Study on the Two-Sides Matching between Multiple Rovers and Multiple Orbiters in Mars Relay Communications

Peng Wan[1,2], Yafeng Zhan[1,2,*]

[1] Space center, Tsinghua University, Beijing 100084, China
[2] Beijing National Research Center for Information Science and Technology (BNRist), Beijing 100084, China
* The corresponding author, email: zhanyf@tsinghua.edu.cn

Abstract: In Mars relay communications, if multiple rovers and multiple orbiters are visible with each other at the same time in certain contact, there are not only issues concerned with the multiple rovers' access to single orbiter, but also the issues concerned with the optimal access orbiter selection for each rover, which is a complex multi-objective decision-making problem relating to the resource allocation optimizations in deep-space networks. In this paper, the two-sides matching between multiple rovers and multiple orbiters in Mars relay communications is proposed based on the access preferences, taking the two-sides combined fitness of preferences and the single-side evaluation equilibrium as the optimization objectives, which utilizes the parallel capsule operations architecture encapsulated with several one-to-many two-sides matching algorithms to obtain stable multiple access matching results. Simulation results show that, our method performs better than the CCSDS Proximity-1 protocols, and could achieve the effective utilization of deep space communication network resources.

Keywords: Mars relay communications; multiple access; resource allocation optimizations; fitness of preference; two-sides matching

Received: Feb. 24, 2020
Revised: Apr. 18, 2020
Editor: Kanglian Zhao

I. INTRODUCTION

With the steady progress of China's independent Mars exploration mission, Mars exploration activities become an essential development stage of China's deep space exploration project in the future. The most important mission is to deploy a rover on the surface of Mars for scientific exploration and sample sampling, and send the field data back to Earth for analysis. It is beneficial to make full use of the existing ESA's orbiters and China's orbiters to provide the effective and reliable cooperative access services for rovers affiliated to both agencies with optimal resource allocations in Mars relay communications.

As described in reference [1], in the long-distance communication scenario between Earth and Mars, limited by the power constraint and the worse signal propagation environment, the Mars surface rovers could only transmit a small amount of telemetry data (several bits per second) to Earth. In order to further improve the data transmission capacity, NASA and ESA have been using the Mars orbiter relay technology in their Mars exploration missions, such as Mars reconnaissance orbiter (MRO) [2], Mars express (MEX)

[3], Mars Odyssey (ODY) [4], etc. CCSDS Proximity-1 space link protocol [5]~[8] is a recommended standard for relay communication between orbiters and rovers proposed by the Consultative Committee for Space Data Systems (CCSDS). Both the Electra units on current orbiters and Electra Lite units on current rovers are equipped with CCSDS Proximity-1 protocol to perform Mars relay communication services. According to the preliminary negotiation with ESA, China plans to adopt CCSDS Proximity-1 protocol for the relay communication equipment installed on the rovers and orbiters, which is capable of interconnecting with the ESA's Mars explorers. Furthermore, in future potential manned Mars exploration missions, there would be multiple rovers/astronauts and orbiters of international space agencies and aerospace enterprises to cooperate with each other to achieve complex scientific exploration activities, such as NASA, ESA, JAXA, RKA, SpaceX [9], etc. Therefore, not only the orbiters of China could provide the data relay service for other agencies' Mars surface activities, but also the rovers/astronauts of China could get access to the orbiters of other agencies for the data relay service support, which enhances the access probabilities and improves the data transmission for all the cooperation agencies with significant benefits.

With the development of deep space exploration missions in the future, there would be more and more deep space rovers and other facilities on the Mars surface. The flexible and efficient access technology is the powerful support for the deep space missions. Current CCSDS Proximity-1 protocol could not provide multiple access services for the rovers working in the neighbor regions, which limits the scientific benefits of Mars exploration mission. In order to provide the multiple access services in Mars relay communications, the optimization method based on the multiple attribute decision making (MADM) [10] is studied with the CCSDS Proximity-1 protocols as the baseline, taking into account the fairness, throughput, queue balance, transmission distance, storage space and other technical indicators.

The multiple access relationships between orbiters and rovers in the common view period could be classified into following four parts:

1) Single rover accessing to single orbiter: As the main mission mode for a space agency to independently carry out Mars exploration activities, CCSDS Proximity-1 protocol should still be used with the access control strategy as "single access, first come first served, & random back-off". On the one hand, it can avoid the upgrading risks due to the increased system complexity; on the other hand, it can be compatible with existing proximity link access technology to provide cooperative services.

2) Multiple rovers accessing to single orbiter: the multiple access optimization has been studied in reference [11] with the design of proportional fair scheduling algorithm based on queue equilibrium, in which the queue length is introduced into the traditional proportional fair scheduling algorithm as a trade-off factor, with the best comprehensive performance in fairness, throughput and queue equilibrium. Operating such algorithm on different orbiters in turn, each orbiter's access preference list to the common view rovers could be calculated.

3) Single rover accessing to multiple orbiters: the optimal selection has been studied in reference [12] based on improved Hotelling oligopoly game theory, in which both the proximity link distance and the orbiters' storage status are introduced into the system model with minimum system cost on unit transmission capacity compared with other algorithms. Operating such algorithm on different rovers in turn, each rover's access preference list to the common view orbiters could be calculated.

4) Multiple rovers accessing to multiple orbiters: if multiple orbiters and multiple rovers are visible at the same time in the common view period, given the orbiters' and rovers' access preferences respectively obtained by the previous research, the two-sides matching between multiple rovers and multiple orbiters in Mars relay communications is proposed, taking the two-sides combined fitness of pref-

In this paper, the two-sides matching between multiple rovers and multiple orbiters in Mars relay communications based on the access preferences is studied.

erences and the single-side evaluation equilibrium as the optimization objectives, which utilizes the alternative optimization under the parallel operations on several one-to-many two-sides matching algorithms to obtain stable multiple access matching results.

In this paper, 'rover' is related to the Mars surface rover, which could extend to all the extraterrestrial planets' facilities on surface; 'orbiter' is related to the Mars orbiter, which could extend to all the extraterrestrial planets' orbiters. Section II introduces the system model in the Mars relay communication resource allocation issues, including two-sides matching model, evaluation factors, and optimal objectives. Section III analyzes the CCSDS Proximity-1 access performance and describes our optimization method with the parallel operations on several one-to-many two-sides matching algorithms. Simulation results are provided in section IV, along with the performance comparison between the CCSDS Proximity-1 and our new designed method. Section V concludes this paper.

II. SYSTEM MODEL

2.1 Two-sides matching

In many to many relationships between the resource suppliers and demanders, the combination optimization method can usually be used to obtain the best resource allocation scheme under the centralized management mode, such as space TT&C resource allocation. However, for common resource allocation issues in the social and economic life, which is concerned with the two-way selection between the resource suppliers and demanders, it is impossible to rely on the third-party institutions for decision-making and resource distribution. Therefore, the game theory should be introduced to solve such issues properly.

