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Frequencies Above 10 GHz and Future Telecommunication Satellite Systems (**)

1. Introduction

A common feature of future satellite systems, at least for fixed services, will be the use of frequencies above 10 GHz, partly due to saturation of lower frequencies, but mostly in connection with an easier electromagnetic compatibility with terrestrial radio relays, the availability of very large frequency bands (fig. 1) and an easier possibility of obtaining highly directive antennas. A particular feature of an on-board directive antenna is the multibeam antenna, shown in figure 2 and to be discussed in the next paragraph. The other side of the picture is that frequencies above 10 GHz suffer propagation impairments in presence of rain, which produce, among other effects, an attenuation, rapidly increasing with frequency and particularly relevant in locations characterized by heavy rainstorms. As a consequence, several experiments have been set up to acquire propagation data, to be used, on a statistical basis, for system design. Sirio has been the first satellite in Europe to allow such experiments, working at 11.6 and 18 GHz, as indicated in figure 1 which shows also the frequencies experimented by OTS (ESA) and the frequencies to be experimented by Olympus (ESA) and Italsat (Italy).

2. Multibeam Antennas

Whilst a single beam covering the full region to be served is the optimum when the same signal interests all users as in broadcasting, a multibeam system is of interest when each particular user is interested in being connected to a single another user as it is common in telecommunications.

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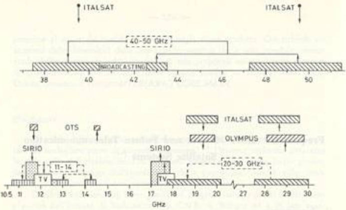

Fig. 1 - Frequency assignments to fixed services in the range between 10 and 50 GHz.

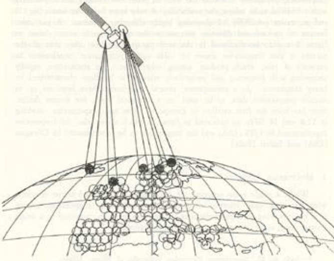

Fig. 2 - Multibeam antennas: case (a): coverage of a certain region with all the beams shown in the figure, each of them serving, in general, a number of stations; case (b): only a few separate beams are activated (for instance the ones particularly marked) each of them serving a single high-traffic station.

In figure 2 case (a) refers to a multibeam configuration in which adjacent beams are used to fully cover a certain service region: it is thus expected that several stations be included in each beam. Case (b) refers to a configuration in which separate beams are used to serve, each of them, a particularly high-traffic station. In both cases, due to the high directivity of each beam, a power gain is achieved, which, concerning the on-board multibeam receiving antenna, increases the power efficiency on the up-link, reducing in particular the power needed from the earth transmitters, and, concerning the multibeam transmitting antenna, increases the power efficiency on the down-link, reducing in particular the power needed from board. Figure 3 shows a configuration in which similar fixed beams are used on the up- and down-links: a switching matrix is needed on board to send to each down-beam the appropriate signals coming from earth. A system of this kind allows to reuse the same frequencies in non-adjacent beams, thus largely increasing the communication capacity. The italian satellite Italsat, working in the 20-30 GHz band and to be launched in 1990, belongs to this category.

3. Propagation

A typical rain — attenuation distribution is shown in figure 4 [3]. From an engineering point of view such distribution report in the abscissae the power

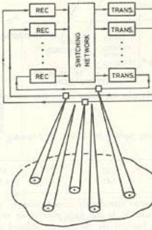

Fig. 3 - A multibeam system with similar fixed beams on the up- and on the down-link.

margin to be adopted to restrict the fractional outage time within the limits indicated in ordinatae.

Characteristic of rain attenuation distributions is that the required power margin is rather low when the accepted outage time is high (for instance 1%) and increases more and more rapidly as the outage time is decreased (down for instance to a few units in 10^{-4}).

Rain attenuation increases very rapidly with frequency: frequency scaling methods have been developed and checked in Europe up to 20 GHz. Approximatively attenuation distributions at 11.6 GHz as shown in fig. 4 can be scaled up in frequency (fig. 5) multiplying the attenuation values according to table 1.

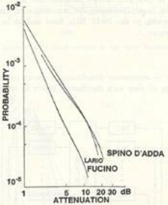

Fig. 4 - Typical attenuation distributions at 11.6 GHz derived from Sirio data.

