

LINK BUDGET ANALYSIS FOR NEW SATELLITE TELECOMMUNICATIONS SYSTEMS

THE MALTE PACKAGE

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ABSTRACT

Nowadays, the future satellite systems for telecommunications are designed to provide multimedia services similar to those offered by terrestrial infrastructures. The main objective in the design of such services is to provide a solution allowing the maximum data rate.

This way, the authors propose a new tool, the MALTE package, to analyse accurately link budgets for new satellites operating in the Ka-Band (30 GHz / 20 GHz) allocated for the Fixed Services. The use of this frequency band implies that new problems have to be understood and new challenges overcome: propagation phenomena affect more strongly the transmitted signals, and new technologies have to be developed. Moreover, in order to ensure a high capacity and availability of the transmission links, adaptive modulations and codes are used.

In a first part, the paper recalls the classical method for link budget computation. In a second part, new systems based on adaptivity are shown. Finally, the last parts introduce a new method based on a statistical approach in order to estimate accurately the spatial and temporal availability of the RF links.

KEYWORDS

Adaptivity, DVB-S, DVB-S2, DVB-RCS, Availability, Modulation, Code, Multi-beam, Interference

1 INTRODUCTION

Future satellite systems for telecommunications are designed today in the Ka-Band (30 GHz / 20 GHz) allocated for the Fixed Services. The use of the Ka-Band implies stronger propagation phenomena, new technologies and new air interface based on adaptive modulations and codes. The classical method for link budget computation is in general used, at the first level, to validate the feasibility of the system.

2 CLASSICAL METHOD FOR LINK BUDGET COMPUTATION

Most of the current satellite communications systems provide TV, radio or news broadcasting services. The C- and Ku- frequency bands are used and the same data are broadcasted to all users. Therefore, to make the radiated power sufficient, a simple link budget has to be computed for a single link corresponding to the worst case. For this worst case, a user located at end of coverage of a spot beam affected by propagation impairments (for example the attenuation exceeded during 0.1 % of time to ensure an availability of the service greater than 99,9% of the time) is considered.

The link budget is computed thanks to the formula:

$$\frac{C}{N_0} = P_T G_T \cdot \frac{1}{L} \cdot \frac{G_R}{T} \cdot \frac{1}{k}$$

where

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- $\frac{C}{N_0}$ is the useful signal to spectral density noise power ratio (dBHz)

- $P_T G_T$ is the transmitter EIRP (Equivalent Isotropic Radiated Power) of the transmitter (dBW)

P_T is the power of the carrier at emission

G_T is the antenna gain of the transmitter

- $\frac{1}{L}$ corresponds to the path losses (free space, propagation) (dB)

- $\frac{G_R}{T}$ is the receiver figure of merit (dB/K)

G_R is the antenna gain of the receiver

T is the system temperature at receiver level

The propagation impairments can be computed as an attenuation exceeded during a given percentage of time equal to the system unavailability thanks to the ITU (International Telecommunication Union) models.

The computation of the link budget is performed for the links from the gateway to the satellite and from the satellite to the terminal user. The total signal to noise spectral density ratio is obtained by the following formula :

$$\left(\frac{C}{N_0}\right)_{Total}^{-1} = \left(\frac{C}{N_0}\right)_{Up}^{-1} + \left(\frac{C}{N_0}\right)_{Down}^{-1}$$

$\left(\frac{C}{N_0}\right)_{Total}$ is the final useful signal to spectral density noise power ratio

$\left(\frac{C}{N_0}\right)_{Up}$ is the uplink useful signal to spectral density noise power ratio

$\left(\frac{C}{N_0}\right)_{Down}$ is the downlink useful signal to spectral noise density power ratio

3 NEW MULTIMEDIA SYSTEMS USING ADAPTIVITY AND KA BAND

Today, new telecommunications systems are migrating from broadcasting services like radio, TV to interactive services such as internet, video on demand, voice over IP...

The most used standard for satellite broadcasting transmission is the DVB-S (Digital Video Broadcasting by Satellite), that proposes a simple and efficient physical layer. To manage interactivity, DVB Forum has defined a complementary solution, the DVB-RCS (Digital Video Broadcasting – Return Channel by Satellite), that combine to a forward link in DVB-S a return link based on MF-TDMA (Multi-Frequency - Time Division Multiple Access) access.

Next figure depicts the principle of a DVB-RCS network.

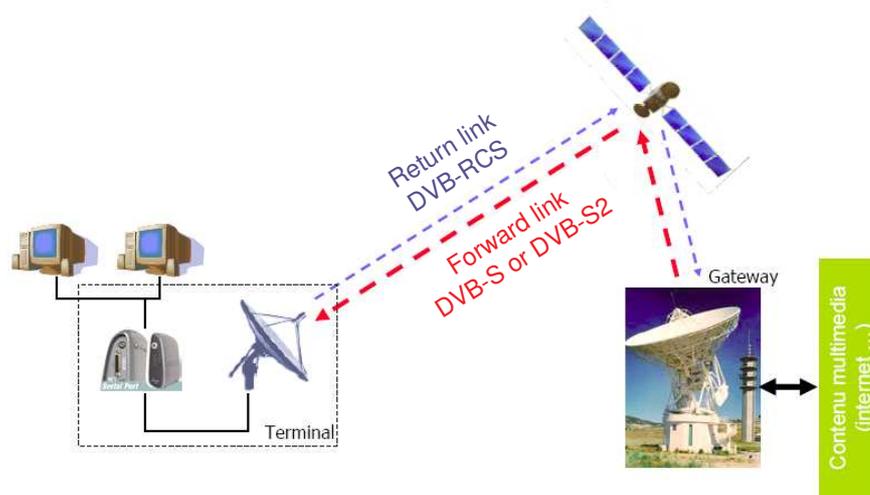


Figure 1 : Overview of a new satellite communications system

In order to have enough frequency resources available, the use of the Ka band (20GHz for space to Earth transmissions and 30 GHz for Earth to space transmissions) have to be considered for these kinds of services. For a sufficient coverage gain, this increase in frequency reduces the spot beam size. Hence, a typical system coverage is composed of several beams (about 40 are needed to provide a service over the whole West-Europe). In order to optimize the use of the frequency bands, schemes with multiple colours are implemented to re-use the frequency bands and/or the polarization angles. This method highly increases the capacity of the communication system.

