, the use of these techniques combined with the different supported modulations (QPSK, 8PSK, 16APSK, 32APSK) enable Quasi-Error-Free operation at about 0.7 dB to 1 dB from the Shannon limit.

On the other hand, in order to maximize the exploitation of the wireless resources, the new standard recommends the use of the Adaptive Coding and Modulation (ACM) mode, which allows adequate adaptation of the modulation and the code rates to the measured noise. This helps in making efficient use of the network resources by keeping the modulation and the code rates always optimal while protecting the system in case of noise augmentation. However, as the reaction time is not negligible, it becomes also necessary to adopt effective and suitable protocols in the transport layer.

Some other protocols have been designed for wireless networks. Some techniques of these protocols may also be applied to space networks, but due to the limit of the paper length, they are not included in this survey.

### *D. Comparative Summary of Data Transport Protocols*

Based on the above discussions, Table II provides a comparative summary of the main features of all the protocols. The features of each protocol include the application environment, problems solved, congestion-control mechanisms deployed, and modifications to the TCP transmission control mechanism. In addition to the major problems associated with satellite channels, including high BER, long delay and channel-bandwidth asymmetry, other problems such as link underutilization, channel efficiency, fault tolerance and fairness are also solved by several protocols. The well known problem of a protocols erroneous congestion decision is considered a different problem although it is related to the channel BER. Congestion control has been critical to the robustness and stability of the Internet and forms a highly important issue in transport protocols. Window-based congestion control mechanisms control the data transmission rate by adjusting size of the windows that reflect the available channel capacity and receiver buffer space. Rate-based congestion control mechanisms directly control the transmission rate of the connection

Table II. Comparison of Data Transport Protocols in Space Internet.

| Protocol Names | Application Environment | Problems Solved | | | | Congestion Control Mechanisms | | Modification to TCP Transmission Control | |
|---|---|---|---|---|---|---|---|---|---|
| | | High BER | Long Delay | Channel Asymmetry | Other Problems | Window-based | Rate-based | TCP congestion control | TCP error control |
| **SCTP** | Satellite Networks | Yes | Yes | Yes | Distinction of congestion and corruption; transmission reliability/fault tolerance | Yes | No | Yes | Yes |
| **STP** | LEO/GEO | Yes | Yes | Yes | No | Yes | Yes | No | Yes |
| **XSTP** | LEO | Same as STP | Same as STP | Same as STP | Erroneous congestion decision | Yes | Yes | No | Yes |
| **TCP Peach** | Satellite (IP) Networks | Yes | Yes | No | No | Yes | No | Yes | No |
| **TP-Planet** | Deep space interplanetary links | Yes | Yes | Yes | Black out condition | Yes | Yes | Yes | No |
| **TCPW** | Wired/wireless networks, especially lossy wireless networks | Yes | No | No | No | Yes | No | Yes | No |
| **XCP** | High BDP Networks | No | Yes | No | High BDP | Yes | No | No | No |
| **P-XCP** | Same as XCP | Yes | No | No | Link under-utilization | Yes | No | No | No |
| **REFWA** | Multihops satellite environment | No | No | No | Efficiency and fairness | Yes | No | No | No |
| **REFWA Plus** | Multihops satellite environment | Yes | No | No | Efficiency and fairness | Yes | No | No | No |
| **SCPS-TP** | Earth-orbit space environments | Yes | Yes | Yes | Erroneous congestion and intermittent connectivity | Yes | Yes | Yes | Yes |
| **I-PEP** | Same as SCPS-TP | Yes | Yes | Yes | Erroneous congestion | Yes | Yes | Yes | Yes |
| **"Split-TCP" Proxy** | Satellite networks | Yes | Yes | Yes | No | Yes | No | No | No |
| **PETRA** | Targeted GEO space but including LEO | Yes | Yes | Yes | No | Yes | No | No | No |
| **BP** | Deep space interplanetary links | Yes | Yes | Yes | Intermittent connectivity | No | No* | No | No |
| **CFDP** | All space environments | Yes | Yes | Yes | Intermittent connectivity | No | No | No | No |
| **LTP** | Deep space interplanetary links | Yes | Yes | Yes | Intermittent connectivity | No* | No | No | No |

*: The specifications for these protocols make no mention of these capabilities, but they can be readily implemented without requiring additional protocol support.

based either on the measurement taken at the end host or feedback from the network. Following these different methods, window-based mechanisms try to inject all data packets in the window to the network in burst manner, while rate-based mechanisms generate a smooth data flow by spreading the data transmission across a time interval. While most of the considered protocols employ window-based congestion control, some perform rate-based congestion control, as shown in Table II. Each protocol is also identified by which transmission control mechanism of TCP (i.e., congestion control or

Table III. Protocol's Techniques in Solving the Space-Internet Problems.

