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The Hierarchical-Cluster Topology Control Strategy of InterPlaNetary Internet Backbone based on Libration Points

Abstract. *The concept of InterPlaNetary (IPN) Internet was proposed by National Aeronautics and Space Administration (NASA). The IPN Internet could provide Internet-like services crossing interplanetary distances in support of deep space exploration, which includes backbone network, access network, and planetary network. The IPN backbone topology control strategy based on Libration points was studied in this paper. Firstly, the location and stability of Libration point is simulated by celestial mechanics. Secondly, a novel Hierarchical-Cluster model of IPN backbone network is proposed to simplify topology design. Then Intra-Cluster Link and Inter-Cluster Link are analyzed in detail. Finally, the optimal handover moment is gotten by critical angle which to use relay theory, and the total number of handover times is calculated within a relative period between Uranus and Neptune cluster.*

Streszczenie. *Koncepcja interplanetarnego Internetu IPN została zaproponowana przez NASA. W artykule omówiono strategię kontroli topologii szkieletu bazującą, na punkcie Libration. Na wstępie przeanalizowano stabilność systemu a następnie model hierarchiczny klastrów. Wreszcie analizowano przełączenie połączeń między stacjami bazowymi – handover. (**Hierarchiczna topologia klastrów w interplanetarnym Internecie**)*

Keywords: Topology control, InterPlaNetary Internet, Libration points, Hierarchical-Cluster.
Słowa kluczowe: interplanetarny Internet.

Introduction

Recently, Deep Space (DS) missions, such as human exploration missions, robotic exploration missions, and planets and its moon observing, require a robust communication architecture which could support high data rates and reliabilities [1]. In the future, the distance of exploration missions will be farther and farther, and its style will be more and more extensive, even its data rates will show that be greater and greater. The traditional Point to Point (PTP) communication links couldn't satisfy the future requirements of DS exploration. In order to transfer scientific data reliably, the National Aeronautics and Space Administration (NASA) enterprises have outlined significant challenges of development in next-generation space network architectures, which is expected to be the Internet of the deep space planetary networks and is defined as the InterPlaNetary (IPN) Internet [2, 3]. The IPN is a common, flexible communication infrastructure. It could significantly support multiple missions and reduce the overall mission costs. As shown in Fig.1, there are three essential networks in the IPN architecture, such as planetary network, access network, and backbone network [4]. In addition, the planetary network contains orbiters, vehicles (rovers, airplanes, and aero-robots), landers, and sensors which spread out on the planetary bodies. The nodes of planetary network are used to collect scientific data. The access network consists of the boundary gateway nodes, which could realize the function of "Plug in" and provide a connection to the backbone network. The backbone network has high-capacity and high-availability relay nodes which could provide extremely high data rates and "Plug in" service for all of the other networks.

In the backbone network, the topology design and backbone nodes selection become more and more important and necessary. And those issues have been solved by the Lagrangian points (also named Lagrange points, L-points, or Libration points). Lagrangian points are the five positions in an orbital configuration, where a small object affected only by gravity, so theoretically they are stationary relative to two larger objects (such as a satellite with respect to the Earth and Moon)[6]. In the Lagrangian points, an object orbit is analogous to geostationary orbit in which the object stays in "fixed" position in space. The Lagrangian point orbits have unique characteristics, which make them have a good choice for performing some kinds of missions. These missions generally orbit the points rather than occupy them directly. At the present time, the operational Lagrangian missions are Advanced Composition Explorer (ACE) of NASA, Solar and Heliospheric Observatory (SOHO) of NASA and Europe Space Agency (ESA), Wilkinson Microwave Anisotropy Probe (WMAP) of NASA, WIND of NASA and so on. In the future, more and more Lagrangian point missions will be proposed and scheduled. Therefore, it is feasible by putting spacecraft or aero-base on the Libration points and then realizing the function of backbone nodes. Here, we do some researches on the topology control strategy of IPN backbone which based on Libration points in this paper.

