Coverage Analysis in Case of Faults of Some Satellites in Low Earth Orbit Satellite Constellations

PARK, Chan-Wang

University of Science and Technology in Lille1
Cité Scientifique, Avenue Poincaré B.P.69
59652, Villeneuve d'Ascq, FRANCE
Tel : +33-3-20-19-78-67
Fax :+33-3-20-47-05-98
e-mail : park@IEMN.Univ-Lille1.fr

Abstract. In this paper we analyze the coverage performance of satellite constellation specially in low earth orbit. Fist of all we analyze the various possible configuration of combinations of failures of satellites in the same orbital plane or in different orbital planes when one satellite or a number of satellites are in faults. To evaluate the performances of constellation we use one parameter, which is the maximum non-visibility time at one receiver position on earth by using simulation software. Also we have simulated by varying the latitude of the receiver position from 0 degree to 90 degrees to analyze the coverage performance variations depending on the receiver position on earth. According to the results of the simulations we compare the maximum non-visibility time depending on the configuration of failure of satellites and identified the worst case of combination of satellite failures in satellite constellation. Finally we evaluate the some orbital maneuver strategy, (phase changing in the same orbital plane), to minimize the non-visibility time on earth in case of failure of number of satellites.

Introduction

There are some satellite constellations[1,2,3] are already proposed and will be providing the commercial service to give the global coverage of communications. All of these satellite constellations with fixed altitude and with determined some number of satellites per orbital plane are optimized to have a optimal coverage.
Although there is inherently some coverage redundancy by adjacent satellites, specially at higher latitudes during system life time maybe there will the random satellite failure and it will give an influence to a large of number of users with significant outage time. So the most of the satellite constellations have some spare satellites in orbit and/or on Earth in case of failure of satellites to provide the given quality of service . But the analysis of failure-configuration of the satellites and the influence of the failure of satellites to the coverage performance of satellite constellation system is reported rarely.

In this paper we will present the various type of the configuration of failures of satellites in LEO and will evaluate the each type of coverage performance. And finally we will propose the some strategy to reduce the degradation of coverage performance.

Constellation of Satellite

The number of satellites required by the global systems varies with altitude. The lowest-altitude system is counting on 66 plus six spares for Iridium constellation and a Medium Earth Orbit (MEO) system needs 10 plus two spare for ICO system. Atmospheric drag and radiation from the inner Van Allen radiation belt are expected to limit the orbital life times of Low Earth Orbit (LEO) satellites, typically from five to eight years. So altitudes between 780 Km and 1400 Km are favored, corresponding with orbital periods between 100 and 113 min. Examples of LEO systems include "Iridium" , "Globalstar", and " Ellipso".

Iridium

Iridium[1] satellites will be distributed among six evenly spaced, near-polar orbits with 86.4 degrees inclination and 780 km above the earth. Sixty-six of the satellites will provide the overlapping global coverage, polar regions included. The other six will be used for in-space spare in case of the failure of satellites.

Globalstar

For Globalstar[2] the system almost covers the globe with a constellation of 48 satellites. They will be located in eight equally populated, circular orbits at 1414 km altitude. Another eight satellites will serve as spares. The orbit are inclined 53 degrees to the equator and spared 45 degrees from one another along the earth's great circle. The inclined orbits concentrate communications between 70 degrees north and south latitude but at the sacrifice of polar coverage. The idea of the Globalstar is that with a minimum number of satellites they can cover the maximum amount of the earth's inhabited territory.

Ellipso

With 17 satellites in three orbital planes for nearly globe coverage Ellipso[3] is expected to operate up to MEO altitude while technically a LEO system. An equatorial ring of seven equally spaced satellites would circle the earth at 8060Km to serve a band between 55 degrees south 25 degrees north altitude. The remaining 10 satellites would equally populate two highly elliptical orbits each inclined 116 degrees. Satellite in these orbit would climb to apogees of 7846 Km in the northern hemisphere and descend to perigees of 520 Km in the southern hemisphere. Thus Ellipso's satellites would appear very high in the sky over the areas of the maximum anticipated demand of communications

In this paper to evaluate the coverage performance we consider the following circular polar orbit constellation. All satellites have the same altitude and each orbital plane has the same inclination angle.