Two-sides matching theory [13] is a branch of economics, which was first studied and proposed by two American mathematicians David Gale and Lolyd Shaplev in 1962 in order to solve such problems as mate matching, factory recruitment and college admission, which have also been widely used for the multiple user access and resource allocation in wireless communication and satellite communications [14]~[17]. "Two-sides" refers to the participants belong to two exclusive sets in the matching such as unmarried men and women, factories and workers, colleges and students. "Matching" refers to the essence of the game between the two sets, which means to select the proper couple according to "preference list" [18].

In Mars relay communications, the participants consists of N orbiters and M rovers, which could be marked as two exclusive sets ORB and ROV respectively. One matching is a mapping from the rovers subset to the orbiter, which determines the each rover's desired orbiter, each orbiter's accepted rovers, and unmatched pairs of rovers and orbiters. A matching is stable, which means that each participant's matching couple is acceptable, and there is no pair of unmatched participants who prefer to match each other.

Two-sides matching could be divided into three types as 'one-to-one', 'one-to-many' and 'many-to-many'. In Mars relay communications, each orbiter could accept multiple rovers, but each rover could only access to one orbiter, which is similar to the labor market, so it is a typical 'one-to-many' two-sides matching issue [19]. The definitions of 'one-to-many' two-sides matching in Mars relay communications are listed as follows.

Definition 1: Matching

One matching FIT is a mapping from set $ORB \cup ROV$ to all the subset of set $ORB \cup ROV$, satisfying that for all N orbiters $s \in ORB$ and all M rovers $r \in ROV$:

(1) $FIT(r) \in ORB \cup \{\varnothing\}, FIT(s) \subseteq ROV$;

(2) $s = FIT(r) \Leftrightarrow r \in FIT(s)$.

Condition (1) shows that FIT is a mapping which indicates the matching relationships between the orbiters subset and the rovers subset, that is, rover r could match with at most one rover, orbiter s could match with no less than one rover. Condition (2) shows the relationship of each matching couples, that is, the fit of rover r access to orbiter s is equivalent to the fit of the rover accepted by the orbiter s as one of its preference couples.

Each orbiter $s \in ORB$ has a complete, strict and transitive preference $P(s)$ on ROV, described as $P(s)=\{r_1,r_2,\ldots,r_M\}$. If s could select preferred rovers on ROV, then the first choice is r_1; if r_1 has accessed to one of other orbiters, then s could select the second preferred r_2; if there are more than one rovers applied to access at the same round, then s could select the most preferred rovers according to its preference order with the access quota. $rP(s)r'$ means s prefers r to r', that is, if r and r' apply to access to s at the same round, then s could select the most preferred r; $rR(s)r'$ means s inclines to r no less than r', that is, if r and r' apply to access to s at the same round, then s could select r or any one of them. This paper assumes that any rover $r \in ROV$ is the accepted couple for each orbiter $s \in ORB$, described as $rR(s)\varnothing$.

Similarly, each rover $r \in ROV$ has a complete, strict and transitive preference $P(r)$ on ORB, described as $P(r)=\{s_1,s_2,\ldots,s_N\}$. If r could select preferred orbiter on ORB, then the first choice is s_1. $sP(r)s'$ means r prefers s to s'; $sR(r)s'$ means r inclines to s no less than s'. This paper assumes that any orbiter $s \in ORB$ is the accepted couple for each rover $r \in ROV$, described as $sR(r)\varnothing$.

$P=\{P(s),s\in ORB\}\oplus\{P(r),r\in ROV\}$ is the preference bundle concerned with all the participants in Mars relay communications. Given a rovers subset $R \in ROV$ and a preference bundle, any orbiter s could determine the most preferred rover subset $C_s(R)$ on R, called the selection set of orbiter s on R. Then $C_s(R)\subseteq R$, and for any $R'\subseteq R$ there exists $C_s(R)R(s)R'$.

Definition 2: Stable matching

If a matching FIT satisfies following two conditions, then such FIT could be seemed as a stable matching.

(1) For all participants, $k\in ORB\cup ROV$, $FIT(k)R(k)\varnothing$;

(2) For all orbiters, $s\in ORB, C_s(FIT(s)) = FIT(s)$.

A key point of two-sides matching is to verify whether there is a stable match in game. Gale and Shapley have proved that there must be a stable matching if both sides of the game were of strict preferences on the other side's preference list. Based on the results of reference [11] and [12], both the orbiter's preference list on rovers and the rover's preference list on orbiters are strict preferences, therefore the two-sides matching between multiple rovers and multiple orbiters in Mars relay communications is a stable matching.

2.2 Evaluation criterion

In this paper, the Fitness of Preference (FoP) is used to evaluate two-sides matching performance, which could provide the quantitative evaluation on the resource allocation results for all the participants with their respective preference list. The calculation procedure could be seen as follows.

2.2.1 Weight vector

Each participant (rover/orbiter) assigns the elements in its preference list with the value related to their priority to obtain the corresponding weight vector, in which:

- The weight vector of the i-th orbiter $\boldsymbol{W}_i=\left[rover_{i,1}->(1/2)^1,\ldots,rover_{i,m_i}->(1/2)^{m_i},\ldots,rover_{i,M_i}->(1/2)^{M_i}\right]$, where $i=1,2,\ldots,N$ is the identify number of each orbiter, N is the number of all the orbiters, $m_i=1,2,\ldots,M_i$ is the sequence of each rover in the i-th orbiter's preference list, M_i is the access quota of i-th orbiter, and $rover_{i,m_i}$ is the rover ranked m_i in the i-th orbiter's preference list with the weight as $(1/2)^{m_i}$.
- The weight vector of j-th rover $\boldsymbol{W}_j=\left[orbiter_{j,1}->(1/2)^1,\ldots,orbiter_{j,n_j}->(1/2)^{n_j},\ldots,orbiter_{j,N_j}->(1/2)^{N_j}\right]$, where $j=1,2,\ldots,M$ is the identify number of each

rover, M is the number of all the rovers, $n_j = 1,2,\ldots,N_j$ is the sequence of each orbiter in the j-th rover's preference list, N_j is the access quota of j-th rover, and $orbiter_{j,n_j}$ is the orbiter ranked n_j in the j-th rover's preference list with the weight as $(1/2)^{n_j}$.

2.2.2 Evaluation value of optimal matching

Each participant (rover/orbiter) sum its weight vector to obtain the evaluation value of optimal matching, then:

- Evaluation value of optimal matching of i-th orbiter: $FoP_i^{(opt)} = \sum_{m_i=1}^{M_i}(1/2)^{m_i}$;
- Evaluation value of optimal matching of j-th rover: $FoP_j^{(opt)} = \sum_{n_j=1}^{N_j}(1/2)^{n_j}$.

