

The Design and Networking of Dynamic Satellite Constellations for Global Mobile Communication Systems.

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ABSTRACT

Various design factors for Mobile Satellite Systems, whose aim is to provide worldwide voice and data communications to users with handheld terminals, are examined. Two Network segments are identified - the Ground Segment (GS) and the Space Segment (SS) and are seen to be highly dependent on each other. The overall architecture must therefore be adapted to both of these segments, rather than each being optimised according to its own criteria. Terrestrial networks are grouped and called the Terrestrial Segment (TS). In the SS, of fundamental importance is the constellation altitude. The effect of the altitude on decisions such as constellation design choice and on Network aspects like call handover statistics are fundamental. Orbit resonance is introduced and referred to throughout. It is specifically examined for its useful properties relating to GS/SS connectivities.

INTRODUCTION

Recently there has been great interest in the provision of a mobile satellite communications service to users with handheld terminals. Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite constellations are expected to play a key role in such mobile satellite communication

systems. These constellations are grouped together here and called Dynamic Satellite Constellations (DSCs) - due to their similar Earth visibility and Networking properties. Current DSC proposals are grouped, approximately, around either 1,000 km or 10,000 km. Earths inner radiation bands, centered around altitudes of 0.4 (electron) and 0.7 (proton) earth radii (6,378 km at the equator) are the main factors cited, however valid, when the avoidance of intervening altitudes is being justified. The futuristic scenario for world mobile communication systems are hybrid systems with fully integrated satellite and terrestrial segments[1]. More pragmatic integration scenarios are envisaged for first generation satellite systems - with interoperability with certain Public Land Mobile Networks (PLMNs), through the use of dual-mode terminals, being the early goal before further system integration is envisaged.

This paper outlines and links together important factors which need consideration for the design of these first generation DSC Networks. These mainly include SS and GS factors but some TS considerations are mentioned. Within the SS the constellation altitude is the fundamental driver. It directly effects satellite numbers and sizes and therefore launch factors. It affects the GS at a Network level in areas such as ground station distribution and call handover frequency. At a

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physical level it effects factors such as doppler shifts and link budget calculations. Aspects such as Free Space Loss (FSL) variations over the coverage area, minimum elevation angle, user terminal antenna gain and satellite antenna gain are all relevant link variables[2]. The TS is important from both an interoperability point of view and also from a GS connectivity point of view

DSC NETWORK SETUP

For this 1st generation DSC Network Architecture (NA) fully transparent satellites are assumed. Although there could be an advantage from a Network connectivity point of view, Inter-Satellite Links (ISLs) are not envisaged. There are both technical (eg. risk associated with new technologies in space) and non-technical (eg. Fixed operators fear of being by-passed) reasons why this approach is favoured. The architecture is shown in Figure 1 and its elements are now described.

A Primary Earth Station (PES) interfaces directly between the Space Segment (SS) and the Ground Segment (GS) and also between the GS and the TS. With transparent satellites each satellite needs to have a controlling PES (PES/c) in close contact with it. These are located within the satellites coverage area. Both PES types (controlling and ordinary) are involved in Network control. They are expected to be distributed around the Network at varying levels of density. Other elements, not shown but which are associated with a PES, are its Home Location Register/space (HLR/s) and its Visitor Location Register/space (VLR/s). These help with user Mobility Management (MM) and interoperability with PLMNs. For the satellite to PES link, the minimum elevation angle, e_{min} , can be lower than for the Satellite to Universal Terminal (UT) link. This is due to less variable propagation factors and results in the satellites radius of coverage for PESs being larger.

Constellation altitude directly affects the GS architecture. Each satellite in the constellation has one PES/c in its coverage area which controls the use of the satellites resources and coordinates all the UTs within the satellites UT coverage area. For LEO DSCs, high numbers of satellites are required