Table 1. Chosen Constellation Type

No. of Total Satellite	66
No. of Orbital Plane	6
No of Satellite per Orbital Plane	11
Orbit Type	LEO
Altitude	780 Km
Inclination	86.4 °
Period	100 min. 28 seconds

Criteria of Analysis

To evaluate the performance of chosen constellation with n number of faulted satellite we chose the parameter which can be compared each others easily. That is the maximum waiting time to see at least one satellite. It give a maximum non-visibility time during the duration of the simulation time. Also the maximum non-visibility time is varied by changing the elevation angle of the receiver on earth. To simplify the simulation we fix the elevation angle with 10 degrees. This simulation is performed by varying the latitude from 0 degree to 90 degrees.

Configuration of Satellites Failures

In the case of many number of failures of satellites in the constellation it is evident that the distribution of failed satellite play a major role for the degradation of the performance of constellation. Figure 1 shows the coverage of a polar satellite constellation. When there are the failures of satellite, specially adjacent satellite is in failure there will be a large holes in the coverage.

Lateral Configuration of Failed Satellites

For the polar or near-polar constellation they have a better coverage in region at high altitude. Thus equatorial regions will have a guaranteed minimum angle of elevation of around 8.5 ° and those near the pole, 12.2 °. By considering that effect if there are some satellites in failure on the same latitude that will be a one type of unfavorable configuration (Type lateral). So as shown in figure 2 we can simulate the lateral failure of satellites from one to six when one observer is on equator (the worst case). Table 2 shows the results of simulation.

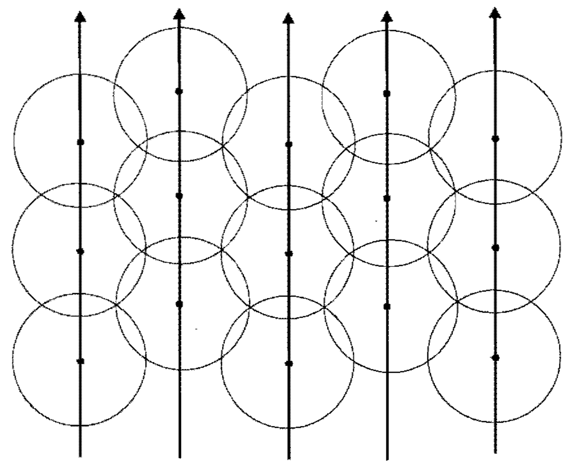

Figure 1. Coverage of a Polar Satellite Constellation

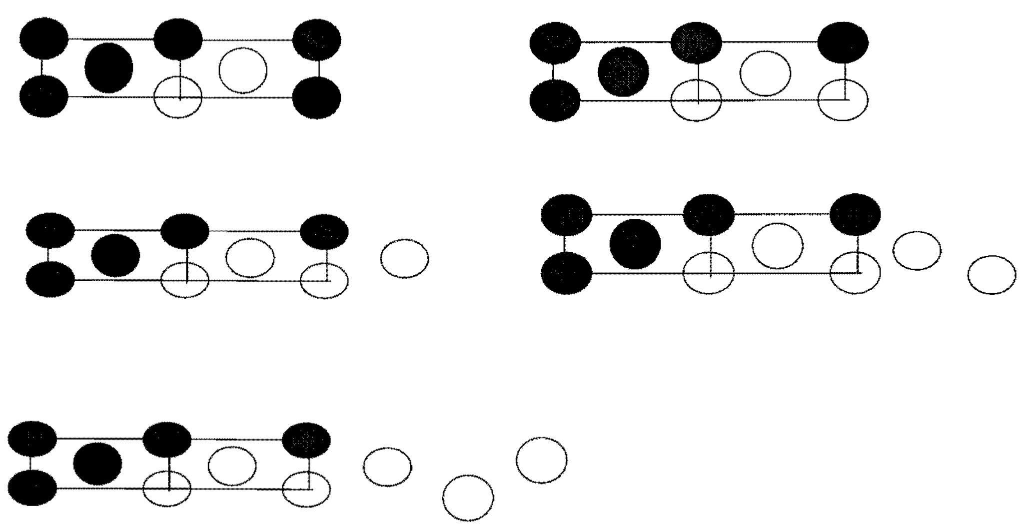

Figure 2 Various Lateral Failure of Satellites

Table 2. Maximum Non-Visibility Time for the Lateral Configuration of Failure

No. of Satellites in Failure	Maximal Non-Visibility Time
1	5 min. 9 s.
2	6 min. 56 s.
3	7 min. 11 s.
4	7 min. 30 s.
5	7 min. 38 s.
6	7 min. 41 s.

As shown the above results the maximum non-visibility time will not be increased from the 2 failed satellites because one observer on earth can not see simultaneously more than three satellite which are in adjacent three orbits.

Table 3 shows the latitude point from which an observer can see at least one satellite permanently even though there are some satellites in failure.