For the one-to-many two-sides matching issues in Mars relay communications, each rover only access to one orbiter with $N_j = 1$, so that the evaluation value of optimal matching of each rover is 1/2.

2.2.3 Evaluation value of real matching

Get the real allocation result through two-sides matching algorithms, and calculate the evaluation value of real matching based on corresponding weight vector, then:

- Evaluation value of real matching of i-th orbiter could be shown as equation (1),

$$\begin{aligned} FoP_i^{(real)} &= \sum_{\hat{m}_i=1}^{\hat{M}_i} \boldsymbol{W}_i\left(rover_{i,\hat{m}_i}\right) \\ &= \sum_{\hat{m}_i=1}^{\hat{M}_i}(1/2)^{seq\left(rover_{i,\hat{m}_i}\right)}, \end{aligned} \tag{1}$$

where, $\hat{m}_i = 1,2,\ldots,\hat{M}_i$ is the sequence of rover access to the i-th orbiter, $\hat{M}_i$ is the number of real matching rovers access to the i-th orbiter with $\hat{M}_i \le M_i$, $rover_{i,\hat{m}_i}$ is the identify number of the rover with access sequence $\hat{m}_i$ to i-th orbiter, $seq(x)$ is the function to obtain the priority of variable x in the desired preference list, so that $seq\left(rover_{i,\hat{m}_i}\right)$ obtains the priority of $rover_{i,\hat{m}_i}$ in the i-th orbiter's preference list.

- Evaluation value of real matching of j-th rover could be shown as equation (2),

$$\begin{aligned} FoP_j^{(real)} &= \sum_{\hat{n}_j=1}^{\hat{N}_j} \boldsymbol{W}_j\left(orbiter_{j,\hat{n}_j}\right) \\ &= \sum_{\hat{n}_j=1}^{\hat{N}_j}(1/2)^{seq\left(orbiter_{j,\hat{n}_j}\right)}, \end{aligned} \tag{2}$$

where, $\hat{n}_j = 1,2,\ldots,\hat{N}_j$ is the sequence of orbiter access to the j-th rover, $\hat{N}_j$ is the number of real matching orbiters access to the j-th rover with $\hat{N}_j \le N_j$, $orbiter_{j,\hat{n}_j}$ is the identify number of the orbiter with access sequence $\hat{n}_j$ to j-th rover, $seq\left(orbiter_{j,\hat{n}_j}\right)$ obtains the priority of $orbiter_{j,\hat{n}_j}$ in the j-th rover's preference list.

For the one-to-many two-sides matching issues in Mars relay communications, each rover only access to one orbiter with $N_j = 1$. In the real resource allocations with the common constraints as $N < M$, each rover could access to at most one orbiter, that is, $\hat{N}_j = 0$ *or* 1. The evaluation value of real matching of j-th rover could be simplified as equation (3):

$$\begin{aligned} FoP_j^{(real)} &= \hat{N}_j \cdot (1/2)^{seq\left(orbiter_{j,1}\right)} \\ &= \begin{cases} (1/2)^{seq\left(orbiter_{j,1}\right)} \le 1/2 & \hat{N}_j = 1 \\ 0 & \hat{N}_j = 0 \end{cases}. \end{aligned} \tag{3}$$

2.2.4 Single-side fitness of preference

With the evaluation value of optimal and real matching, the single-side fitness of preference for the orbiters and rovers subset could be calculated.

- Single-side fitness of preference for the orbiters subset is shown in equation (4),

$$\begin{aligned} FoP_{orbiter} &= \frac{\sum_{i=1}^{N} FoP_i^{(real)}}{\sum_{i=1}^{N} FoP_i^{(opt)}} \\ &= \frac{\sum_{i=1}^{N}\sum_{\hat{m}_i=1}^{\hat{M}_i}(1/2)^{seq\left(rover_{i,\hat{m}_i}\right)}}{\sum_{i=1}^{N}\sum_{m_i=1}^{M_i}(1/2)^{m_i}}. \end{aligned} \tag{4}$$

From equation (4), the single-side fitness of preference for the orbiters subset equals to the sum of all the orbiters' evaluation values of real matching $FoP_i^{(real)}$ divided by the sum of all the orbiters' evaluation values of optimal matching $FoP_i^{(opt)}$, ranged in [0,1]. Value '0' indicates no rover access, which should be avoided in space missions. Value '1' indicates the optimal matching of orbiters subset with resource allocation optimizations. The optimal result is not only related to the access preference of the rover, but also depends on the correlation between the preference lists of the orbiters.

- Single-side fitness of preference for the rovers subset is shown in equation (5),

$$FoP_{rover}=\frac{\sum_{j=1}^{M}FoP_j^{(real)}}{\sum_{j=1}^{M}FoP_j^{(opt)}}=\frac{\sum_{j=1}^{M}\hat{N}_j\cdot(1/2)^{seq(orbiter_{j,1})}}{(1/2)\cdot M},\quad \hat{N}_j=0,1. \tag{5}$$

From equation (5), the single-side fitness of preference for the rovers subset equals to the sum of all the rovers' evaluation values of real matching $FoP_j^{(real)}$ divided by the sum of all the rovers' evaluation values of optimal matching $FoP_j^{(opt)}$, ranged in [0,1]. Value '0' means all the rovers could not access to any orbiter, which should be avoided in space missions. Value '1' means all the rovers access to their most preferred orbiter, which depends on whether the access capacities of the orbiter are sufficient.

2.3 Optimization objectives

2.3.1 Two-sides combined fitness of pReferences

In order to evaluate the resource allocation results at the system level, the mission planner could obtain the two-sides combined fitness of preferences $FoP_{two\text{-}sides}$ by the weighted sum of the single-side fitness of preferences for the orbiters subset $FoP_{orbiter}$ and rovers FoP_{rover} with their inclination, ranged in (0,1). The weights of orbiters and rovers are marked as α and β respectively, with the relationship as β = (1-α) and default values as $\alpha=\beta=0.5$. The calculation equation of $FoP_{two\text{-}sides}$ is shown as follows:

$$FoP_{two-sides}=\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}. \tag{6}$$

$FoP_{two\text{-}sides}$ could be used to evaluate the global performance of the matching results, the larger the value, the higher the overall fitness of preference, which could improve the resource allocation efficiency. Equation (7) gives the optimal objective function.