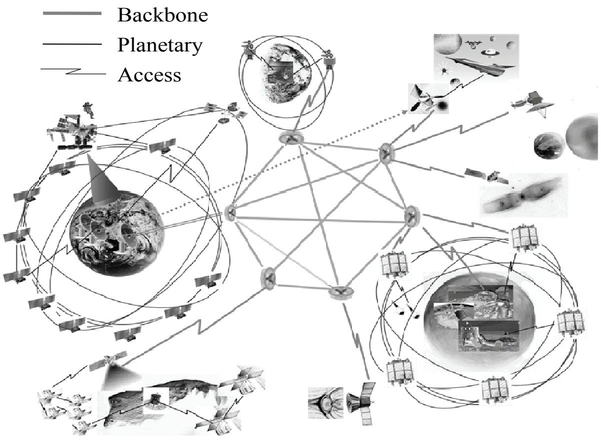


Fig.1. The architecture of IPN

Assumption of the IPN backbone network

In order to analyze the IPN backbone topology, the Libration points should be introduced into the Circled Restricted Three Body Problem (CRTBP) [9], which models the motion of a massless particle under the gravitational attraction of two punctual primaries revolving in circular orbits around their center of mass. In the CRTBP system, there are five particular solutions named Libration points. In the solar system, the basic orbital parameters of the Sun and its planets are shown in Table 1.The AU is the astronomical unit about 149.6 million km.

Table 1 Basic parameters of planets in solar system

	Distance (AU)	**Mass** (Earth's)	**Orbital Inc.**	**Orbital Ecc.**	**Density** (g/cm^3)
Sun	0	332,800	---	---	1.41
Mercury	0.39	0.05	7	0.2056	5.43
Venus	0.72	0.89	3.394	0.0068	5.25
Earth	1	1	0	0.0167	5.52
Mars	1.5	0.11	1.85	0.0934	3.95
Jupiter	5.2	318	1.308	0.0483	1.33
Saturn	9.5	95	2.488	0.056	0.69
Uranus	19.2	17	0.774	0.0461	1.29
Neptune	30.1	17	1.774	0.0097	1.64
Pluto	39.5	0.002	17.15	0.2482	2.03

From the Table 1, the orbits of each planet except of Mercury and Pluto is approximate circled around Sun in ecliptic plane, and the mass rate of planet with Sun is relative small enough, which is a representative CRTBP . Therefore, each planet has five Libration points around the Sun, no including Mercury and Pluto. By putting relay stations on those Libration points and connecting those stations, the IPN backbone sketch map is established as shown in Fig.2. The left map called big scale topology includes Jupiter, Saturn, Uranus, and Neptune, which have longer orbital periods. While the right one called small scale topology includes Mercury, Venus, Earth, and Mars, which have short orbital periods relatively.

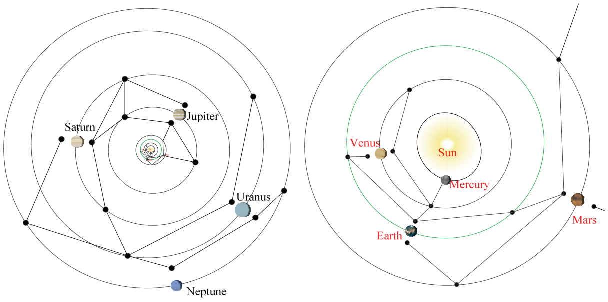


Fig.2. The sketch map of IPN backbone network

From the Fig.2, there are 30 relay nodes totally. Whereas the connecting relationship of each relay node is ruleless. As shown in Fig.3, the vast discrepancy of orbital period makes topology control more difficult. For example the revolution period of Neptune is about 165 years, but the revolution period of Venus is only one-fourth year. The long orbital period makes the whole IPN backbone topology handover times big and unpredictable.

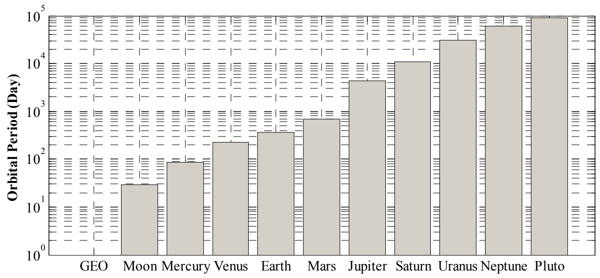


Fig.3. Orbital period comparison of the planets

In view of the factors that influence the topology control strategy, there are several key challenges as follow,

- ●Which Libration points should be chosen as relay node, and which one should be discarded;
- ●The relationship of relay nodes should be taken into account;
- ●When the relay node handover to another relay node;
- ●The total handover times.

The topology analysis of the IPN backbone network

The IPN backbone links have significantly challenging and unique characteristics that need to be addressed as follows:

- ●extremely long and variable propagation delays, from several minutes to hours;
- ●asymmetrical forward (telemeter and telecontrol data, less than kilobytes) and reverse link (videos, photos, and scientific data, more than gigabytes) capacities;
- ●high link Bit Error Rates (BER) for Radio-Frequency (RF) communication channels, long distance and great propagation loss making the high BER;
- ●intermittent link connectivity, planetary revolution, planetary rotation, and sun transit outage making link interrupt ;
- ●lack of fixed communication infrastructure;
- ●effects of planetary distances on the signal strength and the protocol design;
- ●power, mass, size, and cost constraints for communication hardware and protocol design;
- ●backward compatibility requirement due to high cost involved in deployment and launching processes.

