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Cluster-based architecture and network model for InterPlaNetary Internet

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Abstract: Along with the development of the IPN (InterPlaNetary) Internet, the terrestrial Internet and interplanetary exploration network will be seamlessly merged with each other. However, significant challenges in control and management exist in such a complicated network. These include the efficient and reliable dissemination of control information, and the building up of an overlay network. This paper reviews current networking technologies for the IPN Internet and presents a novel architecture that divides it into subnets. A network model based on clusters is proposed to account for the problem of dynamic coupling among subnets and achieve monolithic controllability of the whole network. A new paradigm that separates the control and service planes is presented to reduce congestion and guarantee the reliable distribution of control information. We also present a modified version of a delay-tolerant-network protocol stack that separates the network layer into generalized inter-cluster sub-layers and discriminative intra-cluster sub-layers to improve the transmission efficiency of control information. Simulation results indicate that both the control and service data delivery is more efficient and reliable through clustering of the IPN Internet. Finally, we present recent achievements in network-information theoretical approaches that can be successfully applied to deep-space communication.

Key words: InterPlaNetary Internet, architecture, network model, cluster, protocol

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1 Introduction

NASA (the National Aeronautics and Space Administration) DSN (Deep Space Network) has played an important role in the exploration of our solar system. In August 1989, Voyager 2 encountered Neptune and returned spectacular images of the most distant known planet via a radio-communication subsystem built using 1970s technology. However, space exploration is continuously developing and people have also started to rely on space networks significantly in recent years. A vast amount of scientific data has been amassed from the remote planets and is yet to be fully exploited. Furthermore, future exploratory missions to the Moon and Mars (and potentially even farther) will require a reliable and effective communication infrastructure able to connect astronauts, landers, rovers, and orbiters with Earth facilities. However, there are several challenges in communicating between Earth and the planets. Some of the most

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important issues are the large propagation delay and path loss, intermittent connectivity, limited energy, computation, and storage resources, and asymmetric links. Instead of point-to-point communication, networked communication has become an inevitable trend to overcome the above challenges. Networked communication has the advantages of extending the communication range, improving delivery efficiency and reliability, exploiting cooperative transmission ability, and using limited resources more efficiently. However, increasing number of spacecraft, probes, and relay satellites impose conditions on realizing networked communication among interplanetary nodes.

Therefore, NASA proposed IPN Internet in 1998 for reliable and efficient interplanetary networked communication. This would be the next phase of the DSN to provide communication and navigation services for exploration spacecraft and orbiters[1,2]. Many researchers and several organizations are currently engaged in developing the technologies required for the realization and deployment of an IPN Internet. Attempts are being made to apply the mature architecture and technology of the terrestrial Internet to the DSN and extend its coverage beyond that of single-hop communication. However, factors such as the orbital motion of celestial bodies and spacecraft, the random walks of detectors on planetary surfaces, and the impermanence of nodes will all result in changes in the topology of the entire network. This will also be affected by the networking and application modes, the volume and orientation of service traffic, and the local network environments. In other words, low-dynamic local networks will couple with each other and cause serious problems for the IPN Internet, which results in a serious problem that the network characterizes as high-dynamic changes. These, along with new properties such as node variety, heterogeneity, and network sparseness, will result in difficulties, as will the very large time and distance scales involved in the control and management of the IPN Internet. Thus, it is essential to be able to solve these problems before deploying the IPN Internet.

In this paper, we try to account for the above problems at first by proposing a cluster-based architecture and network model to separate the large and complicated IPN Internet into many clusters according to the location and property of nodes. This decouples a high-dynamic network into many low-dynamic sub-networks. This approach is intended to provide reliable data delivery and efficient navigational control for spacecraft and probes. The remainder of this paper is organized as follows. In Section 2, we present related work on point-to-point communication and the IPN Internet. In Section 3, we present our generalized architecture. The new cluster-based network model that separates the control and service planes is proposed in Section 4. We conclude the paper in Section 5.

2 Related works

In this section, we present the primary achievements in the field of deep-space communication in relation to point-to-point communication, IPN architecture, network models, and space communication protocols.

2.1 Point-to-point communication approaches

The existing approaches to improving the reliability of point-to-point interplanetary communication are summarized in Tab.1. However, these have essentially reached the limits of improving deep-space point-to-point communication performance. Firstly, the transmitted power and antenna apertures cannot be increased without bound because of size and powerdissipation limitations. Secondly, RF (Radio Frequency) communication has been used as standard in space for many years. However,

Table 1 Point-to-point communication technologies

approach	gain
increase the antenna aperture of Earth station to 70 m (compared with 10 m)	16.90
increase the antenna aperture of explorer to 5 m (compared with 0.6 m)	18.42
increase the RF power of explorer to 40 W (compared with 10 W)	6.02
improve the RF frequency (Ka band compared with S band)	22.90
lower the system noise temperature to 6.54 K (compared with 150 K)	13.63
(15, 1/6) convolutional codes and R-S concatenated codes	10.00
source-compression codes (×3 lossless compression)	4.77

RF technology needs to be improved to satisfy increasing data rates. In recent years, free-space optical communication has been considered as a promising technology for space applications. Nevertheless, several challenges are associated with developing and implementing laser communication for space. The high-vibration environment means that optmechanical devices for pointing and beam steering would have to maintain directionality over very long distances without excessive jitter. Acquisition of the beam would be difficult without a nearly instantaneous beacon feedback from the receiver, which is nearly impossible in deep space. Thirdly, the noise temperature is approaching the extreme of refrigeration systems. Fourthly, various channel codes (e.g., convolutional, RS, RS concatenated, Turbo, LDPC) have been recommended for space communication. However, the high coding and decoding complexity is the main obstacle to improving the coding gain. Finally, sourcecompression coding only provides a certain amount of additional finite gain.

2.2 Architecture of IPN Internet

The IPN Internet is a disconnected and store-and-forward based on space communication with large delays and error-prone links. The basic concept of the IPN Internet is to construct a network of Internets in the deep space. This concept contains three aspects: 1) deploy standard Internets in low-latency and remote environments (e.g., other planets, the Moon, remote spacecraft); 2) connect these separate Internets via an interplanetary BN (Backbone Network) that is used to handle the large latency of the deep-space environment; 3) create gateways and relays as the interfaces between the low-and high-latency environments.

The IPN architecture proposed in Ref.[3] contains just three subnets, as shown in Fig.1. The IPN BN provides an infrastructure for communication between Earth and the likes of the Moon, the planets, satellites, and intermediate relay stations. The IPN External Network consists of spacecraft traveling in groups in interplanetary space, clusters of sensor nodes, and groups of space stations. The IPN Planetary Network is composed of planetary satellite and surface networks. This architecture could be implemented at any planet to provide interconnected cooperation among the satellites and surface elements there.

