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Optimizing Space Constellations for Mobile Satellite Systems.

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ABSTRACT

Designing a mobile satellite system entails many complex trade-offs between a great number of parameters including: capacity, complexity of the payload, constellation geometry, number of satellites, quality of coverage ...

This paper aims at defining a methodology which tries to split the variables to give rapidly some first results.

The major input considered is the traffic assumption which would be offered by the system.

A first key step is the choice of the best Rider or Walker constellation geometries - with different numbers of satellites - to insure a good quality of coverage over a selected service area.

Another aspect to be addressed is the possible altitude location of the constellation, since it is limited by many constraints. The altitude ranges that seem appropriate considering the spatial environment, the launch and orbit keeping policy and the feasibility of the antenna allowing sufficient frequency reuse are briefly analysed.

To support these first considerations, some "reference constellations" with similar coverage quality are chosen. The in-orbit capacity needed to support the assumed traffic is computed versus altitude.

Finally, the exact number of satellite is determined. It comes as an optimum between a small number of satellites offering a high (and costly) power margin in bad propagation situation and a great number of less powerful satellites granting the same quality of service.

INTRODUCTION

The market recorded a few years ago a large increase of interest in mobile communications.

The first systems were analogic terrestrial systems with low capacity and low coverage area.

Maritime mobile communications provided by Inmarsat satellites on geostationnary orbits offered global coverage but with low capacity requiring powerful terminals.

Today, with the progress of technologies and the expansion of cellular digital systems, the terrestrial systems can provide large capacity with real handset terminals but the problem of large coverage is still remaining. A solution could be to use satellites to complete the cellular coverage for large regions having a low traffic density. The geostationnary orbit shows some limitations for such missions (big antennas, large propagation delays ...); others solutions based on low earth orbit (LEO) or intermediate circular orbit (ICO) are proposed.

However, the choice of such constellation parameters (number of satellites, altitude, inclination angle ...) is difficult because depending on a lot of interleaved variables.

The scope of our study is to propose a simple first optimization method which takes into account the major constraints for a decoupled choice of each of the constellation parameters.

TRAFFIC ASSUMPTION

Several hypothesis sustain the analysis:

- The service is a mobile satellite voice telecommunication service compatible with handset terminals.
- The quality shall be nearly the same than for cellular voice systems in term of availability, the terminal will weight less than 600g, and have an autonomy of approximatively 1 hour in active mode and around 10 hours in sleeping mode.
- The bandwith available is nearly 10 MHz in L band for the mobile return link and nearly 10 MHz in S band for the mobile forward link.

The number of subscriber and their repartition has an important impact on this optimization. As an example, the calculation is conducted here on the basis of the inputs stated in the FCC filings [1].

SATELLITE CONSTELLATIONS

The technical litterature describes a great number of satellite constellations, with elliptical or circular orbits, polar or inclined, different ways to dispose the satellites into planes ...

In term of quality of coverage, the studies of Rider [2], Beste, Walker [3], Luders or Ballard [4] show different kinds of polar or inclinated circular orbits which give the best results for a worldwide coverage. The satellites are homogeneously distributed between several planes equally inclinated.

The High Inclinated Orbit (HIO) with elliptical orbit is a good solution for regional coverage, the satellite stay during long periods on the provided region, however in our case, the problem of such orbit is the same than for geostationnary orbit, the distance between the mobile and the satellite beeing too important.

A constellation can be described with a few parameters. These parameters have been regrouped in 3 major points:

- The number of satellites.
- The orbit altitude (or the period).
- The geometry of the constellation which correspond to the repartition of the satellites into planes, the location of this planes around the world, inclination angle and the phasing angle between 2 satellites belonging to adjacent planes.