Because of the backbone link characteristics, the traditional PTP communication is not feasible for DS future explorations. Therefore, the concept that using relay network to reduce the length of single link could enhance communication quality. Meanwhile, the long propagation delays make the nodes of IPN network move slowly when relative to the communication procedure. In conclusion, the topology of IPN backbone should be easy to design and control.

A. The location of relay node and its stability

Using the Lagrange three-body kinetic theory, we set up a Cartesian coordinate system with adequate units to analyze the motions of the third body. The coordination is descripted in Fig.4.

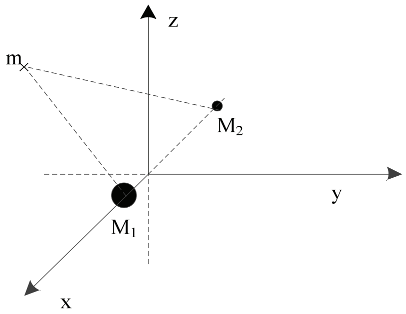


Fig.4. The Cartesian coordinate system of three-body

In this coordinate, the Newton's laws of the CRTBP are presented as follow:

$$(1)\quad \begin{cases} \ddot{X} - 2\dot{Y} = \dfrac{\partial \Omega}{\partial X} \\ \ddot{Y} + 2\dot{X} = \dfrac{\partial \Omega}{\partial Y} \\ \ddot{Z} = \dfrac{\partial \Omega}{\partial Z} \end{cases}$$

where $\Omega(X,Y,Z) = \frac{1}{2}(X^2+Y^2) + \frac{1-\mu}{r_1} + \frac{\mu}{r_2} + \frac{1}{2}\mu(1-\mu)$, $\mu = M_2/(M_1+M_2)$, $M_1 > M_2$ are the masses of the primaries, and r_1 , r_2 denote the distances from the spacecraft to the primaries M_1 and M_2 respectively: $r_1^2 = (X-\mu)^2 + Y^2 + Z^2$, $r_2^2 = (X+1-\mu)^2 + Y^2 + Z^2$.

In order to get the Libration points of the CRTBP, the ordinary differential equations associated with the system should be zero. That is to say,

$$(2)\qquad \begin{cases} \dot{X}=\ddot{X}=0 \\ \dot{Y}=\ddot{Y}=0 \\ \dot{Z}=\ddot{Z}=0 \end{cases}$$

Let (X_0, Y_0, Z_0) be the Libration point of CRTBP. So, the right hand side terms of equation (1) are zero [10]. That is,

$$(3)\qquad \begin{cases} \dfrac{\partial\Omega}{\partial X_0}=X_0-\dfrac{1-\mu}{r_1^3}(X_0-\mu)-\dfrac{\mu}{r_2^3}(X_0+1-\mu)=0 \\ \dfrac{\partial\Omega}{\partial Y_0}=Y_0-\dfrac{1-\mu}{r_1^3}Y_0-\dfrac{\mu}{r_2^3}Y_0=0 \\ \dfrac{\partial\Omega}{\partial Z_0}=-\dfrac{1-\mu}{r_1^3}Z_0-\dfrac{\mu}{r_2^3}Z_0=0 \end{cases}$$

From equation (3), the five particular solutions which also called Libration points [11] are calculated finally. The three Libration points that lay in the X-axis, are known as L_1, L_2, and L_3. The others are known as L_4 and L_5. The approximate positions of Libration points are given in equation (4).

$$(4)\qquad \begin{cases} L_1:\left[\mu-1+\left(\dfrac{\mu}{3}\right)^{1/3}-\dfrac{1}{3}\left(\dfrac{\mu}{3}\right)^{2/3},0,0\right] \\ L_2:\left[\mu-1-\left(\dfrac{\mu}{3}\right)^{1/3}-\dfrac{1}{3}\left(\dfrac{\mu}{3}\right)^{2/3},0,0\right] \\ L_3:\left[1+\dfrac{5}{12}\mu+\dfrac{237^2}{12^4}\mu^3,0,0\right] \\ L_4:\left[-\dfrac{1}{2}+\mu,-\dfrac{\sqrt{3}}{2},0\right] \\ L_5:\left[-\dfrac{1}{2}+\mu,\dfrac{\sqrt{3}}{2},0\right] \end{cases}$$