The above architecture has received widespread acceptance. In Ref.[4], the IPN Internet was divided into different parts to solve different problems, as shown in Fig.2. This architecture includes three PNs (Planetary Networks), which are also shown in Fig.2. One is deployed over the remote planet (e.g., Mars) and the other is deployed over the Moon. Two landers are included on each PN surface. In the remote-

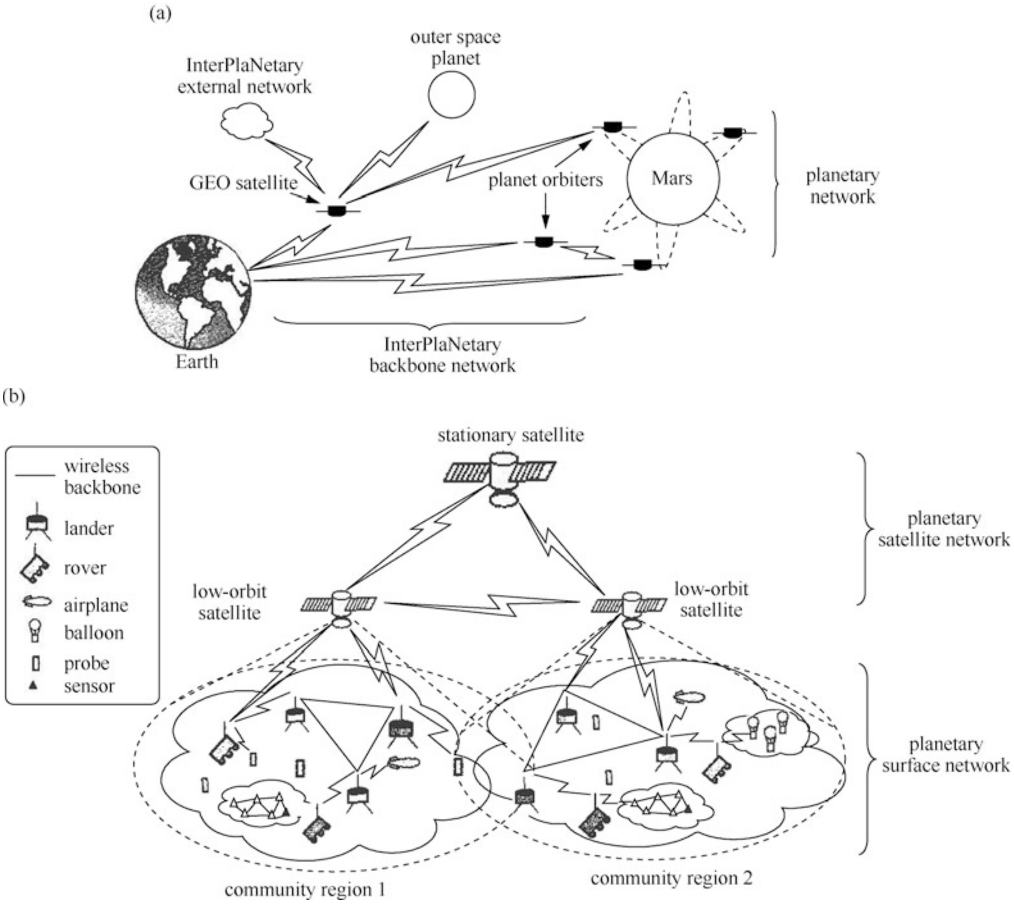

Figure 1 Architecture of IPN Internet: (a) IPN; (b) planetary

planet PN, the two landers are MS1 and MS2; in the lunar one, they are LS1 and LS2. The landers are able to transmit information such as images, video, and sensed data (e.g., temperature, humidity) to the PN Satellite Network. Over the remote planet, this comprises four orbiters (MO1, MO2, MO3, and MO4), whereas the lunar one comprises two orbiting satellites (LO1 and LO2). The Earth's surface PN network is structured with six surface nodes, ES1 to ES6, and three satellites in GEO (GEOsynchronous) orbit, GEO1, GEO2, and GEO3. The six surface nodes act as both the destination of information sent from outer space and the source of control and command messages to the deep-space nodes. The three GEO satellites are ideally spaced by 120°, allowing the maximum coverage of the Earth's surface.

Fig.3 shows a long-term architecture for the IPN Internet. In this figure, the whole IPN Internet has been separated into BN, ANs (Access Networks) and PNs. The BN provides a common infrastructure

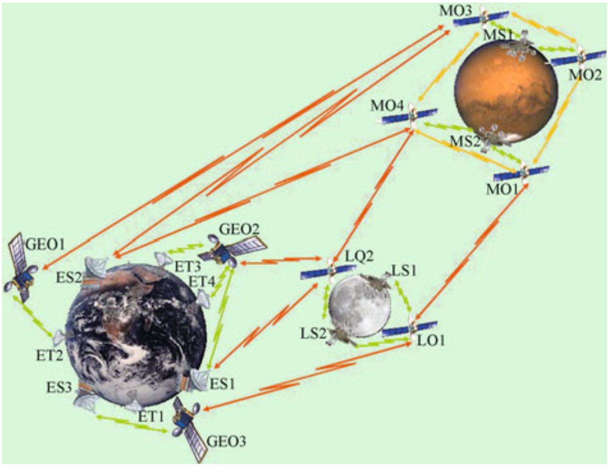

Figure 2 Another IPN architecture

for long-haul and relay communication between Earth, the Moon, the planets, and satellites. Each AN comprises boundary nodes that provide access services between BN and PN nodes. Each PN is composed of PN satellite and surface networks.

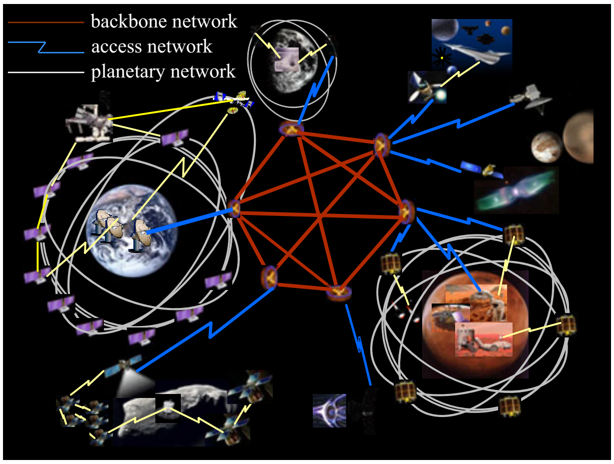

Figure 3 Long-term IPN architecture

3 Protocol in space communication

The SCPS (Space Communications Protocol Specifications) were proposed by the CCSDS (Consultative Committee for Space Data Systems) to improve the performance of protocols in space communication. They are either new protocols or extensions to existing ones.

