Flower Constellation of Orbiters for Martian Communication

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Abstract—Flower Constellations are a particular set of satellite constellations where every satellite covers the same repeating space track. When the Flower Constellations are visualized on an Earth centered Earth fixed reference frame, the relative orbits show flower-shaped figures centered on the Earth. This innovative type of constellation presents features useful to be used in several applications, such as telecommunications, navigation, Earth science and interferometric radar. Several missions are foreseen to explore Mars in the next years to collect data in order to enhance our knowledge of the red planet. This effort requires the development of a reliable orbital infrastructure to support telecommunications with orbiters, landers and rovers. In this paper, a novel telecommunication architecture is presented, based on the previously introduced Flower Constellations. We designed an optimized Flower Constellation for the coverage of sites/regions of interest of the Mars surface. We proved that our proposed constellation provides better performance with respect to a reference constellation called 4retro 111 in terms of access duration and average gap time. [1 2]

TABLE OF CONTENTS

1. INTRODUCTION

The deployment of a constellation of satellites instead of the deployment of a single satellite provides larger coverage areas (localized or even global), while increasing the design complexity and the cost. However in some situations the need to cover large areas justifies the exploitation of satellite constellations. Currently there are several applications that can get benefit from the exploitation of satellite constellations, such as telecommunications, navigation and Earth observation. In thi paper, a novel constellation of orbiters to be used for the so-called Interplanetary Internet, which is defined as the network of planetary networks which interconnects orbiters, landers, rovers, planetary stations, and relay satellites, is presented. In particular, we focus on the communication interconnection of landers, rovers and probes over Mars [1]-[4]. Areas of interest over the Mars surface are the north and south poles and the equator (i.e. between -15 and +15 degrees in latitude) [1]. Each orbiter is equipped with a medium range radio transceiver for the communication with landed elements and a long range radio transceiver for relaying information back to Earth. Several constellations of orbiters have been proposed in order to provide communication between landers and orbiters over Mars. One of the most important constellations has been proposed by the Jet Propulsion Laboratory (JPL), named 4retro111 [1]. This constellation has been optimized to cover the equatorial and the polar regions. This objective has been fulfilled by splitting the overall constellation into two sub-constellations that can be classified as Walker constellations: the first sub-constellation is optimized to cover the equatorial region, while the second one is optimized to cover the polar areas. In this paper we are going to exploit the capabilities of the Flower Constellations (FCs) in order to provide better performance in terms of maximum gap time, availability of Inter Satellite Links (ISLs) and visibility of the Earth, with respect to the constellation 4retro111. The performance metrics are going to be optimized taking into account some constraints such as: maximum number of satellites, orbit inclination and perigee/apogee height. FCs are built using orbits that are compatible with respect to an assigned rotating reference frame [5]-[8]. Therefore, in the FC design methodology, all the satellites follow the same relative trajectory in the rotating reference frame. In order to obtain this result, the values of the right ascension of the ascending node and the mean anomaly cannot be independent. There are also some phasing rules which dictate the satellites distribution property. Compatibility and phasing, which are ruled by a set of five independent integer parameters, constitute the two main properties of the FCs. Our approach to the optimization follows the approach of the 4retro111, that is, we are designing two Flower sub-constellations: the first

1
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sub-constellation is optimized to cover the equatorial region, while the second sub-constellation is optimized to cover the polar areas. The optimization process will make use of genetic algorithms and the final paper will compare the proposed FC with the already developed 4retro111.

2. INTERPLANETARY INTERNET AND MARTIAN MISSIONS

Mission Needs

Interplanetary Internet is defined as the network of planetary networks which interconnets landers, orbiters, rovers, planetary stations, and relay satellites. It encompasses both UpLinks/DownLinks (ULs/DLs), Inter-Satellite Links (ISLs), and Inter-Planetary Links (IPLs).