In reference [11], the Stability of Libration points is analyzed mathematically by Vila in detail. The CRTBP is a Hamiltonian system. Let $p_x=\dot{X}-Y$, $p_y=\dot{Y}-X$, and $p_z=\dot{Z}$, the Hamiltonian function is given by,

$$(5)\qquad H=\frac{1}{2}\left(p_x^2+p_y^2+p_z^2\right)+Yp_x-Xp_y-\frac{1-\mu}{r_1}-\frac{\mu}{r_2}$$

The Hamiltonian equations are given following,

$$(6)\qquad \begin{cases} \dot{X}=p_x+Y \\ \dot{Y}=p_y-X \\ \dot{Z}=p_z \\ \dot{p}_x=p_y-\dfrac{1-\mu}{r_1^3}(X-\mu)-\dfrac{\mu}{r_2^3}(X-\mu+1) \\ \dot{p}_y=-p_x-\dfrac{1-\mu}{r_1^3}Y-\dfrac{\mu}{r_2^3}Y \\ \dot{p}_z=-\dfrac{1-\mu}{r_1^3}Z-\dfrac{\mu}{r_2^3}Z \end{cases}$$

However, the CRTBP has at least one integral of the motion, known as Jacobi integral or energy level, defined as,

$$(7)\qquad C\left(X,Y,Z,\dot{X},\dot{Y},\dot{Z}\right)=2\Omega(X,Y,Z)-V^2$$

where V is the velocity of system, and $V^2=\left(\dot{X}^2+\dot{Y}^2+\dot{Z}^2\right)$. It can be proved that $C\left(X,Y,Z,\dot{X},\dot{Y},\dot{Z}\right)=-2H\left(X,Y,Z,\dot{X},\dot{Y},\dot{Z}\right)$. Let $V=0$, zero velocity curves can be calculated in Fig.5, in which the potential energy curves should be in synodic energy level C .

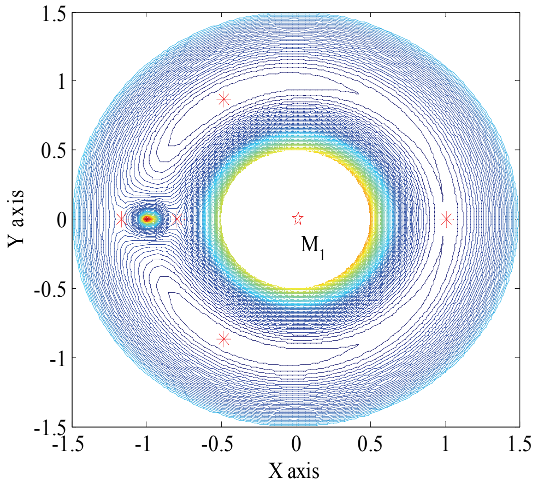
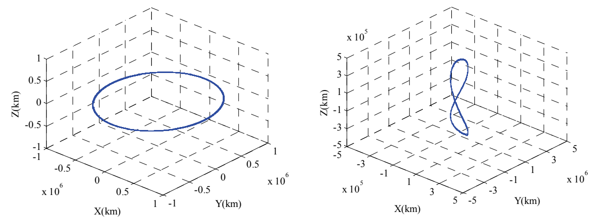
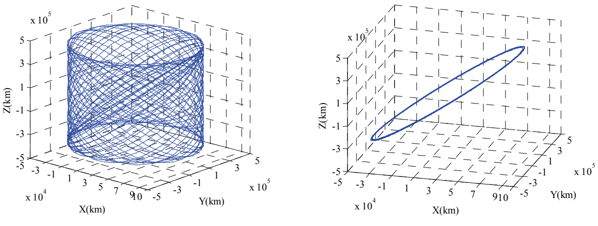


Fig.5. Energy level and zero velocity curves

From the Fig.5, the L_1, L_2, and L_3 locate in the saddle of the potential energy curves and they are unstable, while the L_4 and L_5 locate in the valley of the potential energy curves and they are stable. In order to conquer instability, the spacecraft on L_1, L_2, and L_3 should run in periodical or non-periodical orbit. As shown in Fig.6, the motion in the vicinity of L_1 and L_2 are moving in type saddle×centre×centre by using the Lindstedt-Poincarè procedures[13] and the KAM theorem[14], which include the planar Lyapunov orbit, the vertical Lyapunov orbit, Lissajous orbit, and Halo orbit[15].



(a) Planar Lyapunov orbit (b) Vertical Lyapunov orbit



(c) Lissajous orbit (d) Halo orbit.