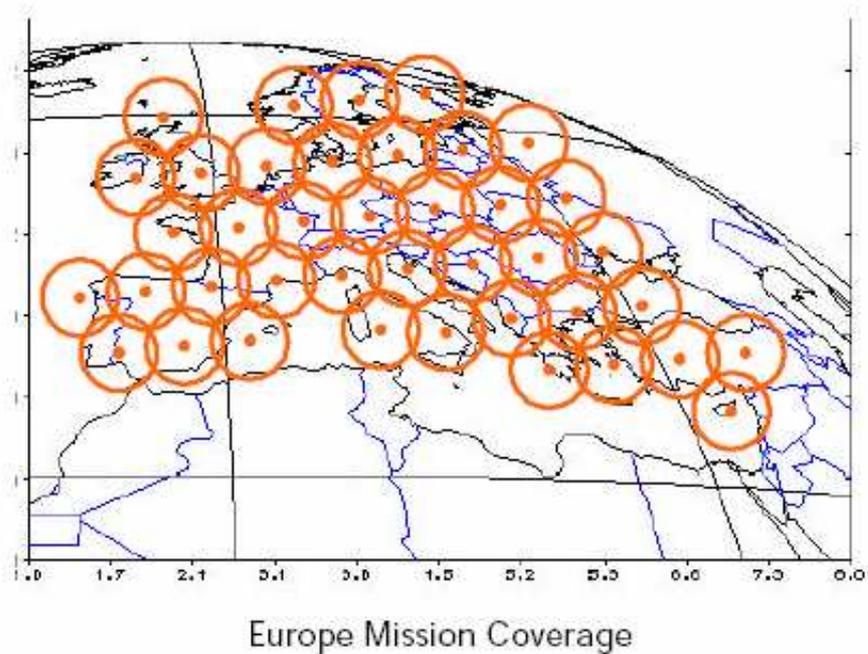


Figure 2 : Typical coverage of a Ka Band telecommunication system

However drawbacks of operating transmissions in the Ka-Band with frequency and/or polarization re-use have also to be taken into account:

- High interfering signals can affect the transmission links depending on the users locations,
- The power fade due the propagation phenomena can reach tens of decibels (for example during rain events),
- The difference of antenna gain between the centre and the end of the coverage can reach several decibels.

Propagation is affecting the transmitted waves: the signal power is attenuated due to three major phenomena :

- atmospheric gases absorption : the wave energy is absorbed by the oxygen and the water vapour. The gaseous attenuation depend on local meteorological parameters (pressure, temperature and water vapour concentration). It can be considered as a constant attenuation as its fluctuations are very slow and low.
- rain and cloud attenuation : the hydrometeors can highly attenuate the transmitted signal power. These impairments depend on local meteorological parameters (liquid water vapour and rain intensity). Since the attenuation can reach several decibels, it has to be considered in the link budget as a value exceeded during a given percentage of time corresponding to the specified system unavailability.
- scintillation : discontinuities of the refractive index are the source of fast fluctuations of the signal power. This attenuation is also considered in the link budget as a value exceeded during a given percentage of time corresponding to the specified system unavailability.

The figure below is giving an example of time fluctuations of the attenuation due to these propagation phenomena.

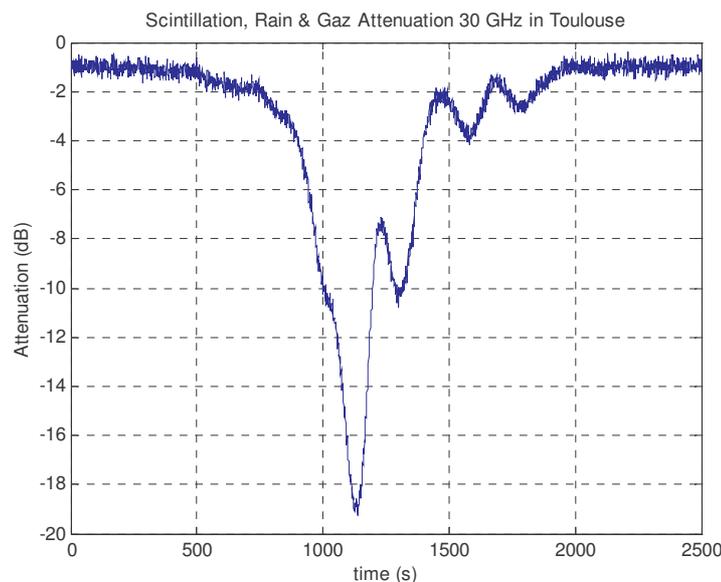


Figure 3 : Time series of total attenuation

To optimize the availability of the link and the frequency resources depending on the configuration in which the signal is transmitted, adaptive modulations and codes have to be used. This adaptivity consists

in matching the data rate with the fluctuation of the channel conditions. To do this, several codes and modulations are used for forward link and several codes and sizes of carriers and uplink power control are used for return link.

To design these new satellite telecommunications systems, the link budget has to be computed, taking into account all these new features. Therefore, the worst case approach described in §2 is not sufficient and the behaviour of every transmission links on the coverage have to be estimated. Methods used for these computations (forward link and return link) are described in the two next paragraphs

4 FORWARD LINK

4.1 A NEW STANDARD, THE DVB-S2

DVB-S2 has been built to improve DVB-S and to allow an increase in data rate from 30% for a given transponder bandwidth or the transmission of the same data rate at a significantly lower signal-to-noise ratio. Moreover DVB-S2 is a very flexible standard covering broadcast but also multicast and unicast applications by satellite as needed for the DVB-RCS forward link. This way, DVB-S2 can provide adaptive coding and modulation, targeting each down-link spot by controlling the transmission mode of the traffic addressed to it. The idea is to act on spectral efficiency (modulation, coding, spreading) to compensate the down-link signal variations due to propagation conditions, while maintaining the transmitter output power at same saturation operating point.

4.2 NEW METHODS FOR COMPUTING LINK BUDGET

To compute the forward link budget, a two-steps method is suggested and described through the two next paragraphs.