Table 3. Permanent- Visibility Latitude to See at Least One Satellite

No. of Satellites in Failure	Permanent-Visibility Latitude
1	70 °
2	70 °.
3	80 °.
4	80 °
5	80 °
6	90 °

Longitudinal Configuration of Failed Satellites

If there are satellites in failure on the same orbital plane there will be large hole consecutively.

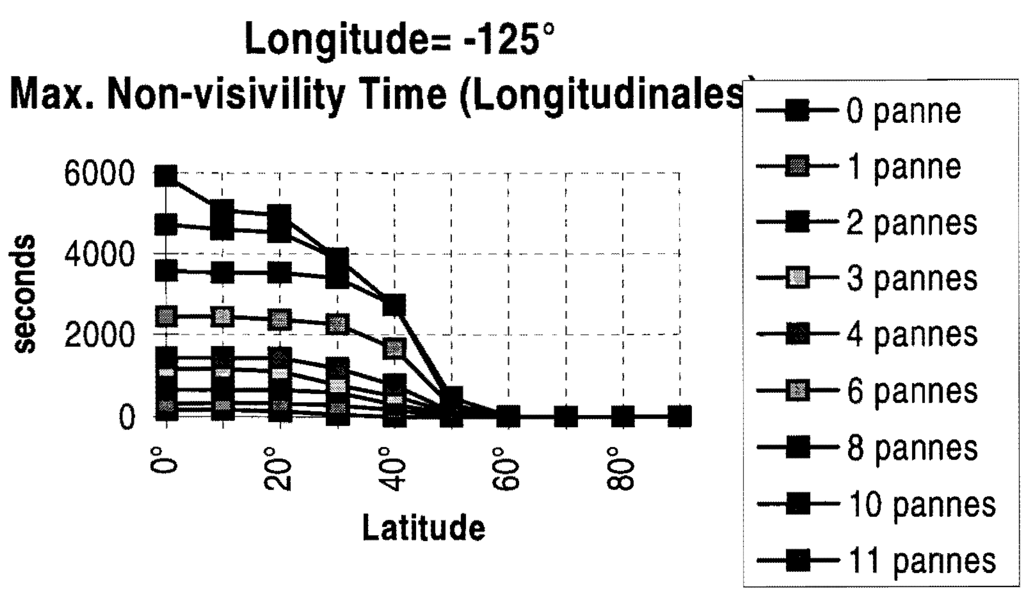

Figure 3. Maximum Non-Visibility Time for Longitudinal Satellites in failure

Two Satellite in failure

In the case of two satellites in failure on the same orbital plane or the different orbital plane the worst case of the maximum non-visibility time is happened when two satellite in series on the same orbital plane (Longitudinal Configuration) as shown in figure 4. Comparing the other type of mixed configuration (longitudinal and lateral) the longitudinal configuration is the worst case and two times bigger than others for the maximum non-visibility time. When we compare the type 2v and 2j on figure 4, the maximum non-visibility time of type 2j is half of than that of type 2j.

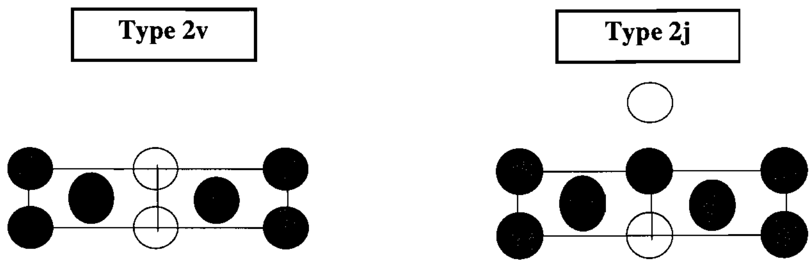

Figure 4. The Worst Type of Two Satellite Failures

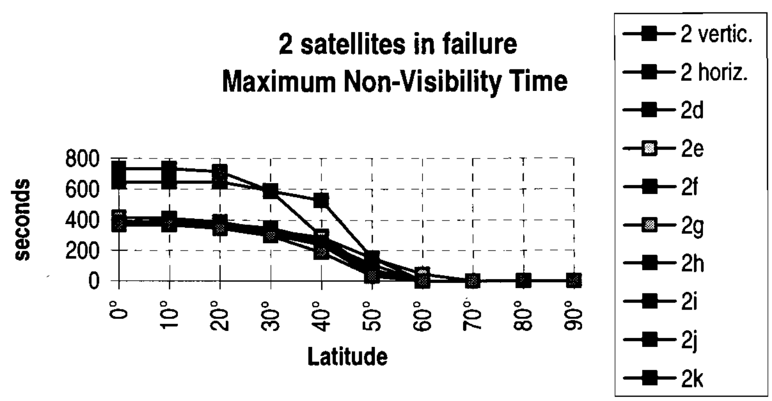

Figure5. Maximum Non-Visibility Time for the Various Type of the Two Satellites Failures in the Constellation

Three Satellite in failure

In this case we can divide three categories of the maximum non-visibility time performance according to the results of the simulation.