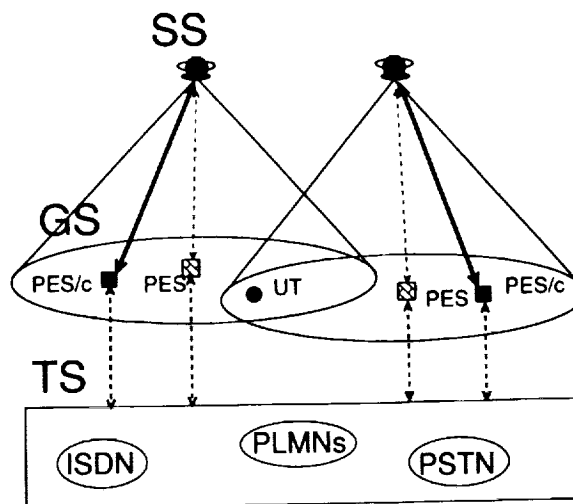


Figure 1

in order to provide even a low elevation angle coverage. This results in the Network requiring equivalently large numbers of PES/cs. For MEO DSCs, with fewer satellites, fewer PES/cs can be used. System e_{min} can also be more easily increased in MEO DSCs and this helps improve UT propagation conditions.

Satellite diversity is a very useful DSC Network property which involves the UT being in range of more than one satellite. The UT therefore has a choice of satellites available to it, through which the Network can route a call, as current traffic loadings determine. MEO DSCs, because of their greater satellite coverage overlap, generally offer the UT a higher level of satellite diversity, especially in mid-latitudes. For polar LEO constellations, satellite diversity is generally very low (eg. the Iridium constellation). The location of PES/cs could be such as to take advantage of satellite diversity, allowing lower numbers of PES/cs than satellites and thus simplifying Network control.

CONSTELLATION FACTORS

Having now introduced a baseline NA this section examines Network and link parameters which are affected by the choice

of constellation altitude. Resonant orbit altitudes, which result in very useful DSC coverage properties, are specified and explained. The Physical and Network implications of these altitudes are then reviewed.

Resonant Altitudes

The best known resonant orbit is the Geostationary Earth Orbit (GEO) at an altitude of about 36,000 km and with the satellite orbit plane having an inclination of 0 degrees. This means that the satellite remains over the same point on the equator throughout its lifetime. For other altitudes and inclinations, the satellite is always in motion relative to the earth and so a satellite ground track results. By choosing specific altitudes whose period relates to integer divisions of a sidereal day (about 23^h 56 min), the satellites ground track can be made to repeat on a daily basis. This is called orbit resonance.

Orbit resonance is described using a ratio, commonly referred to as L:M with L and M both coprime integers. The satellite then orbits the earth L times every M days. With M set to 1, the repetition period is minimised to one day. Resonant orbits along with some of their coverage parameters for the DSC altitudes of interest, are given in table 1.

Table 1: Resonant Orbits

Orbit L:M	altitude (km)	P_{10} (deg.)	P_{30} (deg.)	P_{10} (km)	P_{30} (km)
15:1	554	15.0	7.2	1,820	1,003
14:1	880	20.1	10.5	2,518	1,511
13:1	1,248	24.6	13.6	3,225	2,071
12:1	1,666	28.7	16.6	3,925	2,652
11:1	2,146	32.5	19.6	4,648	3,302
9:1	3,367	39.9	25.5	6,378	4,848
8:1	4,163	43.4	28.4	7,350	5,790
7:1	5,144	47.0	31.4	8,565	6,942
6:1	6,391	50.5	34.4	9,993	8,339
5:1	8,041	54.2	37.5	11,886	10,147
4:1	10,354	58.0	40.7	14,439	12,583
3:1	13,892	62.0	44.2	18,222	16,332

Resonant Orbit Properties

In a resonant orbit the satellite ground track repeats itself after completing L orbits in M sidereal days, having covered 360 degrees geographical longitude. Resonant orbits therefore have the significant advantage of providing all regions of the globe with coverage patterns which repeat daily[3]. The most important advantages that this lends to the DSC Network concern satellite and frequency control. In any DSC constellation satellite ground tracks are continuously overlapping. As satellite coverage zones overlap, the Network needs to ensure that coverage zones which overlap do not result in harmful interference on DSC Network users. In resonant constellations this can be done most effectively, since, once the control procedure has been devised for one day, the same procedure can, in principle, be used throughout the constellation lifetime.