At present, Mars is the focus of Interplanetary Internet. Actually, since the last few years space community has shown an increased interest in the Solar System exploration, especially for Mars. This trend is also confirmed for the next ten/twenty years. The fourth planet will be the key target of orbiters, landers and rovers, designed by the main space agencies, firstly NASA and ESA. The main scope of these efforts is to gather more and more science data about the red planet in order to characterize in detail the martian geology and meteorology, as well as the search of the water ice. Final objective is to define and to design manned missions to Mars, identifying possible landing sites.

In references [2][3], the authors showed some future trends for missions into deep space, especially growing data richness and more data-intensive instruments. This evolution requires an increase in returned data volumes and higher data rates, envisaging the need of data relay nodes in space. The future scenario foresees spacecraft fleet in orbit around Mars, providing telecommunications, navigation, observation services. They will exchange data with rovers, landers on the surface and with the Earth, creating an infrastructure that will have to answer to the needs of flexibility and reliability over time in order to support this effort.

At present, a NASA/ASI mission, Mars Reconnaissance Orbiter (MRO), is the last one arrived to Mars in order to characterize the surface, subsurface, and atmosphere of red planet. Its objective is also to identify potential landing sites for future missions. This orbiter hosts some telecommunications systems that will establish a fundamental support for future spacecrafts, becoming the first link in a communications bridge back to Earth, an "Interplanetary Internet". It will help the communications of the international spacecraft fleets in coming years.

Selection of landing sites for Mars exploration missions require an intensive study. The criteria was defined as:

- safe landing;
- scientific interest (areas of geological and/or meteorological interest, possible presence of water ice, etc.);
- local environmental conditions (surface characteristics, lighting status, temperatures and so on).

We have analyzed the areas of interest for communication and navigation (Doppler based) services over the Mars ground for past, present and future missions and we defined the following targets [1]:

1. **spot coverage**: four sites of interest have been identified:
   - Spirit Rover: lat=-14.5deg, lon=175.3deg;
   - Opportunity Rover: lat=-1.9deg, lon=-5.9deg;
   - Mars Polar Lander: lat=-76.1deg, lon=164.7deg;
   - Phoenix Lander: lat=65deg, lon=-120deg;
2. **regional coverage**: the regions of interest are North polar region (latitude>80deg), South polar region (latitude<-80deg), Equatorial region (-15deg<latitude<15deg).

Rovers, landers and probes on the surface of Mars require relay contacts at the same times every day so that they can design their missions and their operations based on invariant communications patterns. This requirement can be satisfied by designing constellations of orbiters with repeating ground tracks as is provided by FCs.

Communication Architecture

The task of the Interplanetary Internet is to develop a communication system architecture able to connect landers, rovers and orbiters with Earth facilities.

Each orbiter is equipped with a medium range radio transceiver for communicating with landed elements and a long range radio transceiver for relaying information back to Earth. Scientific missions require:

- Time insensitive transfer of large size data (images and videos) from planets towards the Earth
- Time sensitive live video streaming for the control of rovers

- Telemetry, tracking and command of landed elements and orbiters

Several issues have to be taken into account. The most important are:

(1) Large propagation delay

(2) Limited quantity of energy

(3) Discontinuity of the links

A solution to the first issue is to develop space communication protocols optimized for long Round Trip Time (RTT), while the second issue requires the exploitation of large solar panels. In this paper, a constellation of orbiters of Mars, optimized to cover the areas of interest for most of the time, is developed. The areas of interest over the Mars surface are the equatorial belt and the poles, where most of the landing elements are expected to be placed.

3. CONSTELLATION DESIGN

In this Section, the design parameters and properties of Walker and FCs are described.

Walker Constellations

Walker constellations are the classical type of satellite constellations. The design of a Walker constellation is easier with respect to the design of a FC since the number parameters is lower. A Walker constellation is characterized by three integer parameters *t*, *p*, *f* and three real parameters *h*, *i* and *RAANspread*. The parameters *t*, *p*, *f* define respectively the number of satellites, the number of orbit planes and the relative spacing between satellites in adjacent planes. The parameters *h*, *i* and *RAANspread* define the orbit height, the inclination and the constraint on the maximum spreading of the RAAN for the satellites.