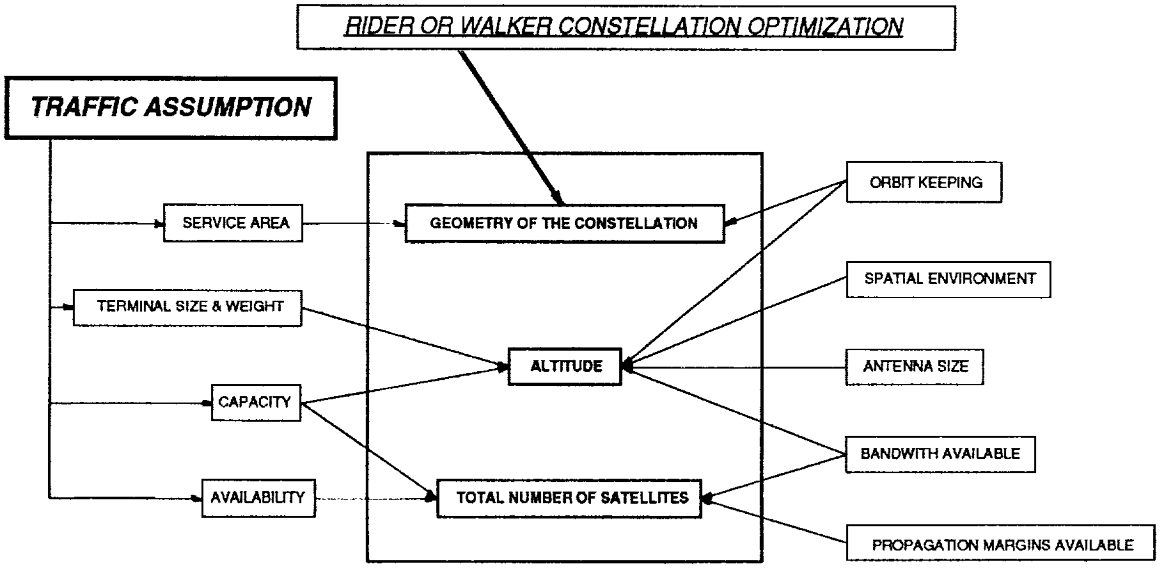

figure 1: Constellation optimization methodology

The method leads to an optimization of each of these 3 points separately in order to minimise the cost of the mission for the service required. For a first approach of this problem, only the most important constraints are taken into account for the optimization of each parameter (figure 1). Further comparisons around these solutions would of course be needed to validate and refine the results.

The first study is on the constellation geometry which is chosen to provide the best quality of coverage for the desired regions. Then, the altitude and number of satellites are analysed.

OPTIMIZATION

Geometry of the Constellation

The constellations which are taken into account are the polar Rider constellations and the Walker or Ballard constellations.

Polar Rider Constellations

The best polar constellations for a large range of number of satellites, global or zonal coverage and for single or multiple visibility have already been identified by Rider.

For such constellations the coverage becomes better as latitude increase. There is no way to favour some medium latitude.

For single visibility and global coverage the Rider constellations are the best ones already identified for a number of satellites greater than 15.

Walker Constellations

The other kind of constellations studied are the inclinated regular Walker [3] or Ballard [4] constellations. They are identified to provide worldwide coverage with single or multiple visibility levels.

For single visibility, the Walker constellations are better than Rider ones when the number of satellites is equal or less than 15.

However, this is not the only interest for Walker constellations. In fact the coverage of the entire world is not always a priority for a mobile telecommunication system. The coverage of high populated land masses could be sufficient. In such a case, "Walker-like" constellations can favour the latitude where the majority of the subscriber occur.

To analyse the quality of coverage for these constellations, large computations have been initiated. The time and space distribution of D, the distance between a location on the earth and the nearest sub-satellite point is calculated for each latitude and for a number of satellites varying from 5 to 99 (for a given altitude, this distribution directly corresponds to the elevation angle distribution).

For a number of satellite lower than 13, all the factorisation of the number of planes versus the number of satellite per planes with every possible phase number [3] and every inclination angle between 30° and 90° are computed.

For larger number of satellites, the number of satellites per planes shall not exceed 4 times the number of planes and vice versa: too many planes will be very costly to be launched and too many satellites per plane create overlaps incompatible with the optimization.

Several thousand of constellations have been analysed.