TABLE 1 — *Multiplying factors for scaling in frequency attenuation data at 11.6 GHz.*

Frequency (GHz)	20	30	45	50
Multipl. Factor	2.45	4.5	6.3	7.5

Rain attenuation varies considerably from location to location as reported in fig. 6. Here, in addition to the Lario distribution measured using Sirio, distributions for other locations are reported, as predicted from rain rate data at earth using the « exponential cell » method. Such method [4, 5] appears to

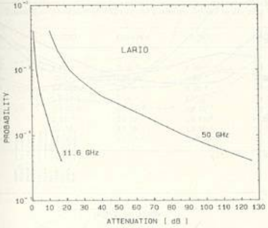

Fig. 5 - Scaling up in frequency to 50 GHz the Lario distribution at 11.6 GHz.

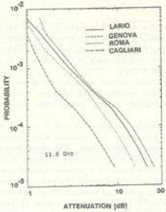

Fig. 6 - Attenuation distribution for various italian locations as predicted from rain rate data, using the « exponential cell » method.

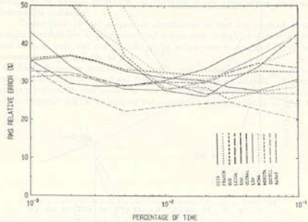

Fig. 7 - Comparison between various methods to predict rain attenuation distributions for rain rate data. The comparison is made over the single year beacon data obtained in Europe from Sirio and OTS. (EXCELL means exponential cell method).

be particularly accurate as indicated in figure 7. Prediction capabilities of this type are very important for designing systems with stations in many locations. Figure 6 indicates that the Lario location, used in the Sirio experiment and to which further reference will be made in the following, is near to the worst conditions to be found in Italy.

Satellite communication systems at frequencies above 10 GHz can be classified in: high-availability systems (outage time per link 10^{-4} or a few units in 10^{-4}) and low-availability systems (outage time per link 10^{-2} or a few units in 10^{-2}).

An interesting boundary between the two is (in each station) the outage probability at which the increase of attenuation with frequency is exactly compensated by the increase in antenna gain. The above boundary is reported in table 2 for various italian locations (reference frequency 11.6 GHz).

High availability is required in « network oriented systems » i.e. systems to be integrated in the terrestrial network. In such conditions *adaptive methods* must be used at least in unfavoured locations and at high frequencies.

These methods profit of the limited extension of heavy rainstorms and include, on one hand, *site diversity* (fig. 8) and, on another hand, the *shared-resource methods* as indicated in the following table 3.

TABLE 2 — *Outage probability at the boundary defined in the text.*

GHz	LARIO	GENOVA	ROMA	CAGLIARI
11.6	—	—	—	—
15	$8\ 10^{-4}$	$7\ 10^{-4}$	$5\ 10^{-4}$	$1.4\ 10^{-4}$
20	10^{-3}	$1.05\ 10^{-3}$	$7\ 10^{-4}$	$2\ 10^{-4}$
25	$1.4\ 10^{-3}$	$1.5\ 10^{-3}$	$9\ 10^{-4}$	$2.7\ 10^{-4}$
30	$1.7\ 10^{-3}$	$2\ 10^{-3}$	$1.1\ 10^{-3}$	$3.4\ 10^{-4}$
35	$1.9\ 10^{-3}$	$2.3\ 10^{-3}$	$1.2\ 10^{-3}$	$3.9\ 10^{-4}$
40	$2\ 10^{-3}$	$2.6\ 10^{-3}$	$1.4\ 10^{-3}$	$4\ 10^{-4}$
45	$2.2\ 10^{-3}$	$2.7\ 10^{-3}$	$1.4\ 10^{-3}$	$5.1\ 10^{-4}$
50	$2.2\ 10^{-3}$	$2.7\ 10^{-3}$	$1.45\ 10^{-3}$	$5.2\ 10^{-4}$

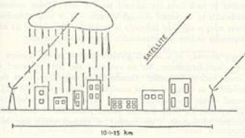

Fig. 8 - Site diversity.

TABLE 3 — *Adaptive methods to counteract rain attenuation in high availability systems.*

site diversity	
	— adaptive coding
shared resource	— frequency diversity
	— control of satellite transmitted power

Adaptive methods can gain: — in power; — in probability. This can be shown easily with reference to site diversity in the limit of statistically independent stations: in this case the overall link outage probability P_0 equals P_{0L}^2, being P_{0L} the outage probability of the single station. For a fixed P_0 the single station must be thus designed to have $P_{0L} = \sqrt{P_0}$. A gain in probability is thus achieved. The gain in power margin is evaluated indirectly by finding on the attenuation distribution the difference between the power margins corresponding to P_0 and to P_{0L}, respectively.