$$\begin{aligned}&\{rover_{i,\hat{m}_i}\},\{orbiter_{j,\hat{n}_j}\}\\&=\underset{\{rover_{i,\hat{m}_i}\}^*,\{orbiter_{j,\hat{n}_j}\}^*}{\arg\max}\{FoP_{two-sides}\}\\&=\underset{\{rover_{i,\hat{m}_i}\}^*,\{orbiter_{j,\hat{n}_j}\}^*}{\arg\max}\{\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}\}\\&=\underset{\{rover_{i,\hat{m}_i}\}^*,\{orbiter_{j,\hat{n}_j}\}^*}{\arg\max}\left\{\alpha\cdot\frac{\sum_{i=1}^{N}\sum_{\hat{m}_i=1}^{\hat{M}_i}(1/2)^{seq(rover_{i,\hat{m}_i})}}{\sum_{i=1}^{N}\sum_{m_i=1}^{M_i}(1/2)^{m_i}}\right.\\&\left.+\beta\cdot\frac{\sum_{j=1}^{M}\hat{N}_j\cdot(1/2)^{seq(orbiter_{j,1})}}{(1/2)\cdot M}\right\}.\end{aligned} \tag{7}$$

2.3.2 Single-side evaluation equilibrium

In order to evaluate the matching equilibrium between the rovers and orbiters, the single-side evaluation equilibrium based on the two-sides combined fitness of preferences could be further calculated, ranges in (-1,1). The calculation procedures are described as follows:

- Ratio of orbiter subset's contribution to the two-sides combined fitness of preferences:

$$Ratio_{orbiter}=\frac{\alpha\cdot FoP_{orbiter}}{FoP_{two-sides}}=\frac{\alpha\cdot FoP_{orbiter}}{\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}}; \tag{8}$$

- Ratio of rover subset's contribution to the two-sides combined fitness of preferences:

$$Ratio_{rover}=\frac{\beta\cdot FoP_{rover}}{FoP_{two-sides}}=\frac{\beta\cdot FoP_{rover}}{\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}}; \tag{9}$$

- Single-side evaluation equilibrium is shown as follows:

$$Ratio_{two-sides}=Ratio_{orbiter}-Ratio_{rover}=\frac{\alpha\cdot FoP_{orbiter}-\beta\cdot FoP_{rover}}{\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}}. \tag{10}$$

$Ratio_{two\text{-}sides}$ could be used to evaluate the difference between single-side evaluation of rovers and orbiters. The plus-minus of $Ratio_{two\text{-}sides}$ indicates the side with comparative advantages, that is, the plus value is beneficial to orbiters subset, and the minus value is beneficial to rovers subset. The absolute value of $Ratio_{two\text{-}sides}$ indicates the equilibrium of resource allocation, that is, smaller absolute value is beneficial to the access fairness in Mars relay communications. Equation (11) gives the optimal objective function.

$$\begin{aligned}&\left\{rover_{i,\hat{m}_i}\right\},\left\{orbiter_{j,\hat{n}_j}\right\}\\&=\underset{\left\{rover_{i,\hat{m}_i}\right\}^*,\left\{orbiter_{j,\hat{n}_j}\right\}^*}{\arg\min}\left\{\left|Ratio_{two-sides}\right|\right\}\\&=\underset{\left\{rover_{i,\hat{m}_i}\right\}^*,\left\{orbiter_{j,\hat{n}_j}\right\}^*}{\arg\min}\left\{\frac{\left|\alpha\cdot FoP_{orbiter}-\beta\cdot FoP_{rover}\right|}{\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}}\right\}.\end{aligned} \tag{11}$$

III. Matching Algorithms

3.1 CCSDS Proximity-1 protocol

CCSDS Proximity-1 protocol works in single access mode, in which one orbiter could only be matched with one rover, and the competitive access mechanism is first come first served, random back-off.

- Evaluation value of optimal matching

Due to the single access mode, each orbiter could only be matched with one rover, $M_i=1$, therefore any orbiter's evaluation value of optimal matching is 1/2, $FoP_i^{(opt)}=1/2$; each rover could only be matched with one orbiter, $N_j=1$, therefore any rover's evaluation value of optimal matching is 1/2, $FoP_j^{(opt)}=1/2$.

- Statistical mean of real matching

Due to the competitive access mechanism as 'first come first served, random back-off', the probability of access application for each orbiter is evenly distributed as $1/M$; the number of real access rovers is $\hat{M}_i=1$. The statistical mean of real matching for *i*-th orbiter is,

$$\begin{aligned}FoP_i^{(real)}&=\sum_{j=1}^{M}(1/M)\cdot(1/2)^j\\&=(1/M)\cdot\left(1-(1/2)^M\right).\end{aligned} \tag{12}$$

Due to the competitive access mechanism as 'first come first served, random back-off' of CCSDS Proximity-1 protocol, the theoretical probability of each rover's access to certain orbiter is evenly distributed as $1/N$; the number of real matching orbiters is $\hat{N}_j=0\ or\ 1$ with the matching probability as $N/M\ (N<M)$, then we could obtain the jointed probability of each rover's real access to certain orbiter as $(1/N)\cdot(N/M)=1/M$. The statistical mean of real matching for *j*-th rover is,

$$\begin{aligned}FoP_j^{(real)}&=\sum_{i=1}^{N}(1/M)\cdot(1/2)^i\\&=(1/M)\cdot\left(1-(1/2)^N\right).\end{aligned} \tag{13}$$

- Statistical mean of single-side fitness of preference

The statistical mean of single-side fitness of preference for orbiters is shown as equation (14),

$$\begin{aligned}FoP_{orbiter}&=\frac{\sum_{i=1}^{N}FoP_i^{(real)}}{\sum_{i=1}^{N}FoP_i^{(opt)}}\\&=\frac{\sum_{i=1}^{N}(1/M)\cdot\left(1-(1/2)^M\right)}{\sum_{i=1}^{N}(1/2)}\\&=\frac{2\cdot\left(1-(1/2)^M\right)}{M}.\end{aligned} \tag{14}$$

The statistical mean of single-side fitness of preference for rovers is shown as equation (15),

$$\begin{aligned}FoP_{rover}&=\frac{\sum_{j=1}^{M}FoP_j^{(real)}}{\sum_{j=1}^{M}FoP_j^{(opt)}}\\&=\frac{\sum_{j=1}^{M}(1/M)\cdot\left(1-(1/2)^N\right)}{\sum_{j=1}^{M}(1/2)}\\&=\frac{2\cdot\left(1-(1/2)^N\right)}{M}.\end{aligned} \tag{15}$$

- Statistical mean of two-sides combined fitness of preferences:

$$\begin{aligned}&FoP_{two-sides}=\alpha\cdot FoP_{orbiter}+\beta\cdot FoP_{rover}\\&=2\alpha\cdot\frac{1-(1/2)^M}{M}+2\beta\cdot\frac{1-(1/2)^N}{M}\\&=\frac{2(\alpha+\beta)-2\alpha\cdot(1/2)^M-2\beta\cdot(1/2)^N}{M}\Big|_{\substack{\alpha+\beta=1\\M,N>>1}}\\&\to\frac{2}{M}.\end{aligned} \tag{16}$$

If $\alpha=\beta=0.5$, $N=4$, $M=8$, then $FoP_{two\text{-}sides}$ = 0.2416.