4.2.1 COMPUTATION OF A POINT TO POINT LINK BUDGET

The first step consists in computing a point to point link budget using the conventional method. This link budget aims to validate the feasibility of the system. In this link budget, the performances of the whole forward link are taken into account. Thanks to this point to point link budget, it is possible to extract the parameters needed for the future simulations:

$\left(\frac{C}{N_0} \right)_{up}$: the Gateway to Satellite link budget

$$\text{Constant} = P_{output} + k + G_r - L_p$$

Where :

P_{output} : the satellite output power (with losses in the satellite)

k : the boltzman constant

G_r : the terminal antenna gain

L_p : the polarization losses

R_s : The symbol rate of the carrier

Parameters of the terminal

$T_{Antenna}$: the antenna temperature in clear sky

T_{Ground} : the ground antenna temperature in clear sky

L_{feeder} : feeder losses

F_r : noise figure of the receiver

4.2.2 COMPUTATION OF THE LINK BUDGET OVER ALL THE COVERAGE

The second step consists in computing the link budget over all the coverage thanks to software simulations using the constant values computed above.

The input parameters are the antenna patterns, the antenna interferences level and some hypothesis on the link budget.

The antenna pattern and interferences level have been kindly provided by the antenna department in a file with the maximum on-board antenna gain among each source and the C/I ratio over all the system coverage. The map is divided in a grid containing for each point the maximum antenna gain and the C/I level.

The C/I level is calculated thanks to the formula :

$$\frac{C}{I} = \frac{P_{b(p_v)} G_{b_em(p_v)}(\theta_v, \phi_v)}{\sum_{i \in A_v} P_{b(p_i)} G_{b_em(p_i)}(\theta_v, \phi_v) + \sum_{j \in B_v} P_{b(p_j)} G_{b_em_cp(j)}(\theta_v, \phi_v)}$$

with

P_b : the onboard power of the satellite

$G_{b_{em}}$: the onboard satellite emission antenna gain

A_v : All the beams using the same polarization and frequency band

An example of antenna gain and C/I level are presented in the following figure

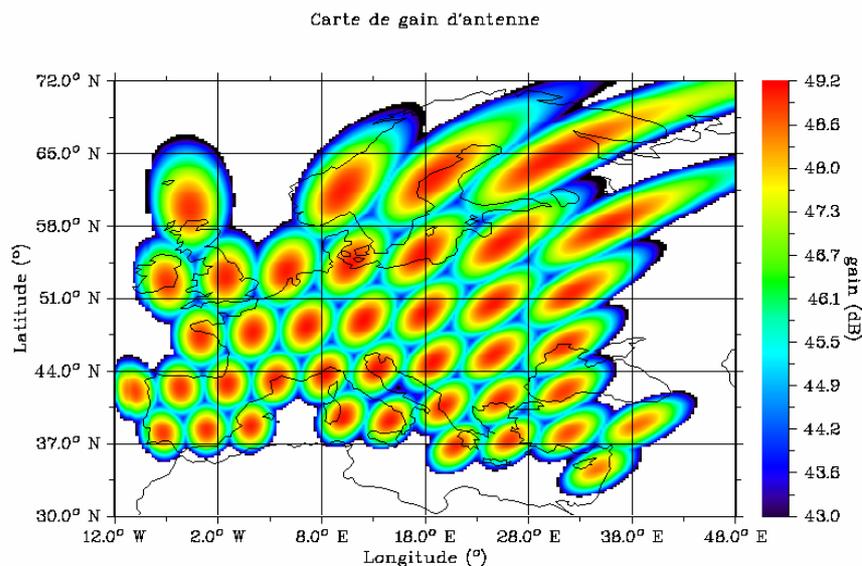


Figure 4 : Example of antenna gain in Ka Band

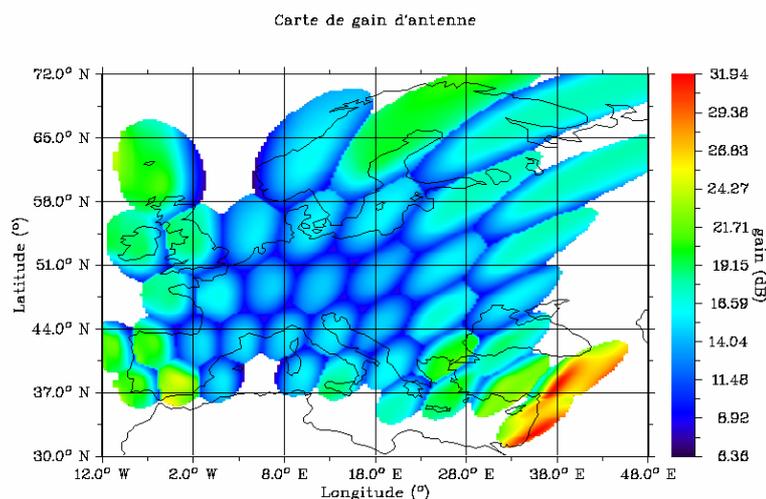


Figure 5 : Example of antenna C/I in Ka Band

By using this antenna pattern file and the parameters given in §4.2.2, it is possible to compute the link budget over all the coverage. This computation is done thanks to the forward link part of the MALTE package.

The program describes the map that has been divided into an $N \times M$ grid (N and M having typically a value of 200 or 300). For each of these points, the program takes the satellite antenna gain and a link budget is computed elementarily from the Gateway to the point. This computation is done like the traditional point to point link budget computation. However, the procedure is simplified because it takes only into account as parameters the results computed in the §4.2.2.

With this computation, it is possible to obtain the margin over all the coverage of a modulation/coding scheme for a given availability or the availability over all the coverage for a given modulation/coding scheme.