The Walker constellation is not designed to show repeating ground track. This means that the satellites belonging to a Walker constellation covers all the longitudes with the passing of time.

Orbital parameters of the proposed 4retro111 constellation are listed in Table 1. Two sub-constellation (Walker type) are designed. The first sub-constellation is composed by satellites no. 1 and 2 and it is designed to provide communication services to near equatorial landed elements. The design parameters of the first sub-constellation are: t=2, p=2, f=0, RAANspread=360deg, a=4189.92km, i=172deg. The second sub-constellation is composed by satellites no. 3,4,5 and 6. The design parameters of the second sub-constellation are: t=4, p=4, f=1, *RAANspread*=360deg, a=4189.92km, i=111deg.

Table 1. Orbital elements for the 4retro111 constellation

Sat #	h_p **(km)**	e	i **(deg)**	ω_p **(deg)**	*RAAN* **(deg)**	M **(deg)**
1	800	0	172	0	0	0
2	800	0	172	0	180	0
3	800	0	111	0	0	0
4	800	0	111	0	90	90
5	800	0	111	0	180	180
6	800	0	111	0	270	270

Flower Constellations

The FC design methodology has been extensively described in [1-5]; a summary of the main underlying principles is briefly presented in this subsection for the benefit of the reader.

As previously outlined, the name Flower Constellation has been chosen because of the compatible orbit relative trajectories in the Earth-Centred Earth-Fixed (ECEF) reference frame, resemble flower petals. A FC is a set of spacecrafts characterized by the same repeating space track, a property obtained through a suitable phasing scheme.

In general FCs are characterized by 6 integer parameters:

- N_p: number of petals;
- N_d: number of days to repeat the space track;
- N_s: number of satellites;
- F_n: phase numerator;
- F_d: phase denominator;
- F_h: phase step;

of which the first two define the semimajor axis (or the period), whereas the latter three define the satellite distribution along the relative path. Five more orbital parameters, height of perigee, inclination, argument of perigee, Right Ascension of Ascending Node (RAAN) of the first satellite and Mean Anomaly of the first satellite (h_p, i, ω_p, Ω_0, M_0,, respectively), define the orbit shape, orientation and synchronization with the Earth. The number of orbits is determined by the N_p parameter and all the orbits have identical shape, inclination, and argument of perigee.

They are only rotated in RAAN to obtain an even distribution about the central body.

The choice of a suitable phasing scheme is critical to reveal the most interesting dynamics obtainable by FCs. The chosen phasing scheme is a function of Ω_k, RAAN of the k-th satellite, $T_k(t_0)$ the true anomaly of the k-th satellite at the initial time and the phasing parameters F_n, F_d, and F_h. The chosen scheme is designed to guarantee that every satellite is placed in a position compatible with the repeating space track constraint.

The FC approach provides great flexibility and interesting dynamics that reveal the presence of the so called secondary path, a relative motion of the satellites resulting in intriguing motion patterns that can be exploited to obtain useful properties as those described in [2, 3, and 5]. More details, insights, and interesting properties are provided in [6] and [7].

4. FC Optimization

In Section 2, it has been stated that the objective of the present study is to develop an optimized Flower Constellation of orbiters for:

1. spot coverage;
2. regional coverage.

We are going to find a solution to our optimization problem that is at least nearly optimal.

The optimization problem has been decomposed in two steps. The first step consists in finding an orbit with a repeating ground/space track that allows the observation of all the sites/regions with an access duration of each site as long as possible. The second step consists in finding a distribution of satellites along the repeating space track that provides an average gap time duration to the ground sites/regions as short as possible.

The first step of the optimization process has been approached by using a genetic algorithm for a single satellite track [9]. The FC parameters that are optimized during the first phase are: N_p, N_d, h_p, i, ω_p, Ω_0, M_0.

Since the genetic algorithm methodology is well known and has been extensively studied, its theory will not be reviewed here; the interested reader can refer to [9].