Apart from SS frequency coordination the other Network advantage provided by resonant constellations is stabilised and fully predictable visibility periods between satellites and the GS - in particular the earth stations (but, for example, it is also relevant to remote, data reporting, UTs). As a satellite passes beyond the range of its current PES/c a new PES/c must be allocated control of that satellite. With resonant orbits this passing over of satellite control can be easily defined, allowing for simple GS coordination between PES/cs. The PES/c must also know, for Resource Management (RM) purposes, which PESs are in visibility of the satellite which it controls. This is very straight forward with resonant orbits. Also, since in the initial DSC design the positioning of a satellites ascending node can be chosen, ground tracks can be optimised to some degree. More significantly, the locations of PES/cs can be made in such a way that allows them to be adapted most effectively to the satellite constellation.

Link Implications

Based on the resonant constellation altitudes of interest, link distance calculations were performed. The results are also tabulated in table 1. Various maximum slant path distances (r) are calculated according to the e_{min} value

used. Through this slant path distance, constellations can be effectively compared in terms of FSL. The significance is clarified with an example - the 4:1 altitude at 10,354 km with $\theta_{min} = 30$ degrees has $r = 12,583$ km. It is 7 dB worse off in terms of FSL than the 14:1 altitude of 880 km with a worldwide θ_{min} of 10 degrees having $r = 2,518$ km. The size of satellite antennae and therefore their gain is related to the satellites final size and intended coverage geometry. DSC satellite numbers and launch implications are also very relevant here.

Satellite Angular Velocity, w

The satellite angular velocity, w , is a basic constellation parameter which depends directly on the constellation altitude. For circular orbits it is a constant. It affects the following: the doppler shift between the UT and the satellite and, also, the velocity of the satellites Sub-Satellite Point (SSP). Table 2 shows the maximum doppler shift (ie. at the highest frequency and at the minimum elevation angle) in the two UT frequency bands of relevance - UT Tx. 1610 - 1626.5 MHz and UT Rx. 2483.5 - 2500 MHz for the resonant altitudes of table 1. The satellites velocity and also its SSP velocity are also given. These magnitudes are important when considering call control statistics such as handover frequency - for both sat(ellite)-to-sat and cell-to-cell handover types.

DSC NETWORK FACTORS

This section mainly concerns the GS of the DSC Network. UT and call related topics are examined, with consideration mainly given to the implications of the physical parameters discussed in the previous section.

Coverage Zone Dimensions

The implications of satellite coverage radius on UT specific aspects are now related with satellite coverage aspects mentioned previously. This basically concerns approaches to user MM and to Network RM. Table 1 shows the earth centered half angle of coverage (b) for specified resonant altitudes and θ_{min} values. These figures are now related

Table 2:Satellite Motion Effects

Orbit L:M	$\omega(10^{-4})$ rads/s $\theta_{min}=10$	V_{sat} km/s	V_{ssp} km/s	Doppler Rx. kHz	Doppler Tx. kHz
15:1	10.94	7.6	7.0	57.6	37.5
14:1	10.21	7.4	6.5	53.8	35.0
13:1	9.48	7.2	6.0	50.0	32.5
12:1	8.75	7.0	5.6	46.1	30.0
11:1	8.02	6.8	5.1	42.3	27.5
9:1	6.56	6.4	4.2	34.6	22.5
8:1	5.83	6.2	3.7	30.7	20.0
7:1	5.1	5.9	3.3	26.9	17.5
6:1	4.37	5.6	2.8	23.0	15.0
5:1	3.65	5.3	2.3	19.2	12.5
4:1	2.92	4.9	1.9	15.4	10.0
3:1	2.19	4.4	1.4	11.5	7.5

to satellite coverage radii and, through different multibeam coverage geometries, to sizes of coverage zones on the earth. For cell-to-cell handovers, satellite coverage zone numbers are required.

Based on the seven cell coverage pattern, the number of coverage zones, N_i , is given by: $N_i = 1 + 3(n+1)n$, where n is the number of layers surrounding the center cell. Three different multibeam configurations are considered: 19 beams ($n = 2$), 37 beams ($n = 3$) and 61 beams ($n = 4$). Using these figures and satellite to UT coverage radii, important information on user Mobility Management (MM) and Network handover statistics can be obtained, which can then be used in studies on examining and optimising the Networks approach in these areas. In the following sections these sizes are considered in terms of Network MM and Network handover statistics. Table 3 lists the satellite coverage radius for different DSC altitudes and a given θ_{min} value. Coverage zone radii for some different multibeam configurations are given in the other columns.