The SCPS protocol stack is divided into application, transport, network, link, and physical layers, and contains the SCPS-FTP (extension of the File Transfer Protocol), SCPS-TP (extension and modification of the Transfer Control Protocol), SCPS-SP (Security Protocol) and the SCPS-NP (Network Protocol). The system will use these protocols according to different application environments. Some are for near-Earth satellites, while others are for deep-space communication, but almost all of them solve the major problems of space communication: high BER (Bit Error Rate) and long link delay[5]. The LTP (Licklider Transmission Protocol) is another delay-tolerant point-to-point protocol for space communication, which provides retransmission-based reliability over links that are characterized by extremely long RTT (Round-Trip Times)[6].

A DTN (Delay/disruption Tolerant Network) is an overlay architecture. It operates above the protocol stacks of the distinct ICNs (Intermittently Connected Networks). DTNs achieve end-to-end reliable communication through the use of storage capacity, a variety of protocol techniques, replication and parallel forwarding, forward error correction, and many other techniques for overcoming communication impairments[7].

In the terrestrial Internet , the TCP provides end-to-end reliability by retransmitting the information that is not acknowledged by the destination. However, DTN routers and gateways can forward bundles between the source and destination. In DTNs, the bundle layer provides communication reliability with a store-and-forward mechanism and custody transfers. Bundles are delivered from one node to the next, independently of other bundles expect for responses. Fig.4 gives the DTN protocol stack.

DTNs support node-to-node retransmission of lost or corrupt data at both the transport and bundle layers. However, end-to-end reliability can only be ensured at the bundle layer because no protocol is used at transport layer operates end-to-end . The custody transfers that are arranged between bundle layers are used to support node-to-node retransmission. Once a bundle has been sent to the next node upon the current bundle layer custodian , a time-to-acknowledge retransmission timer is started. If the bundle layer of the next node accepts this bundle, it returns an acknowledgement to the sender. If no acknowledgement is returned before the sender's time-to-acknowledge expires, the sender retransmits the bundle.

The bundle will not be released from the buffer until

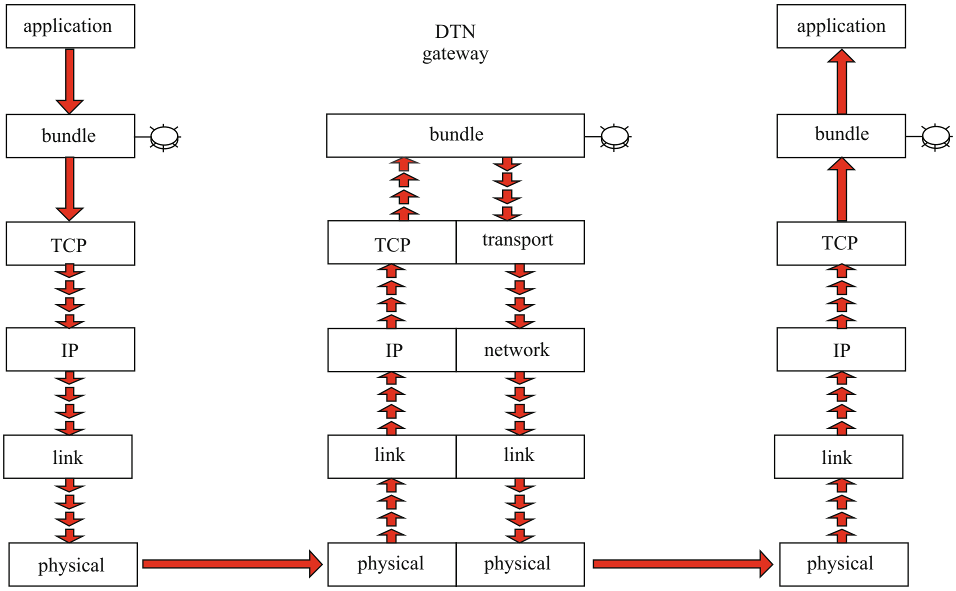

Figure 4 DTN protocol stack

either the next-hop node accepts it or this bundle's time-to-live expires. The time-to-acknowledge should be long enough to complete reliable transmission.

4 Generalized architecture of cluster-based InterPlaNetary Internet

Networking based on relays and exchanges is the new direction for future deep-space communication. However, deep-space relay networks require the IPN Internet to have certain characteristics other than those described in Section 2, such as diversification of node type and regional distribution. These result in new communication and networking challenges that include primarily a highly dynamic network topology and a heterogeneous network environment. These in turn cause various difficulties with the architecture design and network management. In this section, we give a generalized architecture of the IPN Internet based on a clustered network. In our architecture, the IPN Internet is divided into Earth, backbone, planetary, and ANs. These can be divided repeatedly into many subnets to form a multilayer architecture, as shown in Fig.5.

4.1 Backbone network

The BN comprises deep-space nodes with high processing capabilities and large-capacity links. The basic characteristics of this network are a large propagation delay and loss that turns it into a typical DTN. The BN is the core and basis of the IPN Internet. The challenge is to build backbone nodes and links that can take into account the shade and ultra-long-haul communication.

In our previous research, we built an IPN BN based on the libration points that are also introduced into the CRTBP (Circular Restricted Three-Body Problem). In the CRTBP system, there are five particular solutions called libration points. The orbits of all planets except Mercury and Pluto are approximately circular around the Sun in the ecliptic plane, and the mass rate of planet with sun is relative small enough, which is representative of a CRTBP. Therefore, each planet has five libration points around the Sun, except Mercury and Pluto. The IPN backbone sketch map is established by deploying relay facilities on those libration points and connecting them, as shown in Fig.6. Fig.6(a) shows the large-scale topology that