- Statistical mean of single-side evaluation equilibrium:

$$
\begin{aligned}
Ratio_{two-sides} &= Ratio_{orbiter} - Ratio_{rover} \\
&= \frac{\alpha \cdot FoP_{orbiter} - \beta \cdot FoP_{rover}}{\alpha \cdot FoP_{orbiter} + \beta \cdot FoP_{rover}} \\
&= \frac{(\alpha - \beta) + \beta \cdot (1/2)^N - \alpha \cdot (1/2)^M}{(\alpha + \beta) - \alpha \cdot (1/2)^M - \beta \cdot (1/2)^N} \\
&= \frac{\beta \cdot (1/2)^N - \alpha \cdot (1/2)^M}{(\alpha + \beta) - \alpha \cdot (1/2)^M - \beta \cdot (1/2)^N} \Big|_{\alpha=\beta} .
\end{aligned}
\tag{17}
$$

If $\alpha = \beta = 0.5$, $N = 4$, $M = 8$, then $Ratio_{two\text{-}sides}$ = 0.0303, close to 0, which indicates that CCSDS Proximity-1 protocol performs well in the single-side evaluation equilibrium.

3.2 Two-sides matching based on parallel capsule operations

In this paper, a new 'two-sides matching' based on parallel capsule operations is proposed. Given the preference lists of all the participants (rovers/orbiters), our algorithm utilizes several potential capsule algorithms to solve stable matching solutions concurrently, evaluates matching results by the fitness of preference, and determines optimal matching results according to corresponding optimization objectives.

3.2.1 Potential capsule algorithms

The widely used two-side matching algorithms which could be chosen as the potential capsule algorithms include Boston mechanism [20], Defer-Accept algorithm [13], and Top-Trading Cycles algorithm [21]. In Mars relay communications, the basic steps and comparisons of such mechanism are listed as follows.

a) Boston mechanism

- All rovers $r \in ROV$ apply for access to the orbiters $s \in ORB$ ranked ahead in the preference list $P(r)$;
- Each orbiter s chooses the set of rovers $R \in ROV$ according to the access quota and their own preference list $P(s)$;
- Repeat above steps, until there is no rover left without access to certain orbiter or there is no access quota left for each orbiter.

b) Defer-Accept algorithm

- The orbiters utilize the 'first come first qualified' mode, that is, the rovers applied in the earlier rounds would be preserved as the candidates by certain orbiter;
- In the succeeding rounds, the rover with higher priority could be inserted into the candidate list of certain orbiter, and the rovers whose sequence is larger than the access quota could be discarded by such orbiter.
- Repeat above steps, until there is no rover left without access to certain orbiter or there is no access quota left for each orbiter.

c) Top-Trading Cycles algorithm

- Each rover creates a unidirectional linked list under the rules as: rover i → most preferred orbiter j → most preferred rover k → ... → rover i, which starts from itself and ends at itself. The participants on this linked list could be chosen as the matching couples in order.
- Delete all the participants which have been chosen in last step, then we obtain the remaining access quota and rovers left for further matching;
- Repeat above steps, until there is no rover left without access to certain orbiter or there is no access quota left for each orbiter.

d) Brief summary

The above potential capsule algorithms are applicable for different cases, in which the complexity and performance of these algorithms have their own advantages and disadvantages:

- Through the complexity test of such three potential two-sides matching algorithms, the complexity of Boston mechanism is the lowest, TTC algorithm is the second, and Defer-Accept algorithm is the highest;
- Through the performance test of such three potential two-sides matching algorithms, the Defer-Accept algorithm performs better than other algorithms;
- The characteristic of above algorithms is consistent with well known 'No-Free Lunch' rules, which indicates that the Defer-Accept algorithm exchanges complexity for higher performance.

In this paper, all these potential algorithms are encapsulated into the whole architecture as the parallel matching capsules, by which we could utilizes the alternative optimization under the parallel capsule operations on several one-to-many two-sides matching algorithms to obtain stable multiple access matching results. The complexity of the whole architecture is comparable to the Defer-Accept algorithm.

3.2.2 Matching procedures

Figure 1 gives the matching procedures of 'two-sides matching' based on parallel capsule operations, which is described as follows.

(1) According to the set of rovers and orbiters in common view during current time slot, generate the preference lists for all participants (Rovers/Orbiters):

- On condition of multiple rovers $R \in ROV$ applying access to single orbiter $s \in ORB$ at the same round, utilizing the proportional fair scheduling algorithm based on queue equilibrium [11] to obtain the strict preference order $P(s)$ for orbiter s on the set of multiple rovers $R \in ROV$.
- On condition of single rover $r \in ROV$ applying access to multiple orbiters $S \in ORB$ at the same round, utilizing the optimal selection algorithm based on improved Hotelling oligopoly [12] to obtain the strict preference order $P(r)$ for rover r on the set of multiple orbiters $S \in ORB$.
- According to the preference lists of orbiters to rovers $\{P(s), s \in ORB\}$ and the preference lists of rovers to orbiters $\{P(r), r \in ROV\}$, generate the preference lists for all participants (Rovers/Orbiters) $P = \{P(s), s \in ORB\} \oplus \{P(r), r \in ROV\}$.

(2) According to the preference lists for all participants (Rovers/Orbiters), as well as rover access quota of each orbiter coming from the requirements on deep space missions or simulation test, all three potential capsule algorithms are processed concurrently, in which:

- Capsule algorithm ***a***: Boston mechanism, to obtain the stable two-sides matching result ***a***;
- Capsule algorithm ***b***: Defer-Accept algorithm, to obtain the stable two-sides matching result ***b***;
- Capsule algorithm ***c***: TTC algorithm, to obtain the stable two-sides matching result ***c***.

(3) According to the two-sides matching results by above three potential algorithms, evaluate the fitness of preferences for both orbiters and rovers, and obtain the optimal matching results as follows:

- Take the two-sides combined fitness of preferences as the optimization objective, obtain the matching result with the optimal global fitness of preference.
- Take the single-side evaluation equilibrium as the optimization objective, obtain the matching result with the optimal equilibrium.