Control of satellite transmitted power can be applied using, toward stations in difficulty due to heavy rain, a larger power, for instance by switching a common power amplifier in the beam in difficulty. Such a « shared resource » method is clearly a method gaining directly in power margin, and only indirectly in probability. In practice the additional power margin which can be made available is limited (for instance 10 dB) so that methods of this type are of modest help when the frequency is increased, especially in unfavoured locations. In addition the considered method can help only downlinks.

Adaptive coding is another shared resource method. It consists in introducing a proper high-efficiency coding in the (up- or down-) links subjected to heavy rain, expanding in such links the allotted time in time-division systems or the allotted bandwidth in frequency division systems. It is thus a method which gains in power margin and only indirectly in probability. As before its advantages at high frequencies and/or in unfavourable locations are limited.

Frequency diversity is a shared resource method which consists in using normally very high frequencies, but in switching the links subjected to heavy rain to a lower back-up frequency. Concerning the high frequencies the system gains in probability as indicated in the examples of figures 9 and 10 [2]. P_{0L} is the link overall outage probability, F_{oo} is the intrinsic outage probability of each higher-frequency link, F_{ss} is the intrinsic outage probability of each back-up link, S is the number of stations, i the number of stations which may be assisted simultaneously.

To evaluate the performance of shared resource methods it is necessary to know the joint attenuation probability distributions. A model which we used (also in figures 9 and 10) is the following: suppose that rain occurs in the overall system only for a fraction 1/h of the total time and that over this fraction of time the attenuation at the various stations be statistically independent. Over the total observation time $h = 1$ means statistical independence whilst $h > 1$ measures the statistical dependence. From the Sirio experiment a few first data have been collected which seem to indicate $h = 20$ for a distance of 85 km and $h = 2$ - 4 for distances of 500 -600 km.

Using figure 7 with $h = 20$ (pessimistic assumption), $P_0 = 4.10^{-4}$ for a full earth-satellite-earth-link, table 4 has been derived for a system working at 20-30 GHz with a back-up band at 12-14 GHz, in which all stations behave like Lario (fig. 4 and 6).

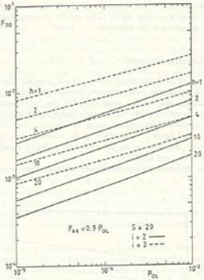

Fig. 9 - F_{00} versus P_{OL} in various conditions.

From table 4 or from figures 9 and 10, it is seen that frequency diversity allows the high-frequency system to be designed as a low-availability system.

So far for high-availability systems and in particular « network oriented systems ». « User oriented systems », i.e. systems with stations directly set up at user premises can accept lower availability, for instance outage times of the

TABLE 4 — *Lario station.*

	12-14 GHz 10 stations at a time		20-30 GHz 90 stations at a time	
	12	14	20	30
Power margin (dB) without diversity (two independent systems)	9.5	9.5	23.5	32
Power margin (dB) with diversity (integrated use of the two bands)	10	10	4	7.2

order of several units in 10^{-3}, i.e. above the threshold reported in table 2. In such conditions millimeter wave (e.g. 40-50 GHz) can be advantageous, provided that the increase in antenna gain be exploited.

4. Network Oriented Systems

Applications on intercontinental routes should preserve their present role of constituting a worldwide communication network, accessible by all countries, including developing and isolated countries. On the heavy-traffic routes, like transatlantic routes, optical cables will strongly compete, but satellites can further improve their economic performance, using for instance the technique of the mentioned case b) of figure 2. Therefore, at the moment, there are no apparent reasons to abandon, on these routes, the traditional policy of equally dividing the traffic between cables and satellites.

As distance decreases to continental and national dimensions, satellites are

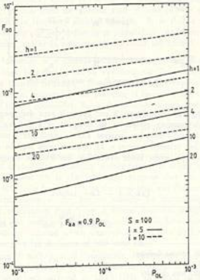

Fig. 10 - F_{aa} verus P_{OL} in various conditions.

in a more difficult situation and must look for applications for which they are particularly suited.

Such applications are based on the following property of the satellite: — capability of anticipating new services, or even the overall communication network as it may happen in developing countries; — capability of connecting isolated locations; — capability of facing emergency situation due to natural disasters or to outages in the terrestrial network; — particular attitude to distribute television programs to the earth transmitters or to local cable networks, etc. Also transmission of live television programs, picked-up in particular locations and sent to studios via satellite, using transportable earth stations, has proved to be a highly appreciated solution.