Fig.6. Types of Libration orbits

In the Fig.6, the orbits are motions around L_1 of Sun-Earth system. When $\mu=3.0025\times10^{-6}$, the amplitude of X-axis is 50000km, and amplitude of Z-axis is 300000 km. For constructing IPN backbone nodes, the Libration points and orbits are chosen in each restrict three-body system, such as Earth-Moon, Sun-Earth, Sun-Mars, Sun-Venus, and so on.

Considering of the L_3 which is far away from planets and unstable, the L_1, L_2, L_4, and L_5 could be set as the backbone nodes. The long PTP link could be divided to several short links which relayed by Libration points to reduce propagation loss. And relay links could avoid the solar interfere when the exploring planet is on the rear of the Sun or block off by other planet.

B. Hierarchical-Cluster model of IPN backbone network

There are four Libration points to be relay node around each planet except Mercury and Pluto, and they have a stable location relationship. In order to simplify the IPN backbone topology design, the solar system is divided to seven layers according to planetary orbit. With the concept of Hierarchical-Cluster, the Libration relay nodes which have fixed links (named as Intra-Cluster Link) could be regarded as a cluster in the orbital layer. The link between clusters is called Inter-Cluster Link. To take the Mars and Earth for an example, the connection relationship of Intra-Cluster Link and Inter-Cluster Link is described in the Fig.7.

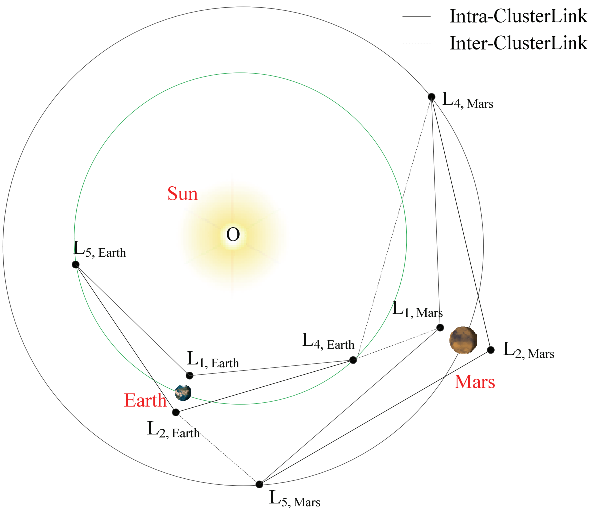


Fig.7 The connection relationship of Intra-Cluster Link and Inter-Cluster Link

As shown in the Fig.7, the full line denotes the Intra-Cluster Link, and the dotted line represents the Inter-Cluster Link. The orbital diameter of L_1 and L_2 is much smaller than the planet orbital diameter, so orbits of L_1 and L_2 could be regarded as points.

C. Links characteristic and relay theory

For analyzing the IPN backbone link, there are two assumptions: (1) the channel is Additive White Gaussian Noise (AWGN); (2) each relay node is equivalent in function.

In Ref.[18] and Ref.[19], the concept of high RF link and optical link, the concept of large, deployable antennas, such as inflatable or gossamer mesh antennas, and the concept of nuclear power, are discussed on how to provide directivity and sensitivity for supporting high rate data communications. In this paper, the Ka (32GHz) band and 20m diametric antenna are used to analyze backbone link. The receiver SNR could be calculated as follow:

$$SNR = 10\,\boldsymbol{lg}\frac{\boldsymbol{P_r}}{P_N} - L_f = 10\,\boldsymbol{lg}\frac{P_t G_t G_r / L_p}{K T_0 B} - L_f \tag{9}$$

where, P_r is receiver power, P_N is noise power, P_t is the transmitter power, $G_t = 4\pi A_e \eta / \lambda^2$ is the transmitter antenna gain, $G_r = 4\pi A_e \eta / \lambda^2$ is the receiver antenna gain, $L_p = \left(\frac{4\pi d}{\lambda}\right)^2$ is the free space loss, L_f is fading margin (including feeding line loss of transmitter and receiver about 6dB), A_e is the effective antenna area, λ is the wave length, η is the antenna efficiency (setting as 90%), d is the propagation distance, K is Boltzmann constant, T_0 is the noise temperature(set to 20K, Ref.[17]), B is equivalent noise bandwidth.

Take Earth relay and Mars relay station as an illustration, when set the equivalent bandwidth to 100MHz, the changing relation of receiver SNR varying with propagation distance is described by different P_t in Fig.8.