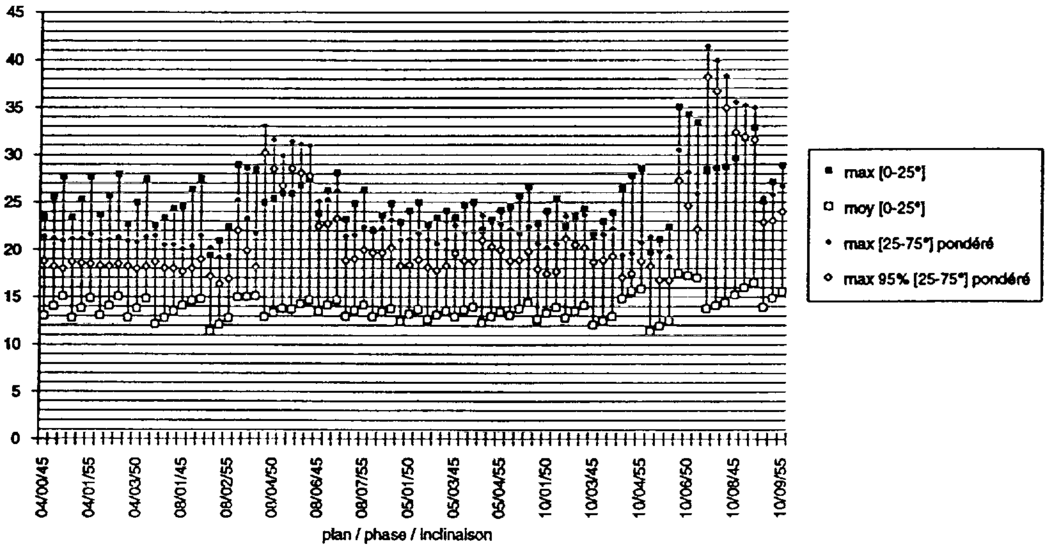

figure 2: 40 satellites geometry quality comparison for 45°, 50° and 55° inclination angles

Optimized Geometry

In accordance with the service area, we will focused on "Walker-like" constellations inclined around 50°. Four quality criterias are defined to perform the best constellations in relation with the assumed traffic distribution:

- The maximum and average values of D - the distance between a location on the earth and the nearest sub-satellite point - for latitudes between 0° and 25°.
- The maximum and the 95% values - over time and space - of D for latitudes between 25° and 70° weighted by the percentage of the traffic density on these latitudes.

In accordance with these coefficient values, for some different numbers of satellites, the best constellation geometries are identified.

An exemple of 40 satellites comparison is given in figure 2

Altitude

The choice of the altitude is the result of a very difficult trade-off due to the number of constraints and implications. But several options can be put aside.

First, the ranges of altitude acceptable for spatial environment and orbit keeping policy reasons must be identified.

Then, the in-orbit capacity is compared for several constellations at different altitudes on the basis of similar coverage quality.

A further point must be assessed: the feasability of the satellite antennas, having the size and the number of beams needed for the capacity estimation.

The best altitude are identified and the launch policy is later approached for these different altitudes.

Spatial environment & orbit keeping

Electronics and solar arrays are affected by the ionizing radiations.

Different kind of radiations occur with more or less intensity depending on altitude and inclination angle [5]. Solar radiations correspond to proton or heavy ions radiations. Galactic radiations are composed of heavy ions.

The terrestrial magnetic field interfere with the magnetic field created by these radiations and trap the particle around the earth. These regions of trapped particle are defined as the Van Allen belts. The location of these belts fluctuate with time depending on solar activity.

3 kinds of phenomena occur in the presense of ionizing radiations:

- Background noise proportional to the radiation flow in the equipments
- Defaults on the material structure due to the quantities of radiations received for a long time. The solars array performances decrease with these quantities. If a maximum loss of a 25% of the capacity is accepted over 10 years, Si cell utilisation exclude altitude ranging between 1500 and 10.000 km on 50° inclinated orbits.
- Single event (SE) which are aleatory phenomena appearing sometimes during the crossing of only one high ionizing particle.

The SE can be destructive (SEL) or can only involve a temporary loss of informations (SEU). The occurence of SE on electronics depend on their level of integration and their technologies. The Linear Energy Transfert (LET) depending on the material (1Mev/mm for Si) and the critical value L_S of the LET define the component sensibility to SE. No SE occur when the LET is lower than L_S but this lead to low integration levels; in the opposite, high integrated component levels with low L_S lead to SE occurence when the particles encountered are sufficiently energetic. A lot of studies have been made on several components by CNES and ESA laboratories using CREME or NOVICE softwares to compute the LET and L_S values. On 50° inclinated orbits it is recommended to avoid the range of altitude between 2000 and 3200 km and above 12.000 km.

Another problem must be assessed: the orbit keeping policy, since the constellation net tends to get distorted with time.

The satellite trajectory is affected by several factors. The principal one is the earth gravitation, then the flattening of the earth at the poles, the atmospheric rubbing, the moon and solar attraction and the solar radiation pressure [7].