- Worst case : three satellite in series in the same orbital plane.
- Two satellite in series in the same orbital plane and one satellite in the different orbital plane.

- mixed lateral configuration without the longitudinal configuration in series.

By comparing the configuration 3v the maximum non-visibility time of type 3h is around half of it (10 min.)

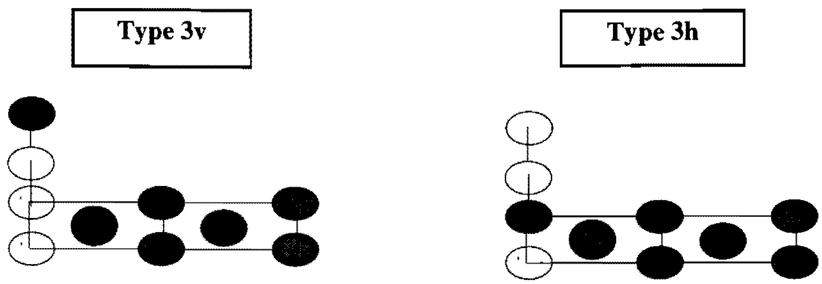

Figure 6. Three Satellites in Failure

Table 4. Maximum Non-Visibility Time for the Three Satellites Failure

	Maximum Non-Visibility Time	**Type of Configuration**
Three satellite in series in the same orbital plane (longitudinal)	19 min. 18 sec.	**3v**
Two satellite in series in the same orbital plane and one satellite in the different orbital plane	10 min.	3d,3e,**3h**,3n,3o, et 3p
Mixed lateral configuration without the longitudinal configuration in series	6min. 30 sec. à 7 min. 23 sec.	3h,3f,3g,3i,3j,3k,3 l, et 3m

Four Satellite in failure

In this case we can divide four categories of the maximum non-visibility time performance according to the results of the simulation as shown on table 5. The worst case is the configuration, type 4v : (four satellites in series in the same orbital plane (longitudinal)). If we compare the following curves of maximum non-visibility time on the function of latitude there are the differences between the configuration linear and block.

- The configuration **linear** :
  - Four satellites longitudinal in series
  - Three satellites in series (longitudinal) with one satellite lateral or one satellite longitudinal
  - Four satellite lateral
- The configuration **block** :
  - Two Satellites in series (longitudinal)in the same orbital plane with the others (e.g. Type 4b)

The curves on figure 8 shows the maximum non-visibility time for the configuration block. Between 40 ° and 90 ° of latitude the maximum non-visibility time is more than that of the others. With this block type of failures the non-visibility time is around 14 min. From 0 ° up to 65 ° latitude on earth.