While the first step of the optimization process is complex and has to be carefully performed on the basis of the number of ground sites (see next two subsections), the second step of the optimization process is very easy thanks to the particular properties of a FC. In fact, since the objective of the second step is to minimize the average coverage gap duration, the satellites have to be evenly spaced on the repeating space track. This task can be accomplished by setting F_nF_d=N_s, where N_s=6 as it is for the reference constellation and choosing F_n=1, F_h=0.

We did not optimize any Walker constellation for our purposes, but we used the already developed 4retro111 as a reference constellation. However, it is worth noting that the optimization of a Walker constellation is more time consuming with respect to the optimization of a FC for the following reasons:

- for the optimization of a Walker constellation each satellite of the constellation has to be propagated, while in a FC it is necessary to propagate only one satellite, since every satellite follow the same repeating space track;

- for the optimization of a Walker constellation each satellite of the constellation has to be propagated for many days (at least 30 days), while in a FC it is necessary to propagate the constellation for exactly N_d days (which is usualy 1 or 2 days).

Furthermore, the performance of a FC repeats every N_d days. Hence, the distribution of the accesses is more uniform with respect to a Walker constellation that does not have a repeating period.

In the next two subsection we define the optimization metric of the first optimization step.

Spot Coverage

The cost function utilized to guide the GA optimization process is designed to maximize the dwell time over each target. For the exact computation of the dwell time, the cost function should be designed such that the satellite has to be propagated for N_d days and the access of the satellite from a given ground site is computed on the basis of a given minimum elevation angle θ_m (where θ_m ha been set to 20 deg). This optimization process is time consuming even if the number of ground sites is low. To this respect we defined the following cost function f_{cost}:

$$f_{\cos t} = \prod_{j=1}^{L} \alpha_j \left(\theta(t_j) - \theta_m\right) d(t_j) \qquad (1)$$

where α_j is the relative weight of the j-th site with respect to the other target sites, t_j is the instant of access of the satellite to the j-th site, $\theta(t_j)$ is the elevation angle at time t_j, $d(t_j)$ is the slant range at time t_j and L is the number of sites. The cost function computed for a series of instants t_j, increases with the increase of the elevation angle and the slant range. For a large slant range the satellite moves slowly; hence, it remains in view for a long time. On the other hand, a large elevation angle (about 90deg) means that the satellite passes over the site with a ground track as centered as possible to the site.

As it is intuitive, this cost function increases with the increase of the dwell time; hence, it is a good heuristic cost function. In order to run the GA, the design space (i.e. the chromosome) must be defined. The following parameters have been encoded in the chromosome string:

$$h_p \ \varepsilon \ (100, 800), \ \ i \ \varepsilon \ [0, \pi], \ \omega_p \ \varepsilon \ [0, 2\pi],$$
$$\Omega_0 \ \varepsilon \ [0, 2\pi], \ M_0 \ \varepsilon \ [0, 2\pi], \ \ t_j \ \varepsilon \ [0, N_d], j=1,...,L$$

It is less intuitive to think that it is convenient, from the simulation time point of view, to increase the size of the design space of the genetic algorithm instead of performing a propagation of the satellite.

In this case, the optimization metric has been computed for the 4 sites defined in Section 2, where each site has a weight equal to 1.

Regional Coverage

For the regional optimization we have evenly distributed a large number of sites within the regions of interest and we have optimized the dwell time for each site. When the number of sites is large, as it is the case of regional coverage, it is no more convenient to use the previous approach for the optimization of the repeating space track and, hence, we have performed the satellite orbit propagation and then we have computed the exact dwell time.

In this case, the optimization metric defined as the dwell time has been computed for a large number of ground sites evenly distributed on the Equator and the North and South Pole as it was defined in Section 2, where each site has a weight equal to 1.

5. PERFORMANCE EVALUATION AND COMPARISON

In this Section we provide the design parameters of the FCs optimized by using the previously described methodologies. When there are several sites or regions largely spaced from each other, a single optimization is not the most suitable mean of performing an optimization. In our case, we can identify two regions (or group of sites), and then we can optimize a FC for each region: the polar region/sites and the equatorial region/sites. In the following subsections we present the optimization results showing FC parameters, and we campare the performance of the single FC (obtained by a single optimization process) and the double FC (obtained by a double optimization process) with reference constellation 4retro111.