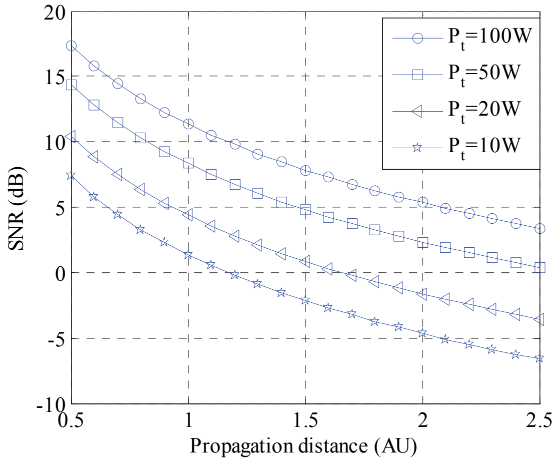


Fig.8 Receiver SNR varying with propagation distance

From the Fig.8, it can illustrate that transmitter power is 100W and propagation distance is 2.5AU, the 3dB SNR is not suit for high quality communication. When the propagation distance is 1.5AU, the 7.5dB SNR can satisfy the communication demand basically.

Using the BPSK transmitting system, the system BER p_e would be given by,

$$p_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = \frac{1}{\sqrt{\pi}}\int_{\sqrt{\frac{E_b}{N_0}}}^{\infty} e^{-t^2}\,dt \qquad \frac{E_b}{N_0} = \frac{S}{N} \bullet \frac{B}{R} \tag{10}$$

where, the B is the band width (unit: Hz), and the R is the data rate (unit: bps).

Taking the L_2 of Earth ($\mathrm{E_{L_2}}$) and L_1 of Mars ($\mathrm{M_{L_1}}$) for an example, the L_4 of Earth ($\mathrm{E_{L_4}}$) or L_5 of Earth ($\mathrm{E_{L_5}}$) can be the relay node. Total power is divided by number of relay links and each part is as the power of one relay station, so it can save the relay node power and keep total power constant. We consider the Decoding Forward (DF) relay model, and the BER could be given as,

$$p_{total} = 1 - \left(1 - p_{\mathrm{E_{L_2},E_{L_4}}}\right)\left(1 - p_{\mathrm{E_{L_4},M_{L_1}}}\right) \tag{11}$$

In this paper, the BER performance will be used to measure the link quality.

D. IPN backbone network handover index

According to the Hierarchical-Cluster model, the Intra-Cluster links are stable fixed, and does need handover. Because of the motion of planets, the handover occurs to where Inter-Cluster links changed. While all the planets have a nearly circle orbit around the Sun, the angle between connections of relay nodes and Sun is introduced into the handover time measurement.

Take the $\mathrm{E_{L_2}}$ and $\mathrm{M_{L_1}}$ for an instance, the α is angle between vector $\overrightarrow{\mathbf{OE_{L_2}}}$ and $\overrightarrow{\mathbf{OM_{L_1}}}$ as shown in Fig.9. The

α is calculated as following:

$$\alpha = arccos\left(\frac{\overrightarrow{\mathbf{OM}_{L_1}} \bullet \overrightarrow{\mathbf{OE}_{L_2}}}{\left|\overrightarrow{\mathbf{OM}_{L_1}}\right|\left|\overrightarrow{\mathbf{OE}_{L_2}}\right|}\right) \tag{13}$$

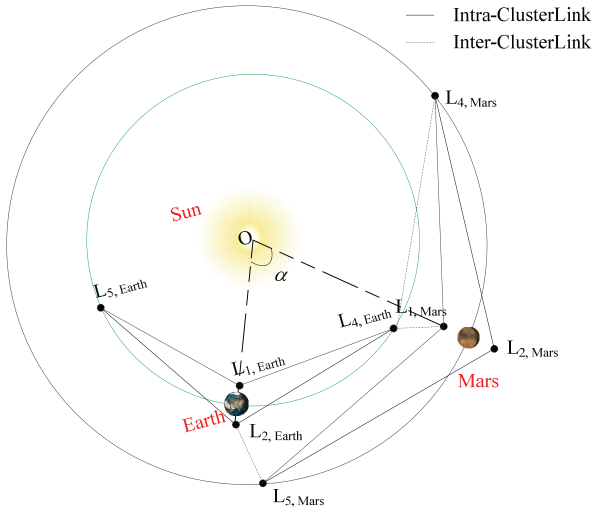


Fig.9 The sketch map of angle α

When the angle α is bigger, the Inter-Cluster Link could be interfered greater by the Sun. But when the α is nearby $\pi/3$, the relay nodes should be put in service. To reduce the handover times, the critical angle should be chosen properly in this paper.