5. User Oriented Systems

The most extensive (and broadband) service offered directly to the users by satellites will be television broadcasting (associated to audio and data broadcasting). This service takes advantage of two important facts: first of all that satellites are able to fully cover the selected region, serving equally well highly populated cities and isolated locations; secondly, that today powerful satellites may be put into orbit, capable of being received by very small terminals (60 centimeters diameter antennas).

Figure 11 shows, according to the conclusions of the World Administrative Radio Conference of 1977 (WARC 77), some coverages of national television satellites in Europe; each country has available five television channels (or the equivalent in terms of audio programs and data). The coverages exceed largely the national boundaries so that an effective international television system will be set up. It is possible that, taking also advantage of the progresses in the earth receivers, a true european television be organized. The signals are transmitted by the satellite around 12 GHz; the feeder frequencies (up-link) are about 18 GHz. In each channel (having a bandwidth of 27 MHz) it is possible to allocate alternatively: 1) a standard PAL television signal with frequency modulation; 2) a color television signal with the same definition as above, but organized on a time-division basis with luminance and chrominance information in analog form and audio and data in digital form; this is the MAC standard defined by the European Broadcasting Union (EBU) in several version; 3) a high-definition color television signal with a double number of lines with respect to the previous standard and an aspect ratio of about 5:3; it can be allocated in the same channel using advanced redundancy reduction techniques and is particularly suited for presentations on large screen.

It appears of importance, in establishing a satellite television service, to give something new in quality of the programs and of the picture; concerning the latter, it is likely that passing directly to high-definition television would be an important step, also in view of the developments which will follow in broadband services based on optical fibers in the user plant. With respect to this point,

Fig. 11 - Coverages of european broadcasting satellites.

satellite broadcasting is an important anticipation, which must also be used to investigate the interest of users on having available a large number of high-definition programs, as will be the case with the broadband fiber network.

If, instead of unilateral services like broadcasting, bilateral interactive services are taken into consideration to be provided by satellites directly to the users, it becomes much more difficult to preserve the simplicity and economy of the earth terminals. Indeed the fact that the power to be transmitted from earth is a relevant cost factor in the terminal becomes particularly critical. On the other hand, systems of this type are of high interest for business users once again to anticipate new services or to achieve economic and functional advantages from peculiar characteristics of satellite systems, like the capability of reaching easily any point in the coverage area. Satellites are particularly suited for providing point-to-multipoint services (and viceversa), as required for instance to connect the headquarters of big enterprises with their peripheral offices, factories or selling points. They are at their best when providing wideband services from the center to the periphery (like in instructional video-conferences to describe for instance characteristics and maintenance procedures of a new car to the various agencies) and narrow band services in the reserve direction.

In order to allow operation with small and economic earth stations, satellite efficiency must be improved: in this respect the multibeam technique has again a fundamental role. Various schemes may be investigated; for instance, efficiency and simplicity are simultaneously achieved by the scheme of figure 12, in which the gain of the multibeam antenna is used in the up-link to improve

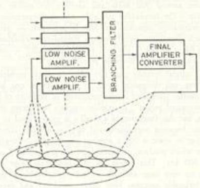

Fig. 12 - Simple system with a multibeam antenna as the up-link (using different frequencies in each beam) and a full-coverage antenna on the down- link for point-to-multipoint operation.

its difficult power budget, while the global coverage in the down-link allows to distribute a common signal to all earth stations in a point-to-multipoint systems [6].

An important remark concerning satellite systems serving directly the business users is that in some applications it could be considered as acceptable, for economic reasons, an outage time as large as 0.5-1%. In such conditions, as mentioned in paragraph 3, frequencies well above 10 GHz could provide very interesting possibilities because the increase in rain attenuation could be well compensated by the increase in antenna gain.

6. Mobile Communications

Mobile communications may only be performed using radio, and satellites can have a fundamental role in this area. For maritime services the Inmarsat organisation has already set up a global network, representing today the backbone for all long distance maritime communications, and can likewise provide aeronautical services. Technical improvements will include once more the adoption of multibeam antennas.