Spot Coverage – Single FC parameters

The design parameters of the single FC for spot coverage (named FC-MARS-single) are provided in Table 2; these design parameters generate the orbital parameters listed in Table 3. In order to visually show the suitability of the designed FC, the ground track and the ground sites are shown in Figure 1.

Table 2. Design parameters of the FC-MARS-single.

N_p	11
N_d	1
N_s	6
F_n	1
F_d	6
F_h	0
h_p	102 km
i	86.9 deg
w_p	17.7 deg
$RAAN_0$	216.6 deg
M_0	289.7 deg

Table 3. Orbital parameters of the FC-MARS-single.

a **(km)**	***e***	***i*** **(deg)**	w_p **(deg)**	***RAAN*** **(deg)**	***TA*** **(deg)**
4130	0.154	86.9	17.7	216.6	272.1
4130	0.154	86.9	17.7	276.6	345.8
4130	0.154	86.9	17.7	336.6	64.9
4130	0.154	86.9	17.7	36.6	125.1
4130	0.154	86.9	17.7	96.6	172.3
4130	0.154	86.9	17.7	156.6	217.7

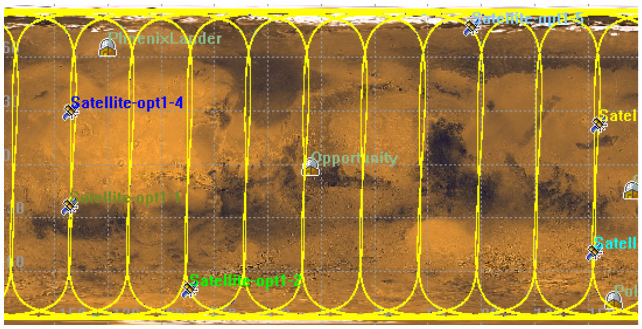

Figure 1. Ground track of the FC-MARS-single.

Spot Coverage – Double FC parameters

The double FC for spot coverage has been named FC-MARS-double. The design parameters of the first Flower sub-constellation are provided in Table 4, while the design parameters of the second Flower sub-constellation are provided in Table 5.

These design parameters generate the orbital parameters listed in Table 6. The ground track and the ground sites are shown in Figure 2.

Table 4. Design parameters for the first sub-constellations of the FC-MARS-double.

N_p	11
N_d	1
N_s	4
F_n	1
F_d	4
F_h	0
h_p	677 km
i	85.8 deg
w_p	303.4 deg
$RAAN_0$	334.8 deg
M_0	210.7 deg

Table 5. Design parameters for the second sub-constellations of the FC-MARS-double.

N_p	11
N_d	1
N_s	2
F_n	1
F_d	2
F_h	0
h_p	100 km
i	22 deg
w_p	164.5 deg
$RAAN_0$	94.4 deg
M_0	314 deg

Table 6. Orbital parameters of the FC-MARS-double.

a (km)	e	i (deg)	w_p (deg)	$RAAN$ (deg)	TA (deg)
4130	0.015	85.8	303.4	334.8	209.8
4130	0.015	85.8	303.4	64.8	299.2
4130	0.015	85.8	303.4	154.8	31.6
4130	0.015	85.8	303.4	244.8	122.2
4130	0.154	22	164.5	94.4	299.45
4130	0.154	22	164.5	274.4	145.2

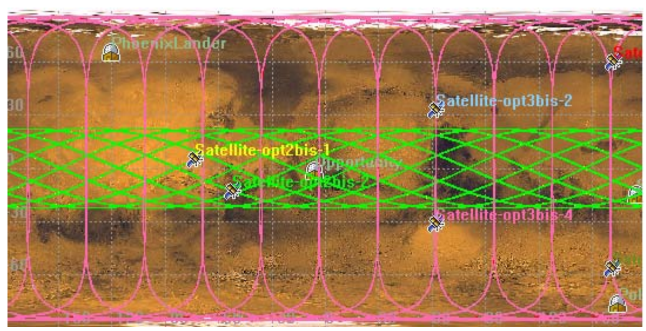

Figure 2. Ground track of the FC-MARS-double.