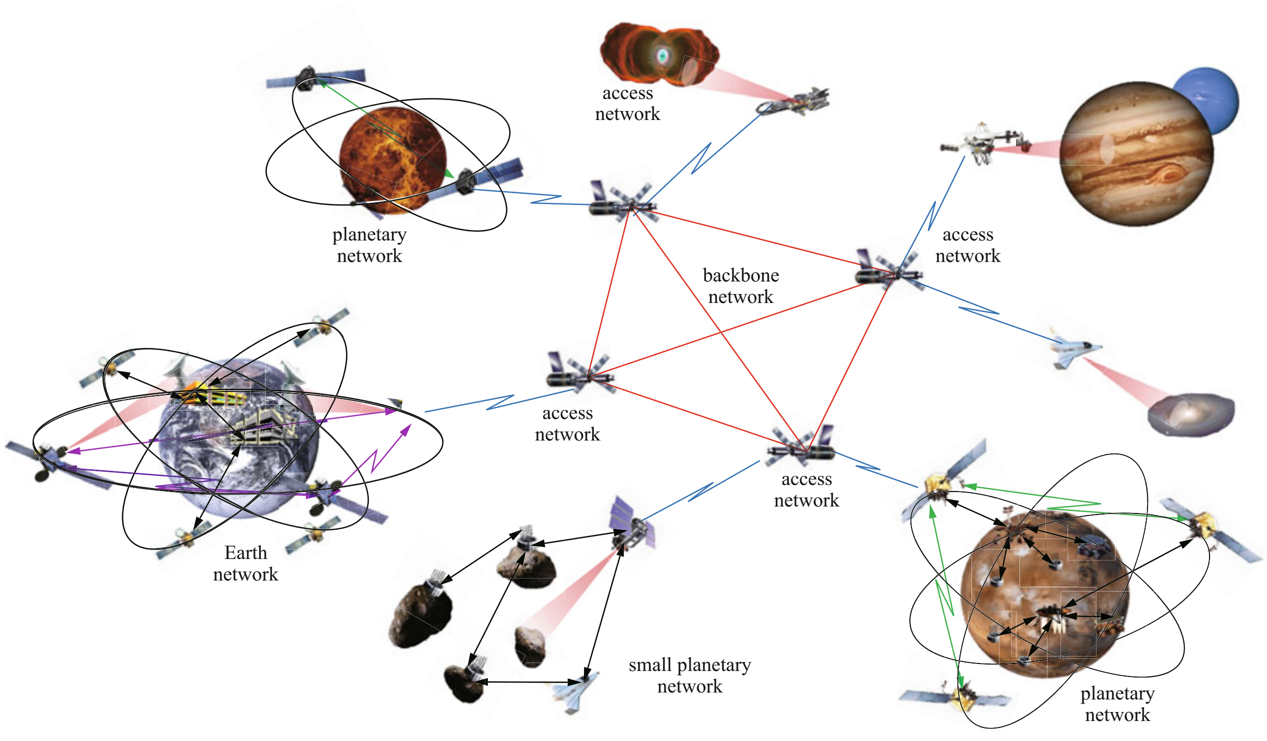

Figure 5 Makeup and architecture of InterPlaNetary Internet

extends to Jupiter, Saturn, Uranus, and Neptune. The facilities move around the Sun with longer orbital periods. Fig.6(b) shows the small-scale topology that includes Mercury, Venus, Earth, and Mars, which have relatively short orbital periods.

4.2 Planetary network

The PN shown in Fig.7 comprises satellites and orbiters around the planet, science balloons in the atmosphere, and landers, rovers, sensors, and probes

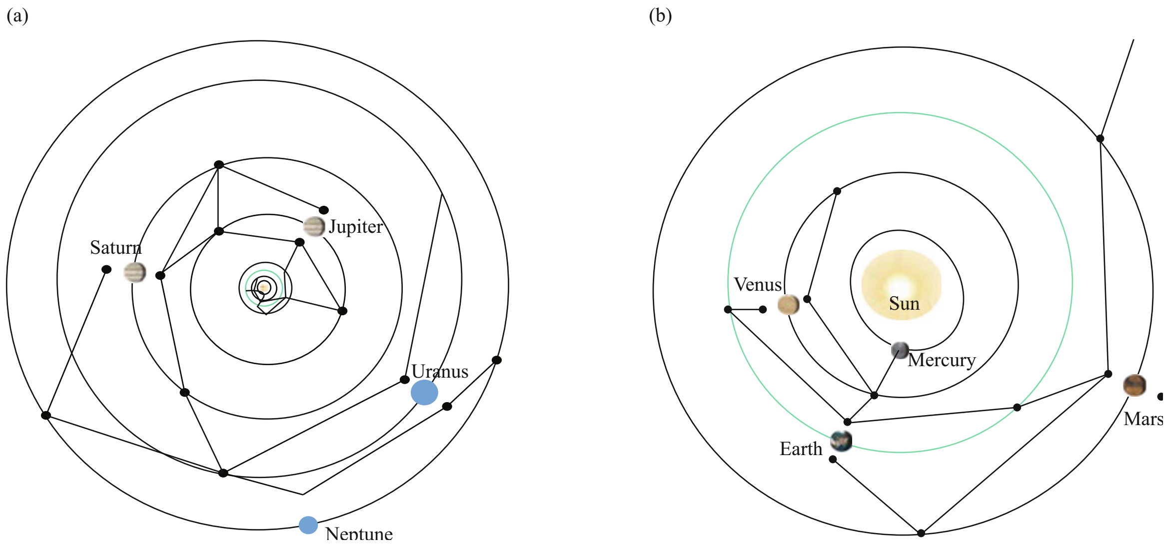

Figure 6 Architecture of IPN Internet: (a) architecture of IPN Internet; (b) architecture of planetary network

on the ground. The PN is also separated into a satellite one and a surface one. The satellite network contains all the satellites and orbiters circling the planet. It is used to provide relay services between Earth and the nodes of the surface network, as well as communication and navigation services for the surface nodes. The surface network contains all the surface nodes (e.g., rovers, landers, sensors), which are connected by wireless links. The surface network includes some elements that cannot communicate with the satellites or orbiters directly. These elements are often organized in clusters and are spread out in an Ad hoc manner, e.g., sensor nodes and balloons as illustrated in Fig.7.

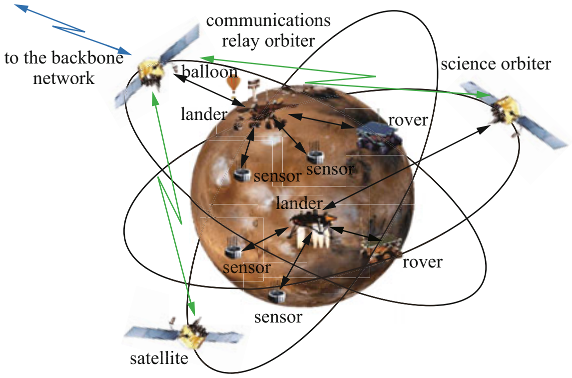

Figure 7 IPN planetary network

4.3 Access network

The AN is the communication interface between the BN and the EN (Earth Network), the PN, and the interplanetary spacecraft. The AN also plays an important role as the relay between the BN and the mission elements. At the same time, the AN is the boundary of the large-scale BN and the small-scale local networks (the EN, PNs, and other outer-space networks). Consequently, a series of switches exist when information flows through the AN, such as the modulation and coding approach, and the network protocol, to accommodate the different characteristics of the BN and the local networks.

4.4 Earth network

The EN is based on the NEN (Near Earth Network), which comprises terrestrial networks and the Earth satellite network. In the near future, the telemetry information from deep space to Earth is likely to outstrip the track and control data from Earth to deep space. In addition, almost all of the telemetry information will be transmitted back to Earth. The communication services present a new characteristic that MSSS (Multiple-Source, Single-Sink). Therefore, the key element in the architecture design of the EN is to ensure efficient and un-interrupted reception of telemetry information from multiple sources.