Concerning land mobile services, satellites are presently in a critical situation in the highly developed areas, where the traffic to be handled is very high. The reasons for that arise from the fact that mobile systems tend to use comparatively low frequencies, in order to avoid pointing problems which inevitably arise in the mobile from the intrinsic high directivity of high-frequency antennas, and to alleviate the difficulties of propagation in presence of obstacles, particularly buildings. In fact terrestrial land mobile systems are presently using at most frequencies around 900 MHz and satellite for mobile services operate around 1.5 GHz. The bandwidth available at such frequencies is very narrow and large communication capacities can only be achieved; — partly by reducing the band of each elementary signal through redundancy reduction (for voice the reduction from 64 to 16 kbit/s is a well established result); — mostly by reusing the same frequencies as many times as possible.

Terrestrial cellular systems (fig. 13) solve the latter problem using, in the high traffic zones, cell dimension down to the order of one kilometer. Such a dimension is mainly controlled by the conditions of visibility of the base station and by the transmitted power. In satellite systems multibeam antennas produce the same effect, but the dimension of a « cell » is proportional to the beamwidth, i.e. on the ratio between wavelength and satellite antenna dimension. At 1.5 GHz, even using in space a 30 m antenna diameter, a beamwidth is obtained of half a degree which produces on earth, from the geostationary orbit, a footprint dimension of 300 km. This means on one hand that large efforts must be devoted to set up very large antennas in space (deployable antennas and, more recently, also inflatable antennas have been considered and experimented) and, on the other and, that, in spite of these efforts, satellites will remain very far from the spectrum efficiency of cellular systems.

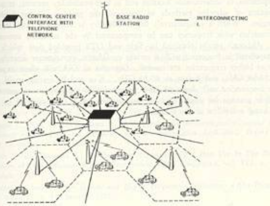

Fig. 13 - Terrestrial cellular system.

In spite of the mentioned difficulties, satellite can play an important role for land mobile services in remote and scarcely developed areas and/or in developed regions (as an alternative to the public cellular system) to complete the coverage of the cellular system and set up private networks within transportation entreprises.

However, satellites could have much better perspectives having available larger frequency bands. Indeed there is a general need that, in revising frequency assignments, large consideration be given to mobile systems, which, as already underlined, may be only set up using radio waves. Another approach is to study the possibility of using with satellites much higher frequencies. This requires first of all to solve the problem of developing a suitable antenna for the land vehicle. Active phased array antennas can be a possible solution, being capable of continuous pointing at the satellite. Also the multibeam on-board antenna can be much easily realized. At the same time investigations are needed concerning propagation in presence of buildings, trees, etc. In this respect an interesting possibility could be the use of highly elliptical inclined orbits in which the satellite is used only around the zenith.

7. Conclusions

Frequencies above 10 GHz are of high interest for future satellite telecommunication systems. They are attenuated by rain by an amount that, at high frequencies, in unfavourable location and in high-availability systems, requires the adoption of adaptive methods to overcome the problem of too high power margins. When a comparatively low availability is acceptable, the increase of attenuation with frequency can be compensated by the increased antenna gain.

Although results obtained by Sirio and OTS provided data which can be estrapolated in frequency with a certain confidence, experiments directly carried out at higher frequencies are needed. Olympus of ESA will allow experiments at 20-30 GHz, and Italsat at 40-50 GHz. Also mobile system could possibly use frequencies well above 10 GHz provided that the problem of pointing the mobile antenna be solved and the propagation amid the buildings be assured by using a satellite at the zenith.

REFERENCES

[1] Carassa F., *Technical Aspects in the Future Development of Satellite Communication Systems with Particular Reference to the Use of Frequencies above 10 GHz.* 19° Convegno Internazionale Scientifico dello Spazio, Roma, 1979.

[2] Carassa F., *Adaptive Methods to Counteract Rain Attenuation Effects in the 20-30 GHz Band.* Space Communication And Broadcasting, Sept. 1984, vol. 2, n. 3.

[3] Carassa F., Mauri M. and Paraboni A., *Long Term Attenuation Statistics at 11.6 GHz in the Three Italian Main Stations.* « Alta Frequenza », vol. LVI, n. 1-2, Jan.-Apr. 1987.

[4] Capsoni C., Fedi F. and Paraboni A., *A Comprehensive Meteorologically-Oriented Methodology for the Prediction Parameters in Telecommunication Applications Beyond 10 GHz*, to appear in Radio Science.

[5] Mauri M. and Paraboni A., *Depolarization Measurements and their Use In The Determination of Dual Polarization Links Performance.* « Alta Frequenza », vol. VLI, n. 1-2, Jan.-Apr. 1987.

[6] Carassa F., *New Satellite Systems and Higher Frequencies Utilisation.* « Alta Frequenza », vol. LVI, n. 1-2, Jan-Apr. 1987.