IV. SIMULATION RESULTS

4.1 Simulation conditions

4.1.1 Simulation parameters

(1) Number of participants

In the common view of Mars rovers and orbiters, there are 4 orbiters ordered by identify number 1~4 and 8 rovers ordered by identify number 1~8, which means the simulation pa-

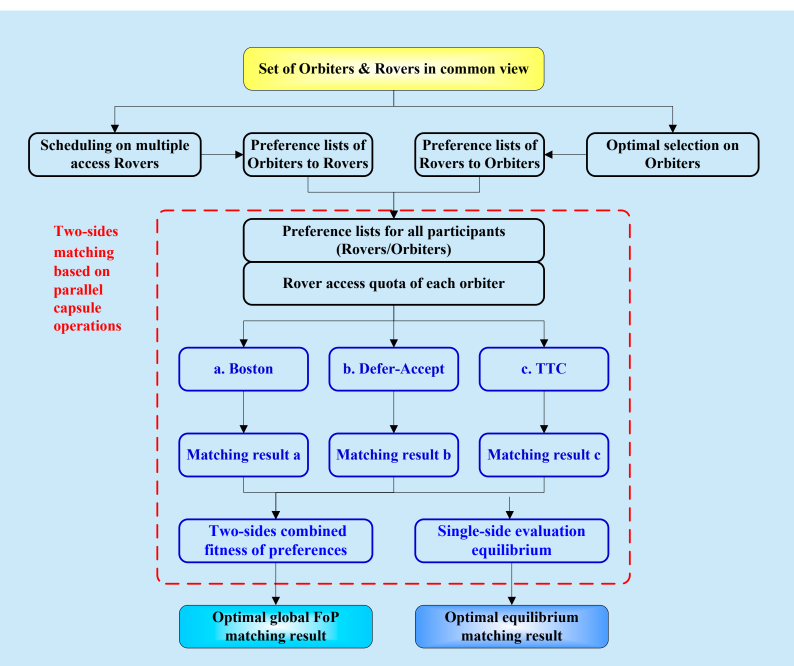

Fig. 1. *The matching procedures of 'two-sides matching' based on parallel capsule operations.*

rameters N and M equal to 4 and 8 respectively.

(2) Weights of orbiters and rovers

The weights of orbiters and rovers are marked as α and β respectively, with the values $\alpha = \beta = 0.5$.

4.1.2 Preference lists of orbiters

In simulations, the preference lists of each orbiter to 8 rovers (identify number 1~8) should be generated by the random sorting function, whose priorities descend from left to right.

- Preference lists of orbiter 1 => [7 8 3 4 1 2 5 6]
- Preference lists of orbiter 2 => [3 1 6 2 4 8 5 7]
- Preference lists of orbiter 3 => [1 8 3 5 4 7 2 6]
- Preference lists of orbiter 4 => [4 3 5 1 8 2 6 7]

4.1.3 Preference lists of rovers

In simulations, the preference lists of each rover to 4 orbiters (identify number 1~4) should be generated by the random sorting function, whose priorities descend from left to right.

- Preference lists of rover 1 => [4 3 2 1]
- Preference lists of rover 2 => [4 3 2 1]
- Preference lists of rover 3 => [3 4 1 2]
- Preference lists of rover 4 => [4 1 3 2]
- Preference lists of rover 5 => [4 3 1 2]
- Preference lists of rover 6 => [2 4 3 1]
- Preference lists of rover 7 => [4 3 1 2]
- Preference lists of rover 8 => [3 1 4 2]

4.1.4 Matching constrains

- **CCSDS Proximity-1 protocol**

  As described above, CCSDS Proximity-1 protocol works on the mode of 'Single access, first come first served, random back-off', which indicates that each orbiter could accept the application of only one rover, and each rover could get access to only one orbiter; in case of access collision, random back-off is adopted to delay random time period and apply to access again.
- **Two-sides matching algorithms**

  According to the 'one-to-many' two-sides matching model, the constrain in Mar relay communications for multiple rovers and multiple orbiters is that the access quota of each orbiter could be adjusted on demand, and each rover could get access to only one orbiter.

4.2 CCSDS Proximity-1 simulation

Based on the preference lists of rovers and orbiters given by section 4.1, the matching performance of CCSDS Proximity-1 protocol is tested by Monte Carlo simulation and compared with our new method proposed in this paper. In the case of relative scarcity of orbiter resources ($N < M$), the scale of permutation problem can be expressed as $A_M^N = M!/(M-N)!$, $N < M$. In order to obtain more accurate statistical performance, the simulation rounds should not be less than 10 times of the scale of permutation, therefore the simulation rounds could be set to 16800 with $N = 4$, $M = 8$.

4.2.1 Two-sides combined fitness of pReferences

The two-sides combined fitness of preferences simulation results of CCSDS Proximity-1 are shown in figure 2. The statistical mean of the two-sides combined fitness of preferences is 0.2420, which is nearly same to the theoretical calculation result 0.2416. Besides, the maximum value of the two-sides combined fitness of preferences is 0.6172 located at about 8300

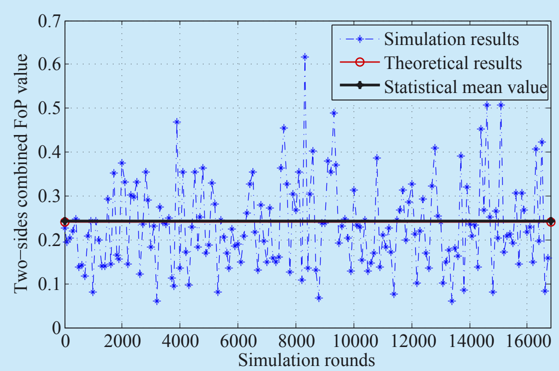

Fig. 2. *Two-sides combined fitness of preferences simulation results of CCSDS Proximity-1.*

round.

4.2.2 Single-side evaluation equilibrium

The single-side evaluation equilibrium simulation results of CCSDS Proximity-1 are shown in figure 3. The statistical mean of the single-side evaluation equilibrium is -0.0601, whose absolute value is nearly same to the theoretical calculation result 0.0303.

4.3 Two-sides matching simulation

In simulations, according to the access quota of the orbiter subset, divide the two-sides matching issues in Mars relay communications into four cases such as short of orbiter supplies, inadequate orbiter supplies, balanced orbiter supplies and abound orbiter supplies.

4.3.1 Shortages of orbiter supplies

In Mars relay communications, the shortages of orbiter supplies mean that the number of rovers subset is much larger than the total access quota of orbiters subset, that is, each orbiter could accept the application of only one rover. Table I shows the stable matching results between rovers and orbiters (Short of orbiter supplies), in which:

- **Optimal Two-sides combined FoP**

Defer-Accept algorithm performs best with the single-side FoP of Orbiter subset as 1.0000 (perfect matching), the single-side FoP of Rover subset as 0.2344, the two-sides combined FoP as 0.6172 (maximum) and the single-side evaluation equilibrium as 0.6203, which is benefit for the Orbiter subset.

- **Optimal single-side evaluation equilibrium**

Boston mechanism performs best with the single-side evaluation equilibrium as 0.2571 (minimum absolute value), which is benefit for the Orbiter subset.

4.3.2 Inadequate orbiter supplies

In Mars relay communications, the inadequate orbiter supplies means that the number of rovers subset is slightly larger than the total access quota of orbiters subset and the access quota for each orbiter is imbalance, that is, some orbiters could accept the application of only one rover, the other orbiters could accept the application of two rovers.