5 Cluster-based network model of InterPlaNetary Internet

There are various types of node in the IPN Internet, such as backbone relays, planetary orbiters, landers, sensors, and probes. These have different characteristics, take on different missions and roles, and are distributed in different patterns. Meanwhile, the orbital motions of the celestial bodies and spacecraft, the stochastic walks of the planetary probes, and the impermanence of the sensors all lead to a highly dynamic local network topology. As a whole, the change of topology, traffic, and network environment of a local network will affect the state of other elements in the IPN Internet. All these factors create difficulty and inefficiency in the management, control, and running of the whole network.

Therefore, we divide the IPN nodes into clusters according to the node attributes, the link capabilities, the mission characteristics, and the distribution regions. Each cluster can be further separated into sub-clusters according to the mission requirements to construct the network architecture and model based on the cluster. The cluster-based architecture and model change the high-dynamic integrated IPN

Internet into many low-dynamic local subnets to account for the problem of dynamic coupling among subnets and achieving monolithic controllability.

5.1 Cluster-based architecture

The cluster-based architecture of the IPN Internet is shown in Fig.8. The whole IPN Internet is divided into four parts, namely the BN, PN, EN, and AN clusters. Each cluster can also be separated into sub-clusters.

5.1.1 Backbone network cluster

The BN cluster includes all the backbone nodes and links between them, which are responsible for the long-haul transmission of data between the EN and PNs. In our solar system, the backbone relays can be deployed in > 30 libration-point regions. These relays and links constitute the BN and form the BN cluster.

According to the architecture design of the IPN Internet discussed in Section 3, the BN can be divided into large-scale and small-scale backbone subnets. These two subnets have distinctly different propagation delays and losses, data volumes, service features, and topology changes. Hence, we divide the BN into a large-scale backbone sub-cluster and small-scale one.

5.1.2 Planetary network cluster

We consider each PN as a cluster, e.g., the Mars cluster, the Jupiter cluster. A PN cluster contains all the elements of a PN that were discussed in Section 3.2.

The nodes in a PN cluster can be separated into multiple sub-clusters according to the regions and connection relationships, which is shown in Fig.9.

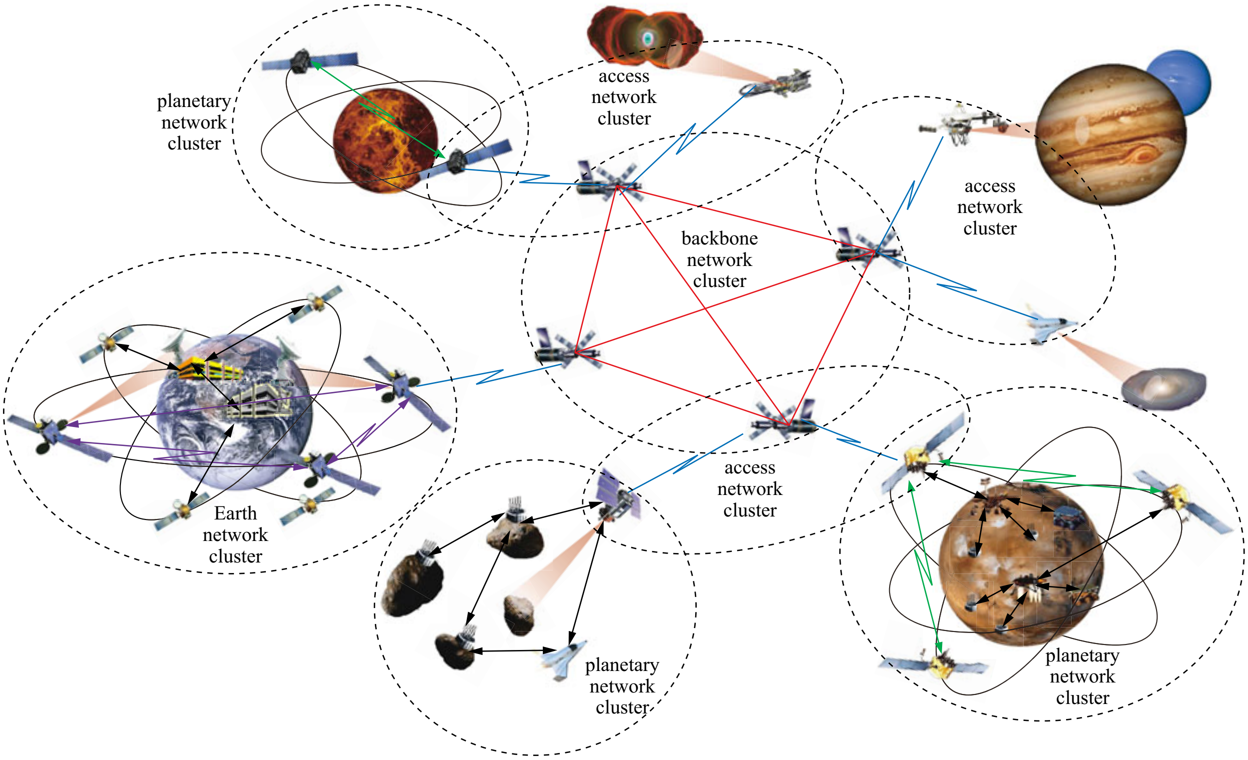

Figure 8 Cluster-based architecture of IPN Internet

For instance, we can divide a PN cluster into a surface network sub-cluster and satellite one. Each sub-cluster can also be separated into further smaller sub-clusters.

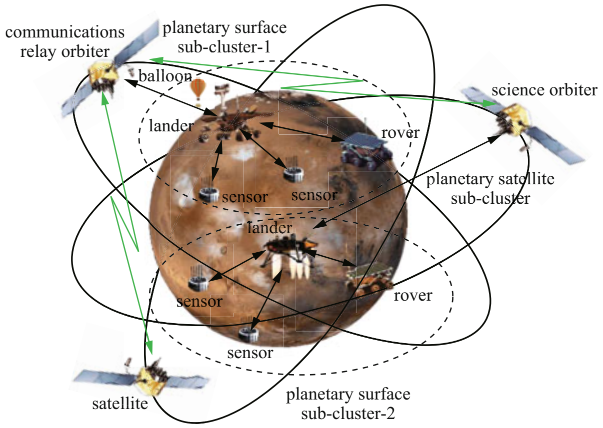

Figure 9 Separation of planetary cluster in sub-clusters

5.1.3 Access network cluster

The AN cluster includes all the nodes of the BN, EN, and PNs that serve as relays and access interfaces, including the outer-space nodes. The AN cluster nodes are not necessarily connected to each other. They may be distributed in the solar system independently, or in the BN and PNs simultaneously.