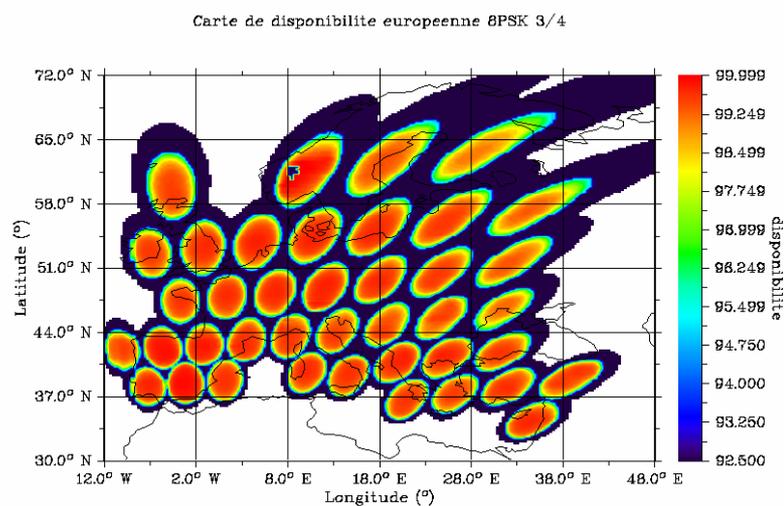


Figure 6 : Example of an availability map for the modulation/coding scheme 8PSK $\frac{3}{4}$

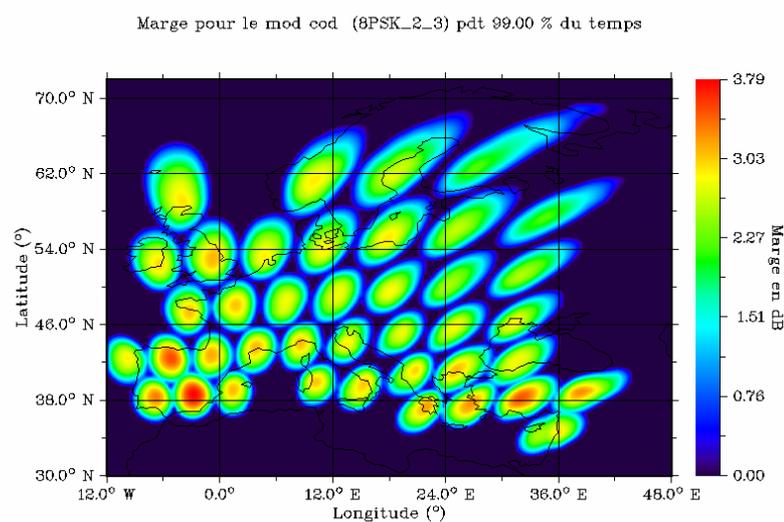


Figure 7 : Example of a margin map for the modulation/coding scheme 8PSK $\frac{2}{3}$ and an availability of 99%

Thanks to these maps, it is possible to obtain the system performances over all the coverage.

Firstly, it is possible to extract a graph giving the availability of a modulation/coding scheme over all the coverage :

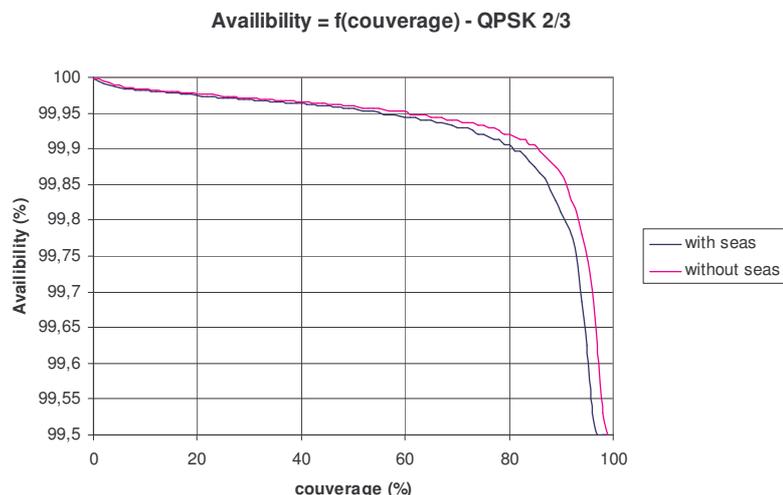


Figure 8 : Availability versus coverage of the modulation/coding scheme QPSK 2/3

As it can be seen on the Figure 8, it is possible to discriminate the performances by taking or not into account the seas into the coverage.

It is also possible to estimate the availability versus the modulation/coding schemes for a given percentage of the coverage. For example, next figure gives this information for a coverage of 98% over Europe :

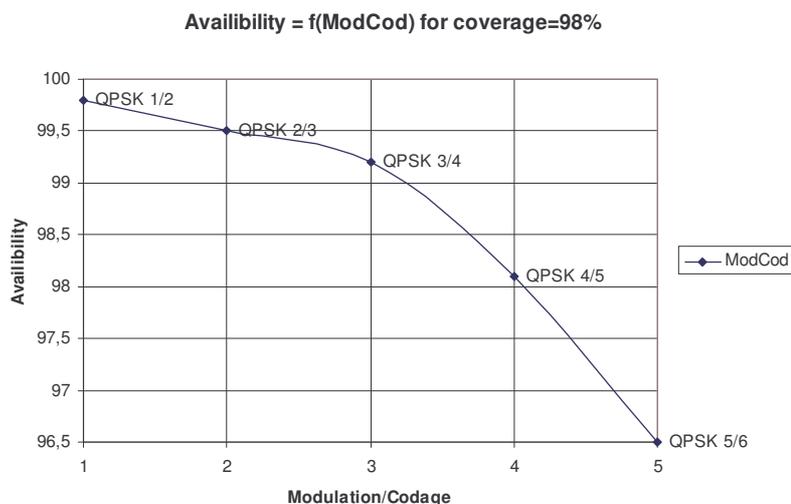


Figure 9 : Availability versus modulation/coding schemes for a coverage of 98%

On Figure 9, it is possible to obtain the availability of the system. For example, it is possible to have an availability of 99,8% for a coverage of 98% using the modulation/coding scheme QPSK 1/2.