These constraints lead to change the orbit parameters. There is a decrease in altitude, fluctuations on inclination angle, an orbit ascension node drift and fluctuations on the true anomaly.

In the case of satellites constellations only the relative location between satellites is important. The ascension node drift and the inclination angle fluctuations are the same for all the satellites in the first order of magnitude. On the contrary, the true anomaly fluctuate differently for different satellites. However this correction doesn't depend much on the orbit altitude.

The decrease of altitude is related to atmospheric rubbing and solar radiation pressure. It depends on the initial altitude orbit, and in a second order of the inclination angle.

h (km)	770	860	1300	1600
Dh (km) atmos. rubbing	140	37	2	1
Dh (km) solar radiation	4.6	4.7	5.2	5.4
ergol consum. (kg)	9.2	4.2	0.7	0.8

figure 3

Figure 3 shows the altitude decrease for a 320 kg satellite with 7 m^2 section on 6 years life.

In term of orbit keeping, the altitude will be kept above 750 km with preference for altitudes greater than 1000 km.

These first studies on the altitude determination identify two ranges of altitude:

- Between 750 km and 2000 km (or 1000 km and 1500 km prefered).
- Between 10.000 and 12.000 km.

In orbit capacity

In the ranges of altitudes already identified, some of the best constellations found with the criteria defined in the " traffic assumption " paragraph, are considered in order to provide equal quality coverage. This leads to select:

A - 99 satellites, 770 km altitude (99/11/1/53).
B - 63 satellites, 1000 km altitude (63/9/1/53).
C - 40 satellites, 1400 km altitude (40/8/2/52).
D - 27 satellites, 2000 km altitude (27/9/5/50).
E - 8 satellites, 10.000 km altitude (8/4/2/50).

These results display an important decrease of the required capacity as the altitude increases.

The choice of the higher altitudes should be the better one; however, for altitude near 10.000 km the number of channels required on a single satellite can be critical.

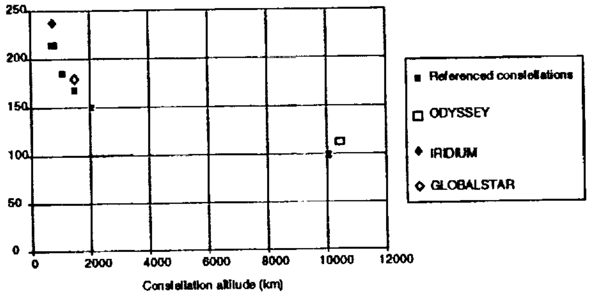

figure 5: Relative capacity in orbit to carry 90% of the traffic

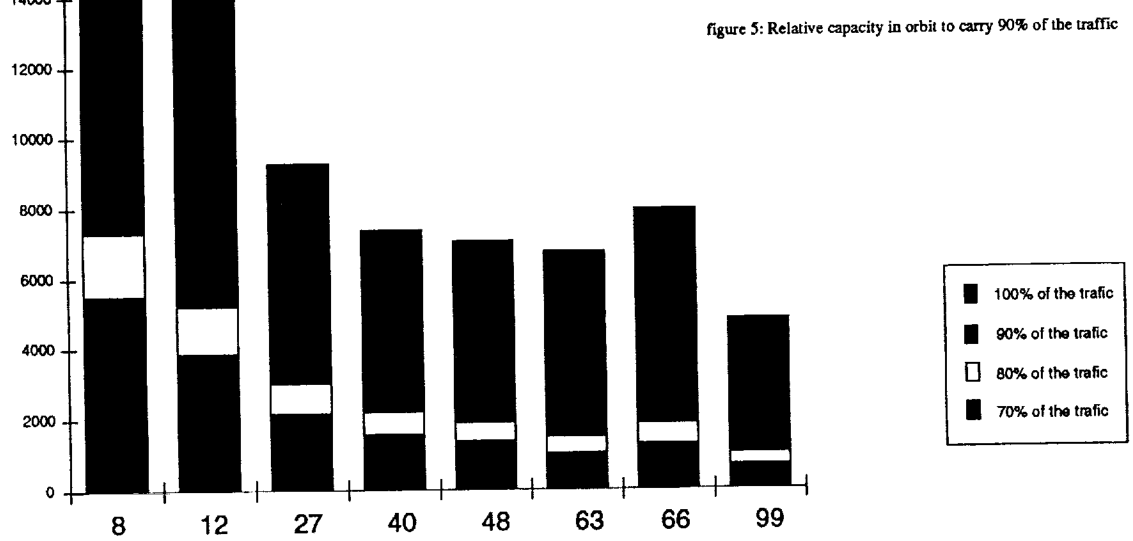

figure 4: Satellite capacity (in number of channels) versus the percentage of traffic carried

An Iridium-like constellation (which provides lower quality of coverage) a Globalstar-like and an Odyssey-like constellation (which both provide better quality coverage) are also considered.