Simulation and analysis of the handover angle

Considering the power restrict of relay nodes, the half power is transported on relay links. For the optimal handover boundary, the BER performance of direct link and half power relay link is contracted along with the angle α as shown in Fig.10.

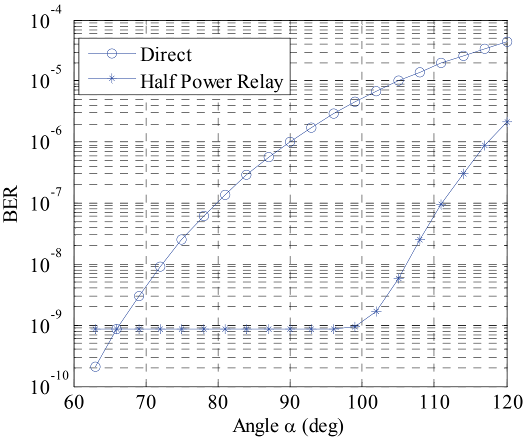


Fig.10 The BER performance curves of direct and half power relay link along with α

From the Fig.10, the critical angle could be easy to get as 65.96Deg in the cross of two BER performance curves. If the α is greater than the critical angle, the BER performance of half relay link is more superior to the direct link. Therefore, the α could be the handover criterion of IPN backbone Inter-Cluster Links.

According to the handover criterion, the topology handover opportunity could be easy to get. When the angle of E_{L_2} and M_{L_1} is as initial α and the connection of all Inter-Cluster Links is considered, the link pairing strategy of Earth and Mar cluster is analyzed as shown in Table 2.

Table 2 The link pairing strategy of Earth and Mars cluster

Handover angle (Deg)	Link status
5.96 ~ 54.04	(E_{L_5}, M_{L_5}) , (E_{L_5}, M_{L_1}) , (E_{L_2}, M_{L_1}) , (E_{L_2}, M_{L_4}), (E_{L_4}, M_{L_4})
54.04 ~ 65.96	(E_{L_5}, M_{L_1}) , (E_{L_5}, M_{L_4}) , (E_{L_2}, M_{L_1}) , (E_{L_2}, M_{L_4}), (E_{L_4}, M_{L_4})
65.96 ~ 125.96	(E_{L_5}, M_{L_1}), (E_{L_5}, M_{L_4}), (E_{L_2}, M_{L_4})
125.96 ~ 180	(E_{L_5}, M_{L_1}), (E_{L_5}, M_{L_4})
180 ~ 234.04	(E_{L_4}, M_{L_5}), (E_{L_4}, M_{L_1})
234.04 ~ 294.04	(E_{L_2}, M_{L_5}), (E_{L_4}, M_{L_5}), (E_{L_4}, M_{L_1})
294.04 ~ 305.96	(E_{L_5}, M_{L_5}) , (E_{L_2}, M_{L_5}) , (E_{L_2}, M_{L_1}) , (E_{L_4}, M_{L_5}), (E_{L_4}, M_{L_1})
305.96 ~ 354.04	(E_{L_5}, M_{L_5}) , (E_{L_2}, M_{L_5}) , (E_{L_2}, M_{L_1}) , (E_{L_4}, M_{L_1}), (E_{L_4}, M_{L_4})
354.04 ~ 360 0 ~ 5.96	(E_{L_5}, M_{L_5}) , (E_{L_5}, M_{L_1}) , (E_{L_2}, M_{L_5}) , (E_{L_2}, M_{L_1}) , (E_{L_2}, M_{L_4}) , (E_{L_4}, M_{L_1}) , (E_{L_4}, M_{L_4})

According to the orbital period of Mars and Earth as shown in Fig.3, the period of Earth compared with Mars could be calculated as following,

$$T_R = \frac{T_E \bullet T_M}{T_M - T_E} \tag{12}$$

where, the T_E is the orbital period of Earth, the T_M is the orbital period of Mars. And then the associated moment of angle α could be given,

$$T_\alpha = T_R \bullet \frac{\alpha}{360} \tag{13}$$

The T_E indicates that the Earth runs a full period relative to Mars, and nine times of handover occurs. The handover moments could be easily gotten by formula (10), the shortest handover interval is 25.8 days. The sketch map of handover along with time is shown in Fig.11.