User MM

The most straightforward DSC Network approach to user MM is through UT beamlocation. A UT reports to the different

Table 3: Coverage Options

Orbit L:M	β_{10} (rads)	$S_0^{(km)}$ ($2\beta_{10} a'$)	Beam (km) n = 2	Diam- (km) n = 3	eter (km) n = 4
15:1	0.262	3,346	669	478	372
14:1	0.35	4,468	894	638	496
13:1	0.429	5,466	1,093	781	607
12:1	0.5	6,381	1,276	912	709
11:1	0.568	7,243	1,449	1,035	805
9:1	0.696	8,874	1,775	1,268	986
8:1	0.758	9,669	1,934	1,381	1,074
7:1	0.82	10,457	...	1,494	1,162
6:1	0.882	11,250	...	1,607	1,250
5:1	0.945	12,058	...	1,723	1,340
4:1	1.011	12,896	1,433
3:1	1.081	13,789	1,532

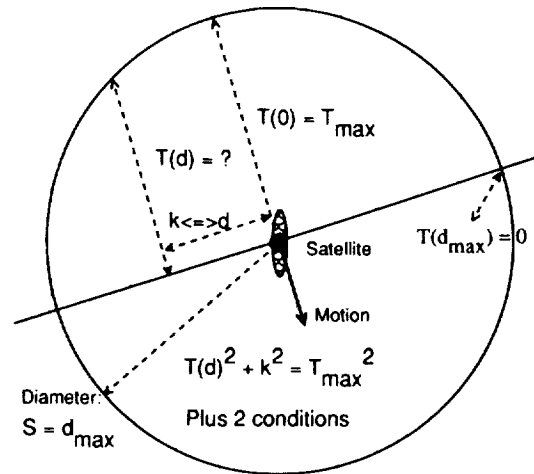


Figure 2

PES/c of the satellites in its visibility. The PES/c(s) concerned then associate the UT, through the coverage zone it used, to a set of Network-specific grid locations. Each of these is individually forwarded to the UTs HLR/s which then selects an appropriate set of grid locations and associates the UT with this set. Variations in the sizes of the satellite coverage zones have a direct bearing on the grid sizes which should be used and hence on the ultimate level of accuracy the Network has concerning the UTs location.

Call Handovers

Based on a satellites orbit period, its coverage diameter and its multibeam geometry, statistics on sat-to-sat and cell-to-cell handover frequencies can be estimated. A simple and accurate approach is now outlined. T(d) is half the visibility period between a satellite and a UT during a satellite pass, with d being the closest approach of the UT to the satellite ground track. T(0) [= T_max] is when the satellite passes directly above the UT and T(d_max) [= 0] is when the satellite passes by the UT at an elevation angle which is just below the e_min of the constellation. The set-up is shown in figure 2 and the problem is to find T(d) for 0 < d < d_max.

From the geometry of Figure 2: $T(d) = (T_{max}^2 - k^2)^{1/2}$. Now since $T(0) = T_{max}$ and $T(d_{max}) = 0$, k becomes: $k = (d \cdot T_{max}^2 / d_{max})$ in which case T(d) becomes:

$$T(d) = [T_{max}^2 (1 - (d/d_{max}))]^{1/2}.$$

Using this simple equation along with a Poisson distribution of call durations, good estimates of sat-to-sat handover statistics can be obtained. Based on initial observations of MEO orbits with reasonable satellite diversity, it is likely that sat-to-sat call handovers can be avoided system through proper consideration at the call routing stage.

A simple extension of the above formula can be used in order to estimate the cell-to-cell handover statistics. The parameters only need slight alterations, depending on the multibeam coverage geometry. The same distribution for mean call duration is used.

CONCLUSION

Many important factors which affect the Networking aspects of DSCs have been reviewed. Through the use of constellation simulation software providing DSC specific data like those detailed above, the basic groundwork is laid from which more detailed DSC Networking studies can be launched.

These would mainly involve the optimisation of the systems approach to user Mobility Management and Network Resource Management. Based on these results, important Network signalling parameters can be studied allowing these channel capacities to be estimated.

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