A model computes the satellites load versus time. For a mobile, the usefull satellite is the satellite which is in view with the highest elevation angle. The model takes into account the subscriber breakdown into several earth regions. A daily variation traffic curve is considered in the model. The satellite capacities needed to carry x% of the traffic are shown for the different constellations in figure 4.

The capacity required to be launched for each constellation is computed and compared to the reference constellation E. Results are shown in figure 5 for 90% of the call request provided.

Antenna size

The choise of the altitude depends also on the satellite feasability.

The mobile system makes the coverage with several spot beams. The number of spot beams needed depends on the maximum capacity that a beam should be able to support and on the total bandwith available. The size of these spot beams needs to be small enough to increase the satellite gain and then minimise the power consumption at both the satellite and the mobile terminal. A 1000 km diameter is assumed.

Circular beams allow a 7 cell frequency reuse pattern over an hexagonal structure.

The antenna size is calculated versus the altitude for the 1000 km diameter spot beams.

Calculation are carried to comfirm that the traffic can be supported by these values.

The antenna diameters found for the various altitudes are given in figure 6. These results point out that a 10.000 km altitude is related with an achievable antenna size and complexity.

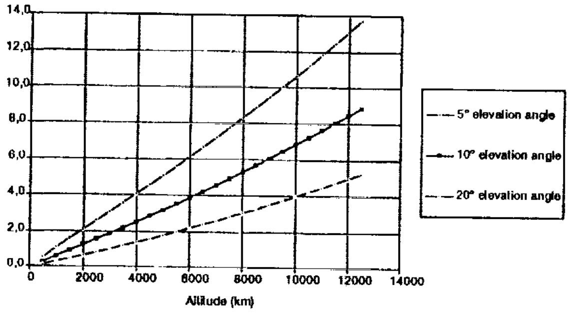

figure 6: L Band antenna size (m) versus the altitude

Altitude Conclusions

Two ranges of adequate altitudes are identified; between 750 and 2000 km and between 10.000 and 12.000 km.

As far as the LEOs are concerned, the prefered altitudes are the higher ones: they minimise the number of satellites to be launched and the in-orbit capacity. In fact, if the required number of channels were much larger, the choice of lower altitudes could be jpreferable. In the case studied here, an altitude around 1500 km is selected to minimise the radiation effect problems: constellation C is a good candidate.

A further study would be required to refine the launch strategy. Considering the launchers available in the late 90ies (including Atlas, Ariane 4 and 5) multiple launches could be used for the LEO C constellation targetting 1 or 2 planes per launch. Dual launches could be used for the ICO E constellation. The satellite design will have to comply with the fairing of volume and the mass performances of the launchers.

Number of satellites

The number of satellites, for a given altitude, influences the quality of the coverage.

Using a simulation model, the average propagation margins necessary on the satellite and on the mobile terminal is computed for some different qualities of coverage through the combination of the elevation angle distribution between the mobiles and the satellite and the differents margins corresponding to these elevation angles.

The different margins are evaluated for each elevation angles through a Lutz propagation model [7]. They are computed for different availability, different Bit Error Rate (BER), different surroundings, different interleaving and different coding rates assumption.

The choice of the number of satellites correspond to a quality of coverage optimizing the average power margin versus the satellite sizing.

CONCLUSION

This paper describes a method to select satellite constellations responding to particular traffic assumption and service quality. Many elements like multiple access, modulation, hand-over technique ..., influence the final performances. However, they mostly stand as possible ways to improve the first approach based on traffic distribution over latitudes, constellation geometry, altitude, capacity and propagation margins.

In the case studied here, Walker constellations inclinated at 50° are prefered. Two altitudes are favorable: around 1500 km or around 10.000 km. The number of satellites will depend of the optimization between the average power margin and the satellite sizing.

A final choice between these 2 alternatives will be based on the comparison of their cost implied to manufacture and launch the 2 systems.

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