Secondly, it is possible to compute the coverage of the modulation/coding schemes for a given availability. These results are depicted below:

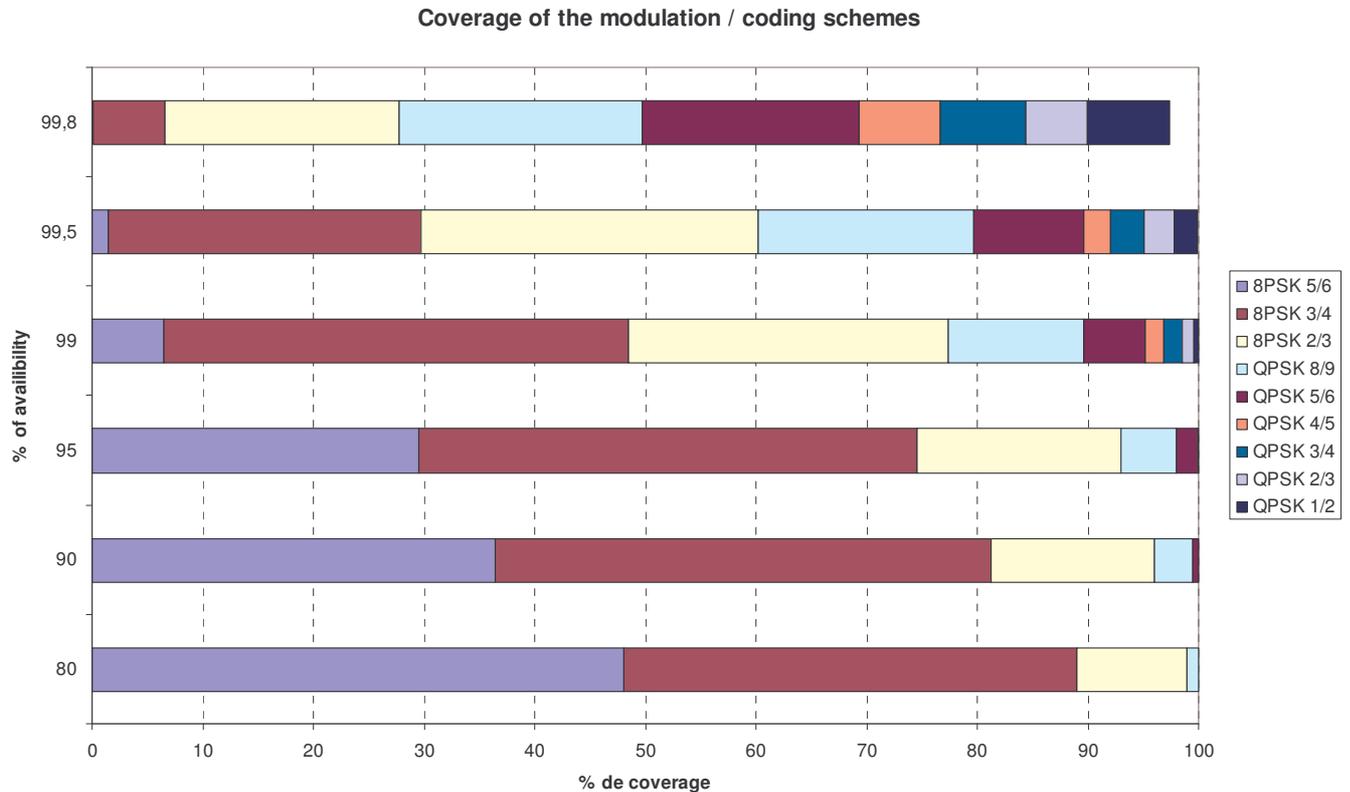


Figure 10 : Coverage of the modulation/coding schemes for a given availability

As we can see on Figure 10, the higher the availability is, the lower the performances are.. The most frequent cases correspond to clear sky conditions or low attenuation, typically corresponding to availabilities below 90%. So, the last two bars of the Figure 10 correspond to the mean performances of the system: the 8PSK 5/6 will be available over 35% to 48% of the coverage, the 8PSK 3/4 from 80% to 90% of the coverage. 8PSK 2/3 and QPSK 8/9 are provided to the other regions of the coverage.

Thanks to this method, it is possible to quickly evaluate the forward link air interface performances over all the satellite coverage.

5 RETURN LINK

On return link, the problem differs. Contrary to the forward link, the transmitted data are not in a single large carrier, being distributed on multiple small carriers due to MF-TDMA access.

5.1 DVB-RCS WITH DRA AND UPC

Depending on the satellite antenna gain, the system load and the propagation conditions, each terminal can modify

- its coding technique, its carrier size, that is DRA (Dynamic rate adaptation)
- its power, that is UPC (Uplink Power Control).

So, to define a DVB-RCS air interface, it is necessary to have several DRA schemes. These one are based on various codes and carrier sizes (proportional to the symbol rate).

As an example, the DRA schemes used for the computation of the performances are given in the table below:

Modulation	BW (kHz)	$(E_b/N_0)_{\text{required}}$ (dB)	R_s (kbauds)	R_b (kb/s)
0 - Unavailability	0,0		0,0	0,0
1 - QPSK 1/2	102,62	3.2	73,28	73,28
2 - QPSK 2/3	102,62	4.2	73,28	98,20
3 - QPSK 2/3	205,23	4.2	152,05	203,75
4 - QPSK 6/7	205,23	6.5	152,05	261,53
5 - QPSK 4/5	410,46	5.8	304,09	486,54
6 - QPSK 4/5	615,70	5.8	456,04	729,66
7 - QPSK 4/5	1231,39	5.8	918,33	1469,33
8 - QPSK 4/5	2462,78	5.8	1836,54	2938,46
9 - QPSK 4/5	4925,56	5.8	3672,82	5876,52

5.2 COMPUTATION OF THE LINK BUDGET

5.2.1 POINT TO POINT LINK BUDGET

This first step consists to compute a point-to-point link budget. This link budget aims to validate the feasibility of the system.

Thanks to this computation, it is possible to estimate some parameters needed for the next step :

$$\text{constant_up} = EIRP_{\text{terminal}} + L_p + T_s$$

where

$EIRP_{\text{terminal}}$ the EIRP of the user terminal

L_p polarization losses

T_s : the satellite antenna noise temperature

$$\text{constant_down} = G_s + L_s + L_{\text{propa}} + \left(\frac{G}{T}\right)_{\text{gateway}}$$

where

G_s : the satellite antenna gain for the link satellite-gateway

L_s : losses at the satellite output

L_{propa} : propagation losses

$\left(\frac{G}{T}\right)_{gateway}$: figure of merit of the gateway

In this part, the amplifier gain is also computed to assess the downlink link budget.