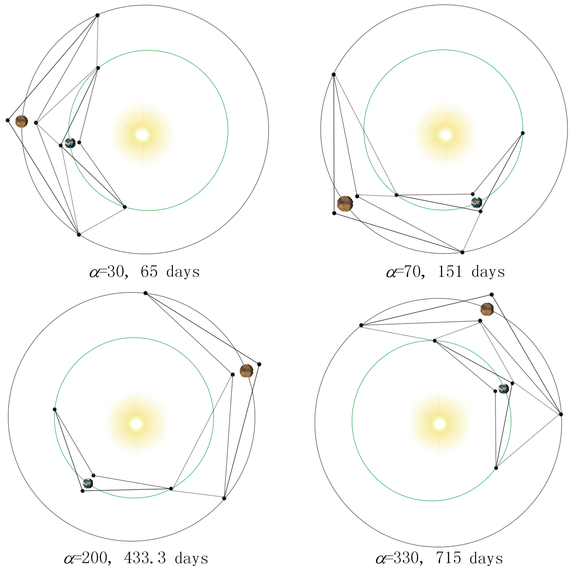

α=30, 65 days
α=70, 151 days
α=200, 433.3 days
α=330, 715 days

Fig.11 The connection relationship of Mars and Earth cluster when α=30,70,200,330

Then, the other planets cluster is simulated in different initial conditions. Considering Mars to Jupiter cluster and

Jupiter to Saturn cluster, the transmitter bandwidth is reduced to 10MHz for the BER increase. And considering Saturn to Uranus cluster and Uranus to Neptune cluster, the transmitter bandwidth is reduced to 1MHz for counteracting the bigger space loss. The simulation results are shown in Fig.12, from which the optimal handover angles could be easily gotten.

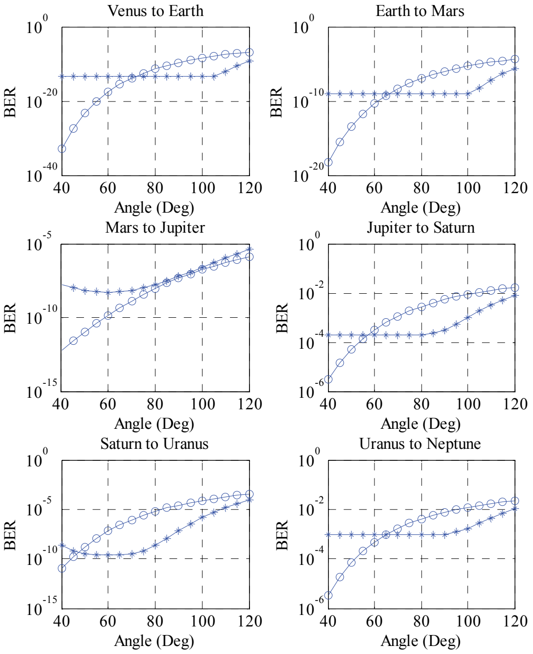


Fig.12 The comparison performance curves of adjacent clusters

When the small scale cluster (Mars cluster) is communicating with the big scale cluster (Jupiter cluster), the relay station of big scale cluster node is much farther than that of small scale cluster node, so the half power relay strategy may not have dominance with the direct links. Thus, the performance curve of between Mars and Jupiter cluster does not have any cross points, and the performance of between relay strategy and direct link have similar BER when the angle is more than 80Deg as shown in Fig.12. Considering of centralized and unified control of IPN backbone topology, the handover angle of Mars to Jupiter cluster is set 80Deg. The critical angles of clusters pairs and the relative periods of each cluster pairs are calculated immediately as shown in Table 3.

Table 3 The critical angle of adjacent clusters

Cluster pair	Venus to Earth	Earth to Mars	Jupiter to Saturn	Saturn to Uranus	Uranus to Neptune
Critical angle (Deg)	71.39	65.9	57	47.2	64.85
Relative period (days)	585.11	777.85	7268.7	16584.2	62483.6

Compared with handover times of Earth to Mars cluster, each cluster pair has nine handover times in a relative period. The total handover times could be easily gotten as 2491 topology tables in one relative period of Uranus to Neptune cluster.

Conclusion

In order to reduce the influence of big propagation loss in traditional DS exploration, the concept of IPN is introduced by setting up several relay nodes. In this paper, the topology control strategy of IPN backbone network is analyzed in detail. By placing relay nodes on L_1, L_2, L_4, and L_5 and connecting them together, the IPN backbone network is deployed. To simply the topology control strategy, the Hierarchical-Cluster theory is introduced, and the backbone links are divided into two types, the Intra-Cluster Links and Inter-Cluster Links. To analyze the optimal handover moment, a handover index named angle α is introduced. Furthermore, the optimal critical angle is calculated by comparing the BER performances of half relay link and direct link. Finally, total handover times are gotten as 2491 topology tables in one relative period of Uranus to Neptune cluster.

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