5.1.4 Earth network cluster

All the EN nodes constitute the EN cluster, which contains the operation and control stations, the ground communication stations, the Internet, and other private networks on the ground. It also contains the satellites, orbiters, planes, HAPS (High-Altitude Platform Stations), and kite balloons. The EN cluster can also be separated into numerous sub-clusters.

Fig.10 shows a cluster-based network model of the IPN Internet. In this model, the IPN Internet has been separated into four types of cluster, namely the EN cluster (cluster-1), AN cluster (cluster-2), PN cluster (cluster-3), and BN cluster (cluster-4). The EN cluster has been further separated into the running and control section sub-cluster and the Satellite constellation sub-cluster. The PN cluster has been further separated into the planetary satellite network sub-cluster and planetary surface network sub-cluster. Terrestrial users can access the IPN Internet through the EN, AN, or BN clusters. Deep-space users can access the IPN Internet through the PN, AN, or BN clusters. The EN cluster and each PN one access the BN Cluster through the AN one.

5.2 Cluster head

In each cluster, the CH (Cluster Head) will be either pre-designated or voted for by all the nodes in the cluster. It is responsible for the generation and exchange of control data among clusters, while acting as the border node. The CH is the control center of the cluster, and its traffic will generally be much heavier than that through the other nodes. Hence, the CH could become the bottleneck of the cluster, so its selection requires the following factors to be taken into consideration.

1) The CH must have significant dataprocessing capacity in order to conduct its own mission and perform management functions such as maintaining intra-cluster routing information and exchanging control data with other clusters.

2) Deep-space resources are severely limited (e.g., power, bandwidth , processing capability). Therefore, the CH should have long-term functionality to avoid unnecessary overheads in changing it.

3) In a cluster, good connectivity should be ensured, with the fewest hops possible between the CH and the other nodes.

4) The CHs among different clusters should set up a relatively stable topology so that the exchange of the control data Cluster-based architecture and network model for InterPlaNetary Internet 7 among

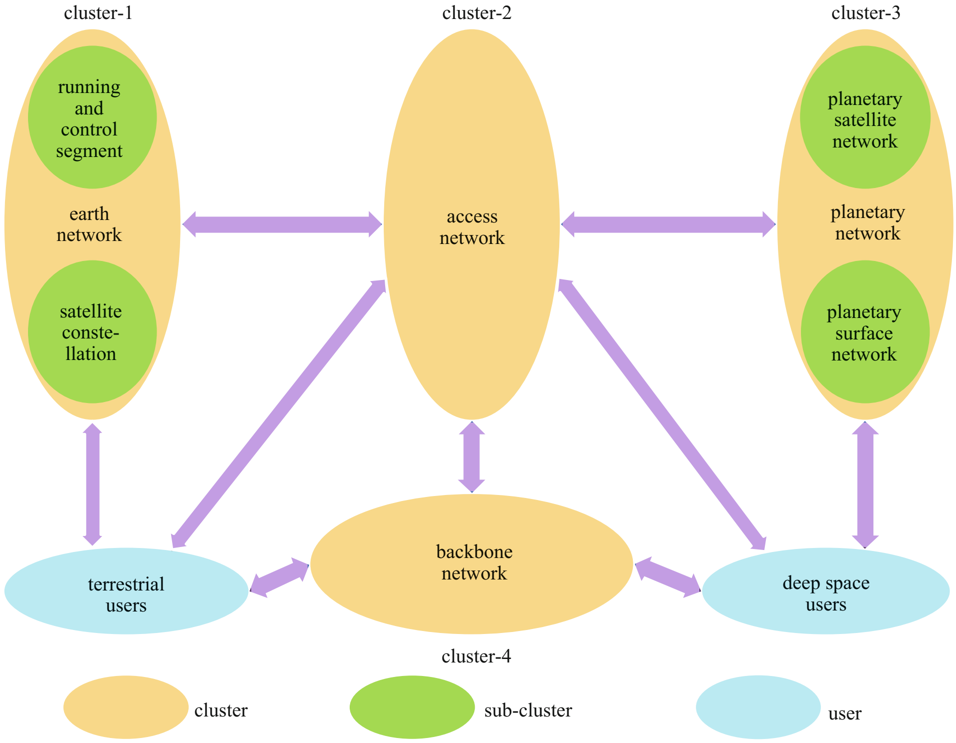

Figure 10 Cluster-based network model

different clusters can be reduced.

5) The control data is not error-tolerant and the reliability is the most important factor to be considered in the selection of the CH.

5.3 Separation strategy of control and service plane

As described in Section 2, achieving an efficient and reliable distribution of the control data is a significant challenge. In this paper, we account for this challenge through separation of the control and service planes, and through separation of the intra-cluster and inter-cluster routings. In our approach, separation of the control and service planes is realized through separation of the control and service links. In addition, the BN routing is generated uniformly at the running and control stations to improve the efficiency and reliability of the control data distribution. The separation steps are as follows.

1) Selection of cluster head. We select the CH in a cluster as a node that has enough communication and processing capability. The CH should also have a better work environment and connectivity with the other clusters. We note that nodes in both the PNs and ANs are natural candidates for CH. The best CH candidate in a PN is the orbiter or satellite that is nearest the BN and that connects to the BN most conveniently. The clusters exchange control data with each other through the CHs.

2) Separation of control and service links. The control links are selected from the most efficient and reliable channels between the backbone node and CHs in these clusters, which are used to deliver the control data generated from Earth exclusively. The massive flows of service data can be isolated from the control-data flow through this separation to reduce the congestion probability of control-data delivery.

3) Separation of intra-cluster and inter-cluster control-data transmission. The control data generated

from the running and control station are delivered to the CHs of every cluster through the BN cluster. Then, the CH transmits the control data to other nodes in its own cluster. Through this method, we can realize the separation of intra- and inter-cluster control data transmissions, including the separated delivery of intra- and inter-routing information. Therefore, the control data is largely reduced in the BN, as is the congestion probability of control data delivery, thus ensuring the delivery efficiency and reliability.

Fig.11 gives an example for routing distribution with separation of control an service planes in IPN Internet.

5.4 Protocol stack model

In the IPN Internet, the CHs and exclusive control links are responsible for the distribution and exchange of control data to realize the separation of the control and service planes. Therefore, the communication protocol at the CHs in different clusters should be compatible while matching their own functions. In addition, the protocol stack should be in agreement with the existing international standardization. Thus, the designed communication protocol requires referring the protocol stack of the terrestrial network and CCSDS standardization.