The last parameters needed is the satellite antenna noise temperature T_s .

5.2.2 COMPUTATION OF THE LINK BUDGET OVER ALL THE COVERAGE

To compute the performances of the return link, it is first necessary to have, like for the forward link, a file containing the antenna gain over all the coverage. This time, the file has to contain the antenna gain over all the coverage for each spot beam.

Then, it is necessary to determine the interference level appearing in the system.

To compute the interfering power level affecting the return link, the C/I given by the antenna gain can not be directly used : Indeed, the computation of the C/I depends also on the number and the location of the terminals in other spots using the same frequency and the same polarization at the same time, on the power level and the carrier size of the victim user and of the interferers and finally, on the spatial variability of the propagation phenomena over the system coverage. It can be computed thanks to the formula:

$$\frac{C}{I} = \frac{P_{t(v)} G_{t_em(v)} G_{b_re(p_v)}(\theta_v, \phi_v) L_{u(v)}}{I_{D_v} + I_{E_v} + I_{F_v}}$$

where

$$\begin{cases} I_{D_v} &= \sum_{i \in D_v} \chi_{iv} P_{t(i)} [G_{t_em_cp(i)} G_{b_re_cp(p_v)} + G_{t_em(i)} G_{b_re(p_v)}(\theta_i, \phi_i)] L_{u(i)} \\ I_{E_v} &= \sum_{j \in E_v} \chi_{jv} P_{t(j)} [G_{t_em_cp(j)} G_{b_re(p_v)}(\theta_j, \phi_j) + G_{t_em(j)} G_{b_re_cp(p_v)}(\theta_j, \phi_j)] L_{u(j)} \\ I_{F_v} &= \gamma \sum_{k \in C_v} P_{t_{ac}(k)} G_{t_em(k)} G_{b_re(p_v)}(\theta_k, \phi_k) L_{u(k)} \end{cases}$$

P_t : the emission power of the terminal

$G_{t_{em}}$: the terminal emission antenna gain

$G_{b_{re}}$: the onboard satellite reception antenna gain

L_u : The propagation losses

v the victim and i the interferers.

D_v interferers using the same frequency band and polarization

E_v interferers using the same frequency band and cross polarization

F_v interferers using the same polarization and an adjacent frequency band

The computation of the C/I ratios in the simulation and of the link budget is performed as described thereafter.

The first step consists in generating a large number of attenuation maps over the system coverage (about 100 000 maps). This panel of maps allows a good representation of the fluctuation of the propagation phenomena over an average year. The generation of these maps is presented at the end of the paragraph

Then, for each map and for each user, the C/I ratio is computed and the more efficient DRA scheme that can be used is estimated with an iterative process. To do that, the following method is used for each map:

1) For each point of the coverage (modelled by a 200x200 points grid), the N-1 interferers located in the spots with the same colour (same polarization and frequency as the victim) are randomly generated. The location of the interferers is estimated using a two-dimensional uniform statistic law.

2) For each terminal of this N-uplet (victim and N-1 interferers), the C/I ratio, the DRA schemes (size of carrier, modulation, coding) and the uplink powers are estimated thanks to an iterative process.

3) The results obtained for each point of the grid are stored in a table to be process at the end of the simulation.

Using this method, MALTE package can provide the following results :