Regional Coverage – Single FC parametrs

The design parameters of the single FC for regional coverage (named FC-MARS-singleR) are provided in Table 7; these design parameters generate the orbital parameters listed in Table 8. The ground track and the ground sites are shown in Figure 3.

Table 7. Design parameters of the FC-MARS-singleR.

N_p	11
N_d	1
N_s	6
F_n	1
F_d	6
F_h	0
h_p	431 km
i	91 deg
w_p	171.1 deg
$RAAN_0$	159.9 deg
M_0	190.2 deg

Table 8. Orbital parameters of the FC-MARS-singleR.

a (km)	*e*	*i* (deg)	w_p (deg)	*RAAN* (deg)	*TA* (deg)
4130	0.07	91	171.1	159.9	188.8
4130	0.07	91	171.1	219.9	242.4
4130	0.07	91	171.1	279.9	303.2
4130	0.07	91	171.1	339.9	11.8
4130	0.07	91	171.1	38.9	78.5
4130	0.07	91	171.1	98.9	136.3

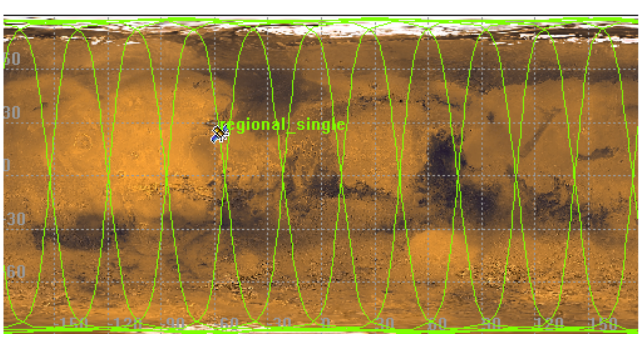

Figure 3. Ground track of the FC-MARS-singleR.

Regional Coverage – Double FC parameters

The designed double FC for regional coverage has been named FC-MARS-singleR. The design parameters of the first Flower sub-constellation, optimized for the coverage of the polar regions, are provided in Table 9.

The first step of the optimization process for the equatorial region resulted in a satellite with an inclination close to 0deg. The design of a FC of two satellites with an inclination close to 0deg results in a couple of satellites positioned always close to each other, and hence, with an overlapping of coverage that is not needed. Thus, we have chosen to space the satellites of 180deg. In conclusion, the second sub-constellation is not exactly an FC, but a constellation of two satellites with repeating ground of the same period N_d. All the parameters of these two satellites are the same, while the *RAAN* is opposite. The orbital parameters of the final constellation are listed in Table 10. The ground track and the ground sites are shown in Figure 4.

Table 9. Design parameters for the first sub-constellation of the FC-MARS-doubleR.

N_p	11
N_d	1
N_s	4
F_n	1
F_d	4
F_h	0
h_p	661.5 km
i	88.1 deg
w_p	313.7 deg
$RAAN_0$	342 deg
M_0	128.5 deg

Table 10. Orbital parameters of the FC-MARS-doubleR.

a (km)	*e*	*i* (deg)	w_p (deg)	*RAAN* (deg)	*TA* (deg)
4130	0.017	88.1	313.7	342	130
4130	0.017	88.1	313.7	72	217
4130	0.017	88.1	313.7	162	306
4130	0.017	88.1	313.7	252	39
4130	0.018	0.7	49.2	235.1	330.8
4130	0.018	0.7	49.2	55.1	330.8

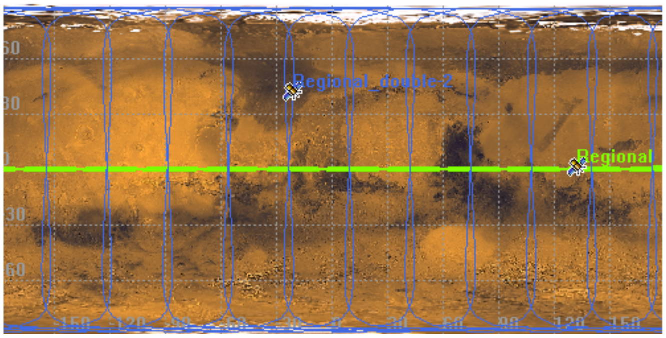

Figure 4. Ground track of the FC-MARS-doubleR.