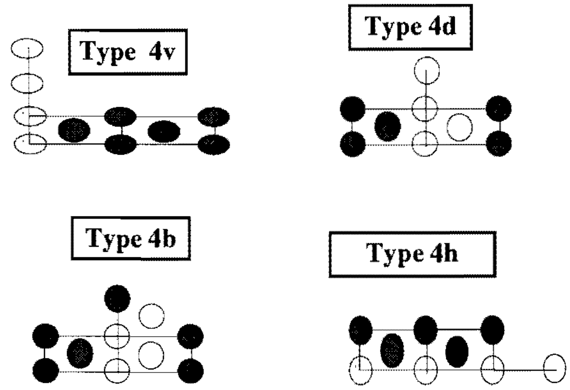

Figure 7. Four Satellites in Failure

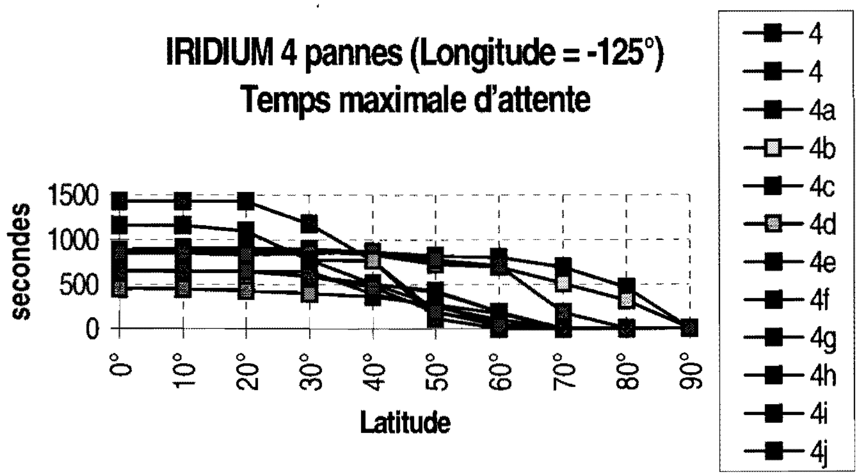

Figure 8. Maximum Non-Visibility Time for the Four Satellites Failure

Table 5. Maximum Non-Visibility Time for the Four Satellites Failure

		Maximum Non-Visibility Time	Type of Configuration
Linear	Four Satellites in series in the same orbital plane (longitudinal)	23 min.	4v (longitudinal)
	Three Satellites in series (longitudinal)in the same orbital plane with one satellite lateral or on satellite longitudinal in different orbital plane	19 min.	4d, 4e, et 4m
	Four Satellites lateral	7 min.	4hor, 4n, 4o
Block	Two Satellites in series (longitudinal)in the same orbital plane with the others	from 10min. to 13 min.	4a, 4b, 4c

Phase Changing Satellites to Reduce the Degradation of Performance

By using the results of the above simulation we can induce a phase changing strategy for the satellite constellation. As we mentioned before most of LEO constellations have their on-orbit spare satellite. So if there are failures of satellites on orbit on-orbit spares can be used to replace the satellite in failure in the same orbital plane or different orbital plane. But far more propellant is needed to change the orbital plane to adjacent planes. So to change the orbital plane is not used generally because of required propellant. So to easily replacing the satellite with a limited time and limited propellant on-orbit spares are stored in each operational orbit and can be used as replacements for satellites in that orbit. So here we consider only the same orbit phase changing to reduce the maximum non-visibility time when there are some satellites in failure on orbit.

One Satellite in failure

The worst case of failure was the type of longitudinal for one satellite in failure. To reduce the degradation of performance we changing the phase of adjacent satellite as shown on figures 9 and 10. By changing the phase we can reduce the maximum non-visibility time from 6 min to 3 min.

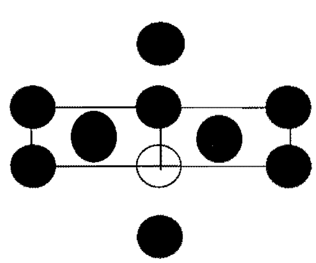

Figure 9. Before Phase Changing

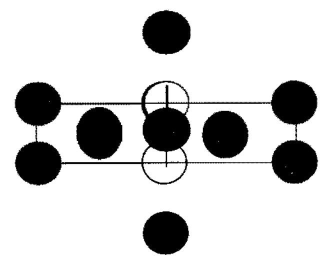

Figure10. After Phase Changing

Two Satellites in failure

we changing the phase of adjacent satellite as shown on figures 11 and 12. By changing the phase we can reduce from 11 min to 6 min.

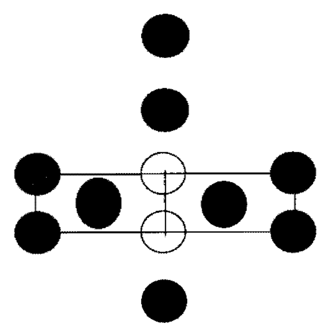

Figure 11. Before Phase Changing

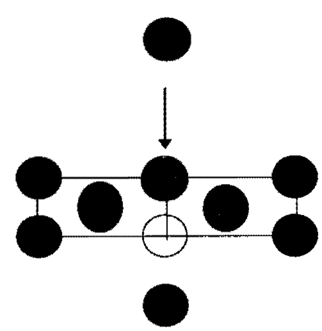

Figure12. After Phase Changing

Two Satellites in failure

we changing the phase of adjacent satellite as shown on figures 13 and 14. By changing the phase we can reduce from 19 min to 9 min.

Conclusions

In this paper we analyze the various possible configuration of failures of satellites in LEO. As a parameter we use a maximum non-visibility time to analyze it. And identify the worst case of configuration of satellites in failure for the each number of failure of satellites. The worst case was the longitudinal case. To reduce the degradation effect we changing the phase of the adjacent satellite in failure and compare the coverage performance. By comparing it we show the enhancement the coverage performance.

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