- Probability of the C/I ratio

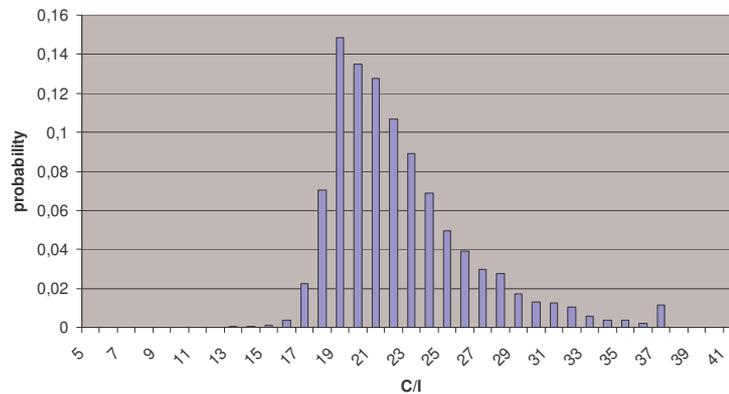


Figure 11 : Probability of C/I in 4°W and 42°N

- Maps of the C/I ratios

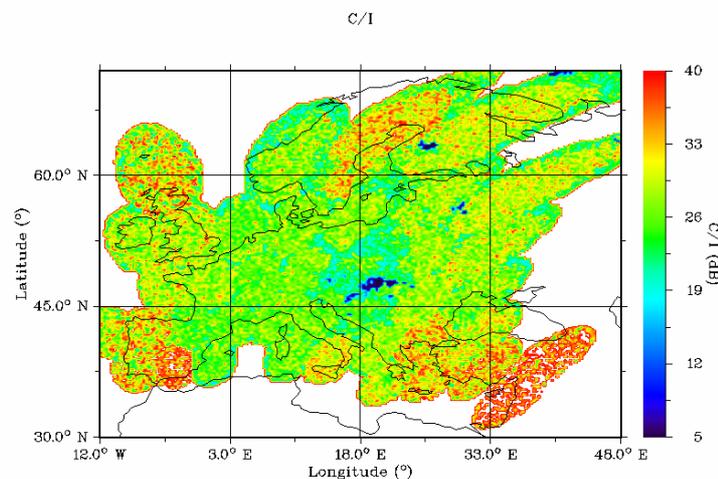


Figure 12 : C/I computed for a unique map

- Maps of the C/I ratios exceeded during a percentage of time

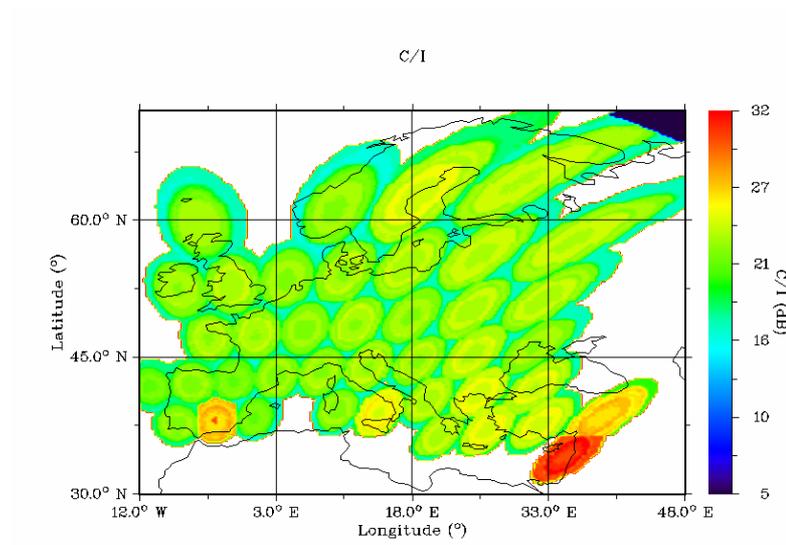


Figure 13 : C/I exceed 95% of the map over all the coverage

- Maps of the used DRA schemes

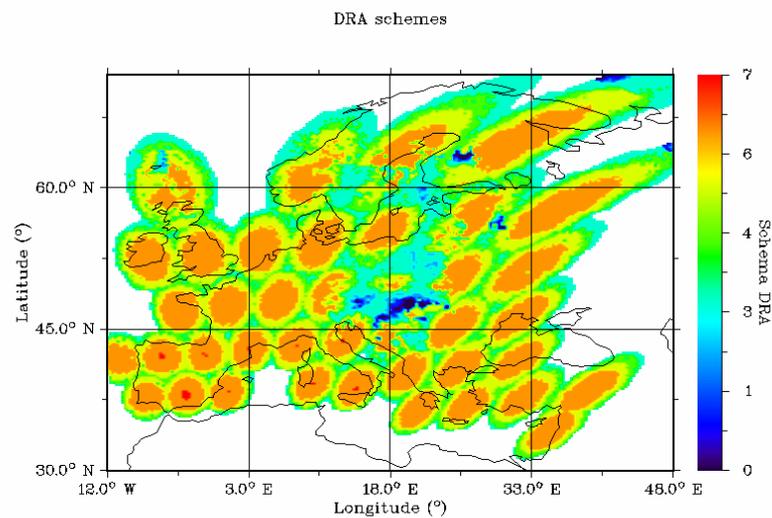


Figure 14 : Spatial DRA Availability for a unique map

This map corresponds to a spatial repartition of the DRA schemes for one propagation map. It is possible to see that propagation effects degrade the link budget locally. The DRA scheme repartition in clear sky depends on the satellite antenna gain.

- Spatial distribution of the various DRA schemes for all the maps

Statistical distribution for percentage of coverage of DRA scheme Nr 6

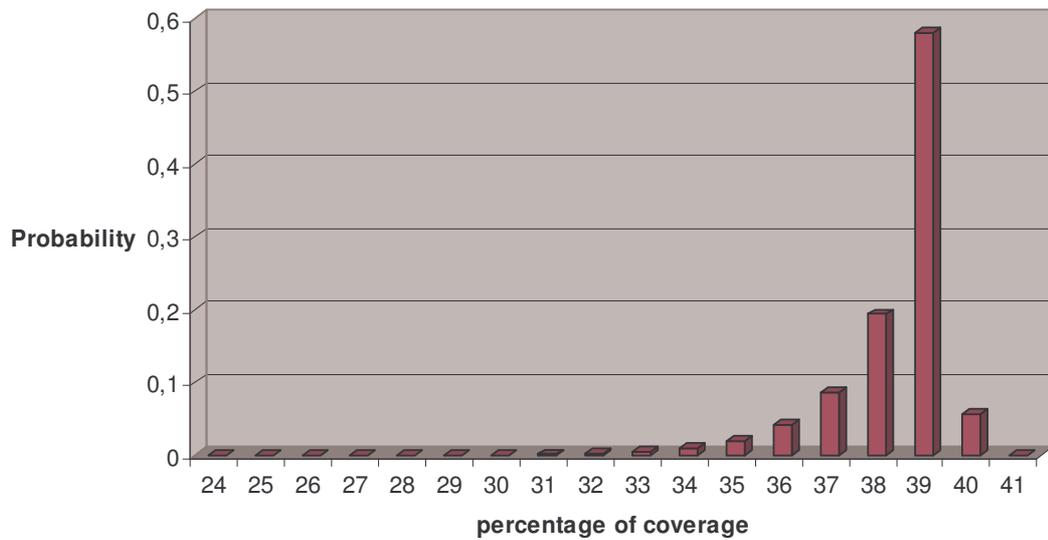


Figure 15 : Statistical distribution of coverage for a DRA scheme

On Figure 15, it is possible to see that the coverage of a DRA scheme isI don't know

- Temporal availability for a given DRA scheme :