| Protocol Names | High BER | Long Delay | Channel Asymmetry | Other Problems |
|---|---|---|---|---|
| **SCTP** | Use of SACK to allow more gap blocks in SACK chunk; Use of multi-streaming to increase channel goodput when the receiverís buffer is limited, over error-prone links | Use of byte counting algorithm to decouple the increase of *cwnd* from arrival frequency of SACKs and to faster increase *cwnd* in high BDP networks | Use of byte counting algorithm to speedup the increase of *cwnd* (especially in slow start phase) when SACK is delayed because of reduced ACK channel rate | Solution to erroneous congestion decision: Use of explicit congestion notification (ECN);<br>Solution to transmission reliability and faulty tolerance: Use of multihoming |
| **STP** | New error-control strategy adaptive to unique error conditions in satellite networks, designed based on an end-to-end probing mechanism | Use of a rate-based congestion control mechanism | Combination of periodical acknowledgment of data and SNACK mechanism. | No |
| **XSTP** | Same as STP | Same as STP | Same as STP | Solution to erroneous congestion decision: New error control strategy based on the end-to-end probing mechanism to measure the RTT both before and after probing to determine the source of data losses |
| **TCP Peach** | Sudden start with the help of low-priority dummy segments | Rapid recovery with the help of low-priority dummy segments | No | No |
| **TP-Planet** | Steady state algorithm to solve erroneous congestion control decisions | Rate-based AIMD congestion control; Initial state to capture link resource faster | Delayed acknowledgment mechanism | Solution to channel blackout: Incorporation of a black out state procedure into the protocol operation |
| **TCPW** | Continuous measurement of the bandwidth used by the connection at the sender via monitoring the arrival rate of acknowledgment, and its use to compute window size and slow start threshold after a congestion event | No | No | No |
| **XCP** | No | Decoupling of congestion control from fairness control, done by matching the aggregate traffic rate to the link capacity | No | No |
| **P-XCP** | Maintaining data sending rate when packet loss is detected; Sending rate adjustment depending only on the congestion header | Same as XCP | Same as XCP | Solution to link underutilization: Adjustment of the aggregate feedback based on the ratio of the number of rate-limited connections to the total number of connections sharing the link |
| **REFWA** | No | No | No | Solution to link efficiency and fairness: Matching the sum of window sizes of all active TCP connections sharing a bottleneck link to the effective network capacity, and providing all the active connections with feedbacks proportional to their RTT values |
| **REFWA Plus** | Distinction between congestion induced packet drops from those due to link errors is based on comparison of the new and old values of the explicit congestion feedback signaled by the REFWA scheme to TCP senders. | No | No | Solution to link efficiency and fairness as the original REFWA scheme. |
| **SCPS-TP** | Split-TCP policy; Explicit corruption response; SNACK option; Loss-tolerant end-to-end header compression | Split-TCP policy | Channel rate-control transmission; Acknowledgment frequency reduction; End-to-end header compression | Solution to erroneous congestion decision: TCP-Vegas;<br>Solution to intermittent connectivity: Link outage support |
| **I-PEP** | Connection Splitting; SNACK option; End-to-end header compression | Similar to SCPS-TP | Similar to SCPS-TP | Solution to erroneous congestion: Explicit Congestion Notification (ECN) |
| **"Split-TCP" Proxy** | Split-TCP proxy mechanism with splitting occurred on board of satellite | Split-TCP proxy mechanism with splitting occurred on board of satellite | Split-TCP proxy mechanism with splitting occurred on board of satellite | No |
| **PETRA** | Split-TCP policy: Subdivision of the path into two segments reduces the relative BER for each segment | Split-TCP policy: Subdivision of the path into two segments reduces the RTT for each segment | Split-TCP policy | No |
| **BP** | Multi-streaming | Late binding of destination endpoint ID to specific network address; Absence of handshaking | Unidirectional nature of the protocol; Absence of handshaking | Solution to intermittent connectivity: Custody-based message transfers operating in stored-and-forward switching mode |
| **CFDP** | Multi-streaming | Multi-streaming | Aggregate acknowledgment used to minimize traffic on the forward channel | Solution to intermittent connectivity: Store-and-forward approach together with suspension of retransmission timers during intervals of disconnection |
| **LTP** | Multi-streaming | Multi-streaming | Aggregate acknowledgment used to minimize traffic on the forward channel | Solution to intermittent connectivity: Suspension of retransmission timers during intervals of disconnection |

error-control) is modified. TCP Peach, TP-Planet, and TCPW involve modifications to TCPs congestion-control mechanism, while STP and XSTP involve modifications to TCPs error-control mechanism. In comparison, SCTP, SCPS-TP and I-PEP modify both the congestion-control and error-control mechanisms of TCP while XCP, P-XCP, REFWA, REFWA Plus, "Split-TCP" proxy, PETRA, BP, CFDP, and LTP modify neither.