In our protocol stack, the network layer is separated into intra-cluster and inter-cluster sub-layers, and a bundle layer is inserted between the application and transport layers. The primary differences between the protocol stack that is established and the conventional protocol stack are detailed as follows.

1) Inter-cluster sub-layer. In our cluster-based network model, the protocol stack structure of the IPN Internet requires a uniform inter-cluster sub-layer to deliver the control data. All the nodes in the IPN Internet hold the same inter-cluster sub-layer and have the same function to avoid the protocol transformation of network layers between different kinds of clusters and nodes. Therefore, the transmission efficiency of control data is improved.

2) Intra-cluster sub-layer. To be in agreement with the existing international standardization, our protocol stack builds up the intra-cluster sub-layer based on

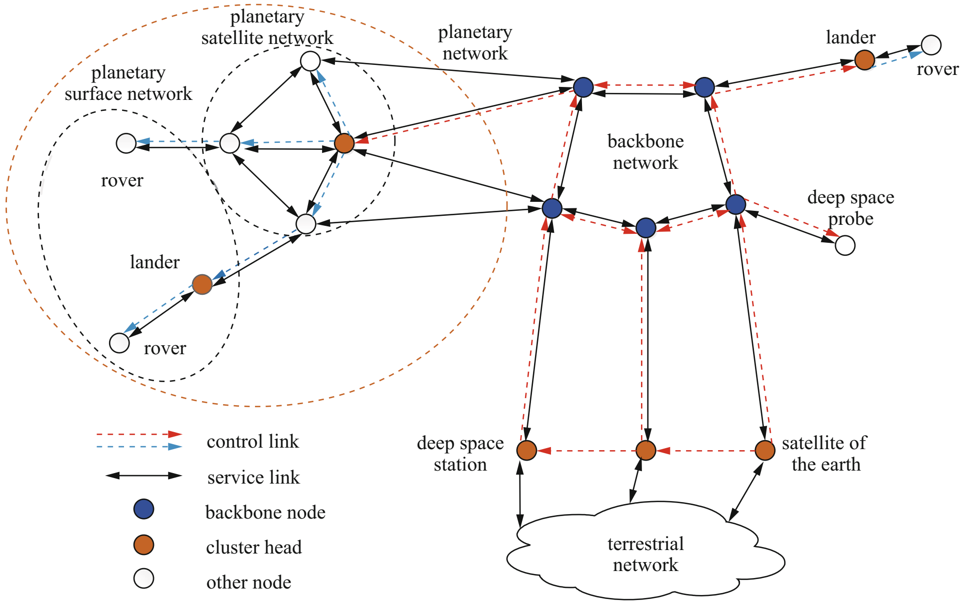

Figure 11 Separation of control and service planes

the existing Internet and other private protocol stack structures. The protocol standardization and function of the intra-cluster sub-layer are similar to those of the network layer of the terrestrial network protocol stack. The configuration and function differ from each slightly other according to the different environments, node attributions, and functions in different clusters. The intra-cluster sub-layer is used to realize the transmission of service data.

3) Bundle layer. We append a bundle layer between the transmission and application layers in our protocol stack to accommodate the large-scale time/space and intermittent connectivity, and to be compatible with the CCSDS protocol. The bundle layer is responsible for storing and forwarding the bundles to set up the store-and-forward mechanism and realize several important functions, such as custody transfer, authentication, and encryption.

In the new network protocol stack structure, the inter-cluster sub-layer and bundle layer run through the overall network. A typical protocol stack structure is presented in Fig.12.

5.5 Analytical and simulation results

Evaluation of the cluster-based network model was performed using the ns-2 network simulator by properly extending the DTN modules and by implementing the LTP within the bundle protocol layer. The performance simulation was conducted by taking the network topology depicted in Fig.13 as the reference. The propagation delay among interplanetary backbone nodes was set to 400 s. The (full-duplex) capacity of links between backbone nodes (as well as between connecting back-bone and CH nodes) was set to 600 kbit/s. However, the propagation delay between nodes inside a cluster (other than the BN one) was set to 0.5 s, and the maximum link rate was set to 2 Mbit/s. We considered CBR (Constant Bit Rate) traffic sources that were kept active for 150 s of simulation. The total data bundle was Rt Mbit/s, while the rate of the control data bundle was 0.05Rt Mbit/s. The rate of each ser-vice data is then the average of the total data flow, except for that of the control data. To realize separation of the control and service planes, 10% of the capacity of each link was used exclusively to deliver the control data. This was generated in node 0 and distributed to all the nodes in the BN and clusters 1~4. In addition, the service data was generated in nodes 1~11 and sent back to node 0.

In Fig.13, we present the BLR (Bundle Loss Rate) performance of the cluster-based and non-cluster-based models. Fig.14(a) illustrates the BLR of the control data versus the total data flow (Mbit/s). This shows that the BLR of the control data in the cluster-based