Performance Comparison

In table 11, the performance comparison results for spot coverage are summarized.

Table 11. Performance comparison of the proposed constellation for spot coverage.

Constellation	Site	Coverage %	Mean Access Time (s)	Average Gap Time (s)
4retro111	Opportunity	19.4	566	2365
	Phoenix L.	13.7	629	4746
	Polar L.	9.3	515	5485
	Spirit	11.3	482	4982
FC-MARS-single	Opportunity	9.6	759	11895
	Phoenix L.	16.3	485.5	2283
	Polar L.	68.65	907	165
	Spirit	18	1296	4908
FC-MARS-double	Opportunity	16.9	993	7299
	Phoenix L.	22.3	689	2116
	Polar L.	33.2	662	922
	Spirit	21.6	691	4156

With respect to coverage percentage metric, the best performance for Opportunity site is achieved with the 4retro111 constellation even if for all the other sites FC constellations provide better results; in particular the FC-MARS-single is the best choice for Polar Lander site, while FC-MARS-double is the best one for both Phoenix Lander and Spirit sites.

When looking at the overall mean access time performance, it can be stated that the best performance is achieved with FC-MARS-single and FC-MARS-double constallations, giving a mean value of 846 and 758 seconds respectively, while 4retro111 has a mean value of 548 seconds.

Considering the third metric, average gap time, the table shows that the best global performance are privided by FC-MARS-double, having a mean value of 3623 seconds; while 4retro111 and FC-MARS-single have a mean value of 4394 and 4812 seconds (even if the low performance of this last FC is caused by the high average gap time experienced by the Opportunity site).

In table 12, the performance comparison results obtained for regional coverage are shown.

Table 12. Performance comparison of the proposed constellation for regional coverage.

Constellation	Site	Coverage %	Mean Access Time (s)	Average Gap Time (s)
4retro111	Equator	19.7	726	2887
	North Pole	15.8	633	3961
	South Pole	15.8	633	3961
FC-MARS-singleR	Equator	10.8	780	8598
	North Pole	56.5	805	242
	South Pole	64.6	805	242
FC-MARS-doubleR	Equator	20.6	749	2762
	North	43.9	807	731

	Pole			
	South Pole	**38**	**807**	**731**

For what concerns regional coverage, the best coverage percentage are given by FCs, in particular FC-MARS-singleR provides the higher coverage for polar areas, while FC-MARS-doubleR provides the best performance for the equatorial belt and also high perfromance for polar sites.

Also considering mean access time, performance of FCs are higher with respect to 4retro111 for both polar and equatorial regions.

Regarding average gap time 4retro111 and FC-MARS-doubleR provide comparable performance for equatorial region, while FC-MARS-singleR one is not quite good; even if for polar regions this last FC offers the lowest values of gap time. Considering overall performance metrics, FC-MARS-doubleR is certainly the best choice.

6. CONCLUSION

The paper analyzed and proposed a constellation of martian orbiters aimed to communication services to landed elements (e.g. rovers, landers, probes) located on areas with scientific interest. We designed optimized FCs providing high access duration and low gap duration. The optimization of the FCs has been performed for spot coverage and regional coverage. It has been found that our proposed FCs provide better performance with respect to the reference constellation 4retro111 in terms of coverage %, mean access time and average gap duration.

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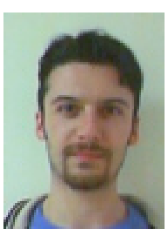

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