Table IV. Performance Evaluation Results available at Present for Each Protocol.

| **Protocol Names** | **Performance Evaluation Results** | |
|---|---|---|
| | **Advantages** | **Disadvantages/Problems Not Solved** |
| **SCTP** | Always achieves slightly higher throughput than TCP; Maintains fairness of link utilization when TCP transmissions co-exist | Header compression over error-prone channel; Bias against long-RTT association in the phase of congestion avoidance; Interaction between retransmission and link layer ARQ; Unavailability of timestamp option |
| **STP** | Achieves up to an order of magnitude reduction in the reverse bandwidth used for large file transfer | Need of STP implementation at end hosts or protocol conversion back to TCP by satellite network; No mechanism to differentiate packet losses caused by link congestion and bit error corruption |
| **XSTP** | Improves the effective throughput and increase the energy efficiency of the protocol under various network error conditions | Large overhead introduced by each protocol layer, impeding the performance |
| **TCP Peach** | Outperforms other TCP schemes for satellite networks in terms of goodput, and provides a fair share of network resources | Requirement of supporting priority drops at routers which is an unavailable feature in present routers. |
| **TP-Planet** | Significantly improves the throughput performance and addresses the challenges posed by the IPN backbone networks | Under evaluation |
| **TCPW** | Improves throughput performance and fairness; Friendly with TCP Reno; Extremely effective in mixed wired and wireless networks where throughput improvement of up to 550% are obtained; Performs as well as localized link layer protocol | Poor performs when random packet loss rate exceeds a few percent; Poor friendliness |
| **XCP** | Outperforms TCP in both conventional and high bandwidth-delay environment, and achieves fair bandwidth allocation, high utilization, small standing queue size, and near-zero packet drops, with both steady and highly varying traffic | Problem with high BER and channel asymmetry remaining; Significant modifications needed at the end system; Need of Internet service providers (ISPs) to upgrade the routers, making it unlikely to be deployed in the near future |
| **P-XCP** | Overcomes the problems of XCP with high BER and link underutilization; Shows a throughput almost double that of XCP when PER is over 0.1; Retains the excellent queue length stability and low congestion dropping of the original XCP | Problem of channel asymmetry remaining; Need of ISPs to upgrade the routers |
| **REFWA** | Substantially improves the system fairness, reduces the number of packet drops, and makes better utilization of the bottleneck link | The issue of link errors is solved in REFWA Plus. Other issues are still under evaluation |
| **REFWA Plus** | Under evaluation | Under evaluation |
| **SCPS-TP** | Solves most space-channel problems and supports space communication configurations in earth-orbit space environment; Implementation available; Well evaluated over emulation testbed and real satellites; Performs significantly better than TCP at the BERs of $10^{-7}$ or greater | Extensive tuning efforts needed to find optimal settings of the options for the best performance |
| **I-PEP** | Under evaluation | Under evaluation |
| **"Split-TCP" Proxy** | Enhances throughput up to threshold for both TCP New Reno and TCPW, in some scenarios, with relatively modest on-board buffering requirement | Cost of on-board store and forwarding |
| **PETRA** | Significantly enhances throughput performance | Under evaluation |
| **BP** | Under evaluation | Need of a large buffer at intermediate routers to store data packets, resulting in a need of an efficient buffer management mechanism to prevent data transmission from being effected by the store-and-forward operation |
| **CFDP** | Achieves satisfying performance advantages over conventional FTP/TCP in terms of throughput and overall transfer time in the presence of high BER and intermittent connectivity over both LEO- and GEO-satellite links | Under evaluation |
| **LTP** | Under evaluation | Designed only for a single-hop link and not for a multi-hop link |

To compare how each protocol solves the space-Internet problems, Table III summarizes the different techniques deployed to overcome high BER, long delay, channel asymmetry and other problems. In Table IV, a summary of the performance evaluation results available at present is presented for each protocol. The evaluation results include the performance advantages of each protocol, evaluated by protocol developers, and performance disadvantages, including the problems that have not been solved.

## IV. SUMMARY AND FUTURE WORK

This article presents a survey on a variety of protocol solutions proposed for reliable data transport in space Internet with a focus on the advanced developments in recent years. Most of these solutions are designed at the transport layer, while some are designed at the application and link layers. The survey discusses the design and operation methods of the protocols, compares and comments on their techniques and performances. The existing protocols are proposed for different application environments, and therefore, their focuses are different. While most protocols are designed for Earth-orbit satellite networks, some of the protocols focus on deep-space interplanetary links. Almost all of the protocols solve the problems of high BER and/or long link delays that are the primary challenges in space communications. Some also solve other problems, such as bandwidth asymmetry, channel efficiency, fault tolerance, and fairness. The protocols solve these problems using different techniques.

Provided that many available protocols cannot fully meet the requirements of space mission, we suggest that, as a lesson learnt from this work, space Internet protocol designers should work more closely with space mission designers for the development of the space network protocols in the future. In addition, as seen in Table IV, the performance evaluation results are unavailable for the major DTN protocols. The authors suggest that they should be evaluated in both simulation and experimental manners, as the future work.

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