(1) Access quota case 1

Table II shows the stable matching results between rovers and orbiters (Access quota case 1 as [2,2,1,1]), in which:

- **Optimal Two-sides combined FoP**

Boston mechanism performs best with the single-side FoP of Orbiter subset as 0.7000, the single-side FoP of Rover subset as 0.4688, the two-sides combined FoP as 0.5844 (maximum) and the single-side evaluation equilibrium as 0.1979, which is benefit for the Orbiter subset.

- **Optimal single-side evaluation equilibrium**

TTC algorithm performs best with the single-side evaluation equilibrium as -0.0684 (minimum absolute value), which is benefit for the Rover subset.

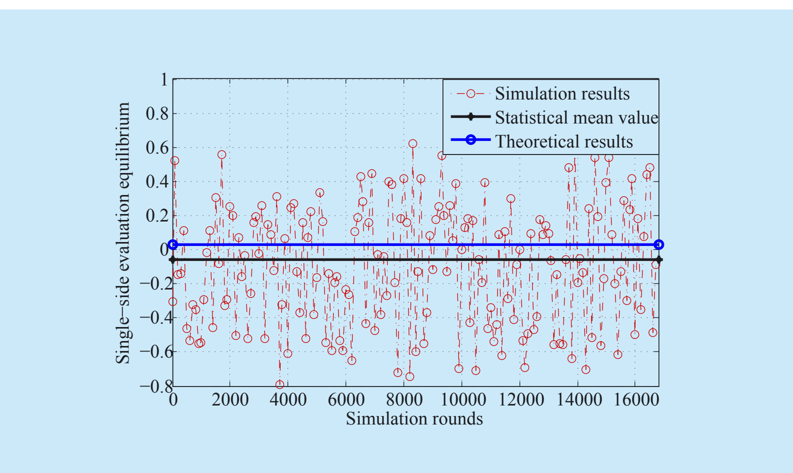

Fig. 3. *Single-side evaluation equilibrium simulation results of CCSDS Proximity-1.*

Table I. *Stable matching results between rovers and orbiters (Short of orbiter supplies).*

Capsule algorithms	Access quota of orbiter 1~4				Single-side FoP		Two-sides combined FoP	Single-side evaluation equilibrium
	1	1	1	1	Orbiter subset	Rover subset		
Boston	7	6	8	4	0.6875	0.4063	0.5469	**0.2571**
Defer-Accept	7	3	1	4	1.0000	0.2344	**0.6172**	0.6203
TTC	3	4	2	1	0.1133	0.2344	0.1738	-0.3483

(2) Access quota case 2

Table III shows the stable matching results between rovers and orbiters (Access quota case 2 as [1,1,2,2]), in which:

- **Optimal Two-sides combined FoP**

  Defer-Accept algorithm performs best with the single-side FoP of Orbiter subset as 0.9500 (nearly perfect matching, that is, orbiter 4 has to accept the third choice rover 5 due to the second choice rover 3 matched with orbiter 2 in prior rounds), the single-side FoP of Rover subset as 0.4844, the two-sides combined FoP as 0.7172 (maximum) and the single-side evaluation equilibrium as 0.3246, which is benefit for the Orbiter subset.

- **Optimal single-side evaluation equilibrium**

  Boston mechanism performs best with the single-side evaluation equilibrium as -0.0048 (minimum absolute value), which is benefit for the Rover subset.

4.3.3 Balanced orbiter supplies

In Mars relay communications, the balanced orbiter supplies means that the number of rovers subset equals to the total access quota of orbiters subset, that is, each orbiter could accept the application of two rovers and the access quota for each orbiter is the same. Table IV shows the stable matching results between rovers and orbiters (Balanced orbiter supplies), in which:

- **Optimal Two-sides combined FoP**

  Defer-Accept algorithm performs best with the single-side FoP of Orbiter subset as 0.7292, the single-side FoP of Rover subset as 0.6563, the two-sides combined FoP as 0.6927 (maximum).

- **Optimal single-side evaluation equilibrium**

  Defer-Accept algorithm performs best with the single-side evaluation equilibrium as 0.0526 (minimum absolute value), which is benefit for the Orbiter subset.

4.3.4 Abound orbiter supplies

In Mars relay communications, the abound orbiter supplies means that the number of rovers subset is less than the total access quota of orbiters subset, that is, each orbiter could accept the application of all the rovers and the access quota for each orbiter is the same. Table V shows the stable matching results between

Table II. *Stable matching results between rovers and orbiters (Inadequate orbiter supplies 1).*

Capsule algorithms	Access quota of orbiter 1~4				Single-side FoP		Two-sides combined FoP	Single-side evaluation equilibrium
	2	2	1	1	Orbiter subset	Rover subset		
Boston	7,3	6,1	8	4	0.7000	0.4688	**0.5844**	0.1979
Defer-Accept	7,3	6,2	1	4	0.7250	0.4063	0.5656	0.2818
TTC	3,7	4,6	2	1	0.3406	0.3906	0.3656	**-0.0684**

Table III. *Stable matching results between rovers and orbiters (Inadequate orbiter supplies 2).*

Capsule algorithms	Access quota of orbiter 1~4				Single-side FoP		Two-sides combined FoP	Single-side evaluation equilibrium
	1	1	2	2	Orbiter subset	Rover subset		
Boston	7	6	8,3	4,5	0.6500	0.6563	0.6531	**-0.0048**
Defer-Accept	7	3	1,8	4,5	0.9500	0.4844	**0.7172**	0.3246
TTC	3	5	2,8	1,4	0.3812	0.4844	0.4328	-0.1191

Table IV. *Stable matching results between rovers and orbiters (Balanced orbiter supplies).*

Capsule algorithms	Access quota of orbiter 1~4				Single-side FoP		Two-sides combined FoP	Single-side evaluation equilibrium
	2	2	2	2	Orbiter subset	Rover subset		
Boston	7,2	6,1	8,3	4,5	0.6302	0.7031	0.6667	-0.0547
Defer-Accept	7,3	6,2	1,8	4,5	0.7292	0.6563	**0.6927**	**0.0526**
TTC	3,7	5,6	2,8	1,4	0.5260	0.6406	0.5833	-0.0982

Table V. *Stable matching results between rovers and orbiters (Abound orbiter supplies).*

Capsule algorithms	Access quota of orbiter 1~4				Single-side FoP		Two-sides combined FoP	Single-side evaluation equilibrium
	8	8	8	8	Orbiter subset	Rover subset		
Boston	-	6	8,3	4,5,1,2,7	0.3029	1.0000	0.6515	-0.5350
Defer-Accept	-	6	8,3	4,5,1,2,7	0.3029	1.0000	0.6515	-0.5350
TTC	-	6	3,8	1,4,2,5,7	0.3029	1.0000	0.6515	-0.5350

Table VI. *Performance comparison between CCSDS Proximity-1 and our two-sides matching.*

Methods	Access quota of orbiter 1~4				Two-sides combined FoP	Single-side evaluation equilibrium
CCSDS Proximity-1	1	1	1	1	0.2426 (Mean) 0.6172 (Maximum)	-0.0658
our two-sides matching method	1	1	1	1	0.6172	0.2571

rovers and orbiters (Abound orbiter supplies), in which we could find that there might be some differences in the rover access sequence, however the final matching results for all three algorithms are completely the same. The single-side evaluation equilibrium is -0.5350, which is benefit for the Rover subset.