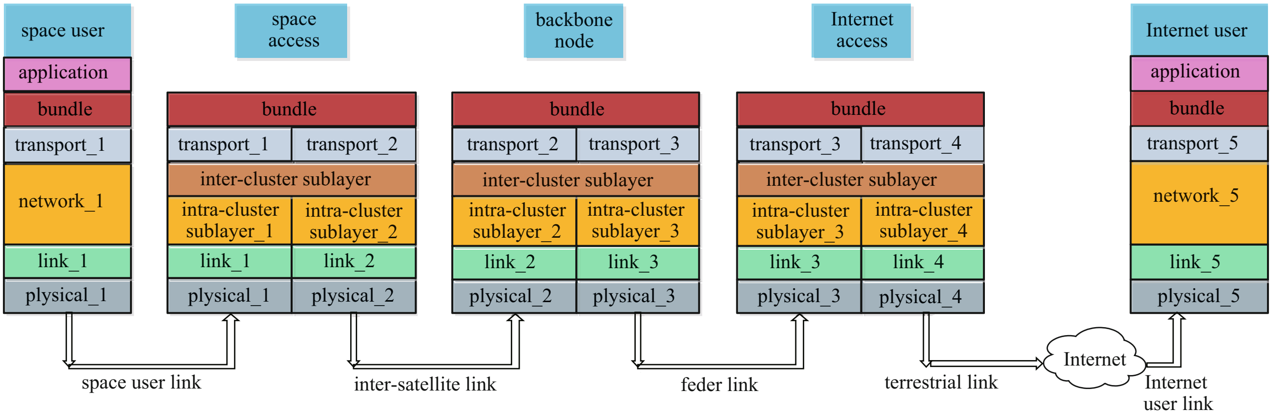

Figure 12 Protocol stack structure of the cluster-based IPN Internet

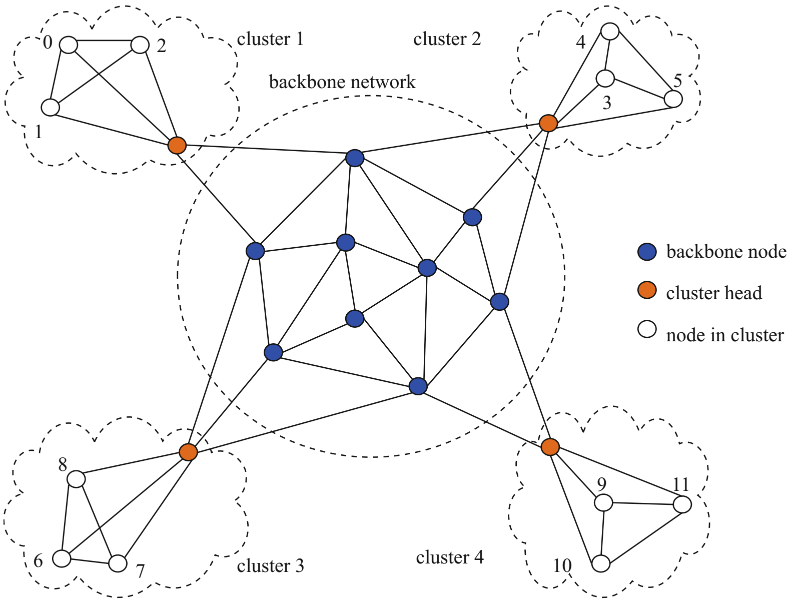

Figure 13 Reference scenario

model is significantly lower than that in the non-cluster-based one. In the other words, the delivery of control data is much more reliable in our model. In Fig.14(b), we present the BLR of the service data in the cluster-based and non-cluster-based models. The performance of the cluster-based model is also better than that of the non-cluster-based one, but the advantage is not obvious.

In addition, as far as delivery delay is concerned, it can be seen in Fig.14 that the delivery delay of both the control and service data is less in the cluster-based model. However, the delivery delay of the control data in the cluster-based model is almost negligible compared with that of the service data. This means that the control data can be delivered to its destination more promptly. This is very important in deep-space missions.

In addition, as far as delivery delay is concerned, it can be observed from Fig.15 that both the delivery delay of control data and service data in cluster based model is less. However, the delivery delay of control

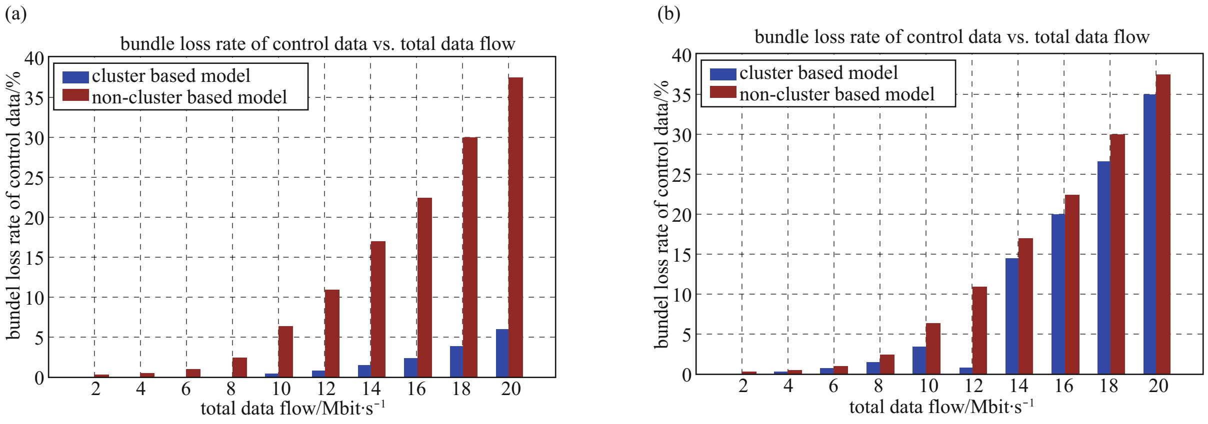

Figure 14 Bundle loss rate vs. total data flow: (a) control data; (b) service data

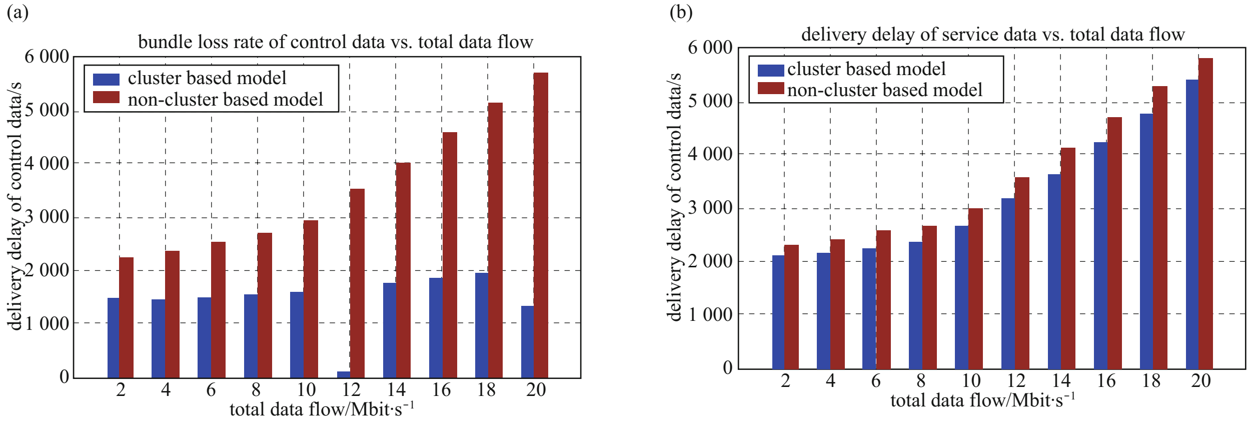

Figure 15 Delivery delay vs. total data flow: (a) control data; (b) service data

data in cluster based model can be negligible almost compared with the delivery delay of service data. It means that the control data can be delivered to the destinations more in time. This is very important to the deep space missions.

6 Conclusion

In this paper, we surveyed the characteristics, architecture, network model, and space communication protocol of a deep-space network. To decouple the influence of changes in one subnet on the others, and to simplify the control of the whole IPN Internet, a cluster-based architecture and network model were proposed, along with the corresponding protocol stack. In this model, the large IPN Internet was separated into several subnets (clusters) and the topology changes in the subnets were insulated from each other. We also tested the validity of our cluster-based model through numerical simulations. Finally, we summarized several network-information theoretical approaches that may suitable for application in the intended IPN Internet.

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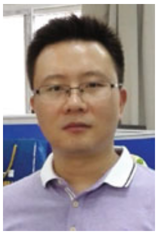

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