4.4 Performance comparison

Table VI shows the performance comparison between CCSDS Proximity-1 and our two-sides matching method, with the access quota of each orbiter as one rover, in which:

- For the two-sides combined FoP, our two-sides matching method performs better than most of the resource allocation results of CCSDS Proximity-1, which also indicates that upper bound of CCSDS Proximity-1 could be simply achieved by our two-sides matching method;
- For the single-side evaluation equilibrium, CCSDS Proximity-1 performs better, and our new two-sides matching method is benefit for Orbiter subset.

V. CONCLUSIONS

With the development of deep space communication network, there would be more and more multiple access requirements on deep space data relay communication. Under the constraints of limited communication links and storage resources, it is important to optimize the resource allocation through reasonable multiple access technology. Current CCSDS Proximity-1 protocol utilizes the 'single access, first come first served, random back-off' as the access control mechanism, which is difficult to realize the resource allocation optimizations. In this paper, the two-sides matching between multiple rovers and multiple orbiters in Mars relay communications based on the access preferences is studied, which utilizes the alternative optimization under the parallel capsule operations on several one-to-many two-sides matching algorithms to obtain stable multiple access matching results and performs better than the CCSDS Proximity-1 protocols in typical simulation test, which could provide the resource allocation optimizations in deep-space networks.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (61971261, 61671263), and Tsinghua University Independent Scientific Research Project (20194180037).

Reference

[1] X. PAN *et al.*, "Review of channel models for deep space communications," *SCIENCE CHINA Information Sciences*, vol. 61, no. 1, 2018, pp. 040304:1-040304:12.

[2] J. Taylor, D. Lee, S. Shambayati, "Descanso design and performance summary series: Mars reconnaissance orbiter telecommunications," *Pasadena: NASA JPL*, 2006, pp. 1-76.

[3] A. Chicarro, P. Martin, R. Trautner, "The Mars express mission: an overview," *Mars Express Sci Payload*, 2004, no. 1240, pp. 3-13.

[4] A. Makovsky, A. Barbieri, R. Tung, "Descanso design and performance summary series Article 6: Odyssey Telecommunications," *Pasadena: NASA JPL*, 2002, pp. 1-78.

[5] CCSDS, "Proximity-1 space link protocol - coding and synchronization sub-layer, issue 2," *Recommended Standard (Blue Book), CCSDS 211.2-B-2*, Washington D.C., 2013, pp. 1-47.

[6] CCSDS, "Proximity-1 space link protocol - physical layer, issue 4," *Recommended Standard (Blue Book), CCSDS 211.1-B-4*, Washington D.C., 2013, pp. 1-36.

[7] CCSDS, "Proximity-1 space link protocol - data link layer, issue 5," *Recommended Standard (Blue Book), CCSDS 211.0-B-5*, Washington D.C., 2013, pp. 1-162.

[8] CCSDS, "Proximity-1 space link protocol - rationale, architecture, and scenarios, issue 2," *Informational Report (Green Book), CCSDS 210.0-G-2*, Washington D.C., 2013, pp. 1-94.

[9] X. GUAN, "Musk announces his plan of Mars colonization," *Aerospace China*, no. 12, 2016, pp. 48-52.
[10] J. XU, W. WU, "Multiple attribute decision making theory and methods," *Beijing: Tsinghua University Press*, 2006, pp. 1-372.
[11] P. WAN *et al.*, "Scheduling algorithm for the multiple rovers' access to single orbiter on the Mars relay communication links," *International journal of satellite communications and networking*. vol. 37, no. 3, 2019, pp. 612-629.
[12] P. WAN, Y. ZHAN, X. PAN, "Study on the optimal access orbiter selection algorithm in Mars automatic relay communications," *IEEE Transactions on Aerospace and Electronic Systems*, DOI:10.1109/TAES.2019.2955811. 2019, pp. 1-13.
[13] U. Kamecke, A. Roth, M. Sotomayor, "Two sided matching: a study in game-theoretic modeling and analysis," *Economica*, vol. 59, no. 236, 1992, pp. 487-489.
[14] F. Pantisano *et al.*, "Matching with externalities for context-aware user-cell association in small cell networks," *Globecom Workshops (GCWkshps), IEEE*, 2013, pp. 4483-4488.
[15] W. Saad *et al.*, "A college admissions game for uplink user association in wireless small cell networks," *Proceedings IEEE INFOCOM*, 2014, pp. 1096-1104.
[16] S. Bayat *et al.*, "Matching theory: applications in wireless communications," *IEEE Signal Processing Magazine*, vol. 33, no. 6, 2016, pp. 103-122.
[17] S. LIU *et al.*, "Distributed caching based on matching game in LEO satellite constellation networks," *IEEE Communications Letters*, vol. 22, no. 2, 2018, pp. 300-303.
[18] B. Klaus, D. Manlove, F. Rossi, "Matching under preferences," *Cahiers de Recherches Economiques du Département d'Econométrie et d'Economie politique (DEEP)*, 2014, pp. 1-39.
[19] R. Martí nez *et al.*, "Single agents and the set of many-to-one stable matchings," *Journal of Economic Theory*, vol. 91, no. 1, 2000, pp. 91-105.
[20] D. Cantala, J. Pereyra, "Priority-driven behaviors under the Boston mechanism," *Review of Economic Design*, vol. 21, no. 1, 2017, pp. 49-63.
[21] T. Morrill, "Two simple variations of top trading cycles," *Economic Theory*, vol. 60, no. 1, 2015, pp. 123-140.

Biographies

Peng Wan, received the B.S. degree in physics from Peking University, in 2004, and the M.S. degree in electronic engineering from Tsinghua University, Beijing, China, in 2007, where he is currently pursuing the Ph.D. degree in aeronautical and astronautical science and technology with the Space Center. His research interests include the system design of space network and deep space communications. Email: wanp16@mails.tsinghua.edu.cn

Yafeng Zhan, received the B.S. E.E. and Ph.D. E.E. degrees from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 1999 and 2004, respectively. He is currently an Associate Professor with the Space Center, Tsinghua University. His current research interests include communication signal processing and deep space communications. Email: zhanyf@tsinghua.edu.cn