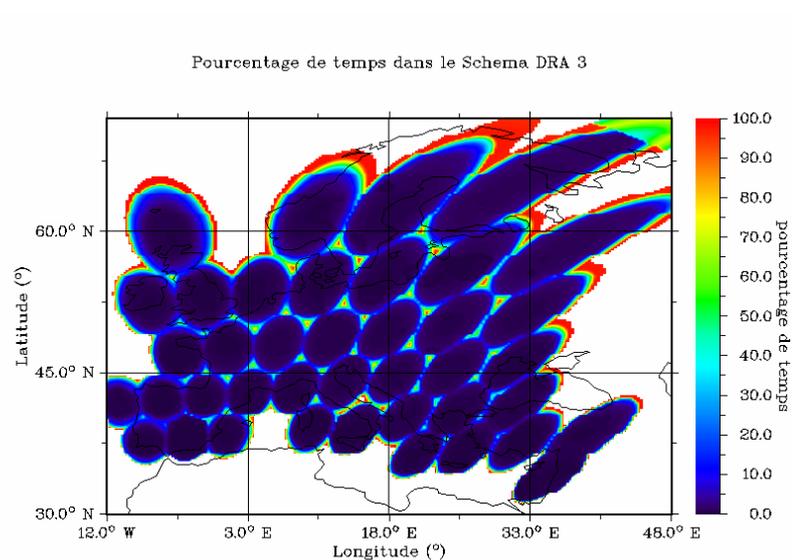


Figure 16 : Percentage of map using DRA Scheme 3 - 203 kbits/s

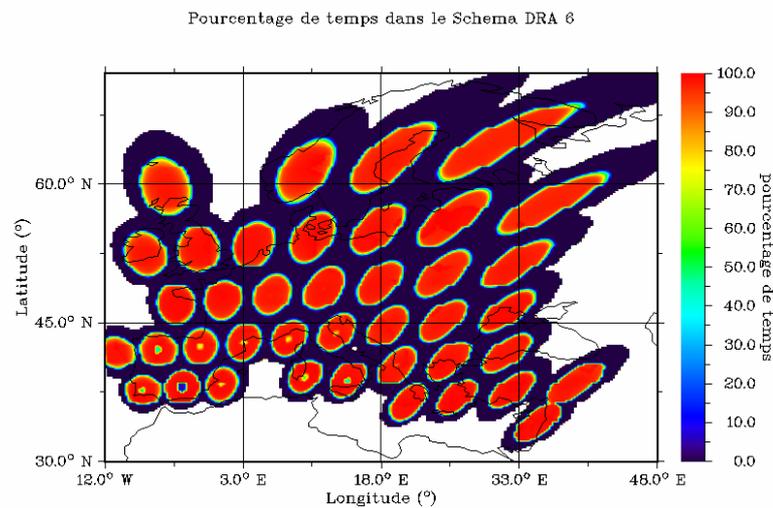


Figure 17 : Percentage of map using DRA Scheme 6 - 730 kbits/s

These maps correspond to the percentage of time during which a user can use a given DRA scheme. Propagation phenomena are not visible on the maps that give the temporal availability of the DRA schemes.

Finally, it is possible to compute the global performances of the system. Thanks to the MALTE package, we can estimate the mean coverage percentage of all DRA schemes presented on the figure below :

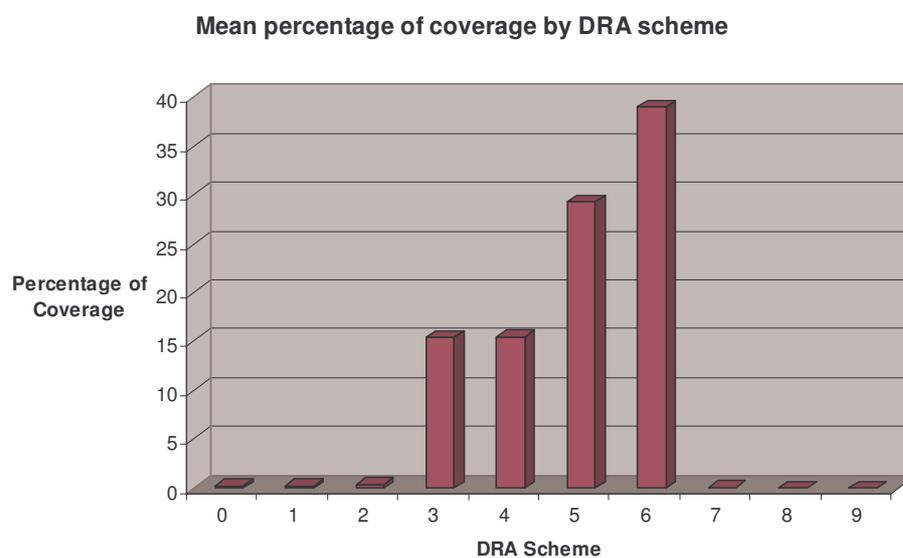


Figure 18 : Mean Percentage of coverage by DRA schemes

Then it is possible to compute the mean performances of the system using percentage of coverage used by the different DRA schemes and their data rates.

The generation of maps of total attenuation is performed thanks to the following method

Step 1 : Generation of 2D-correlated Gaussian fields to identify the regions affected by rain (rain mask)

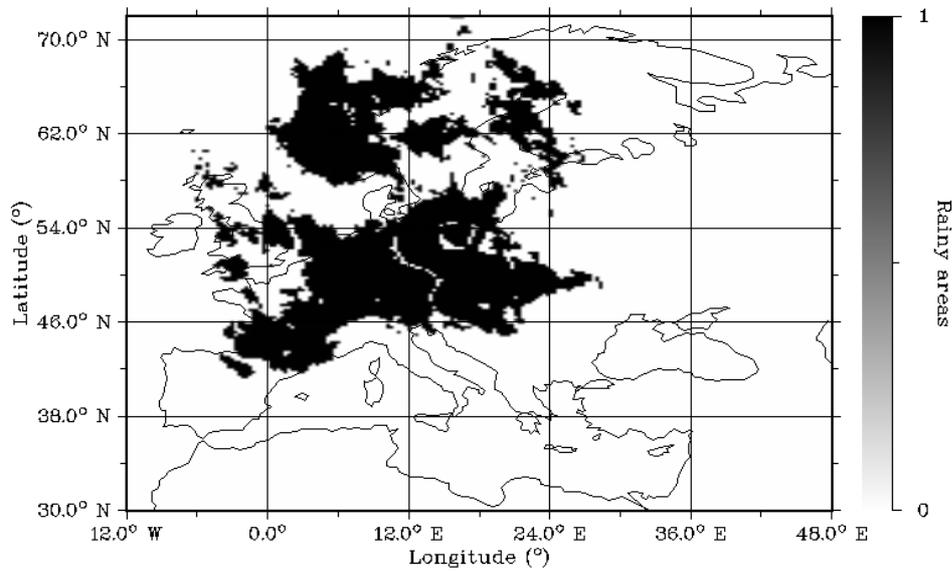


Figure 6 : Rain mask – 15 % of rain regions

Step 2 : Generation and non-linear transformation of 2D-correlated Gaussian fields to obtain a map of attenuation due to propagation (rain, cloud, gases and scintillation) (see [6])

Step 3 : combination of the rain mask and of the attenuation map to obtain the map of total attenuation

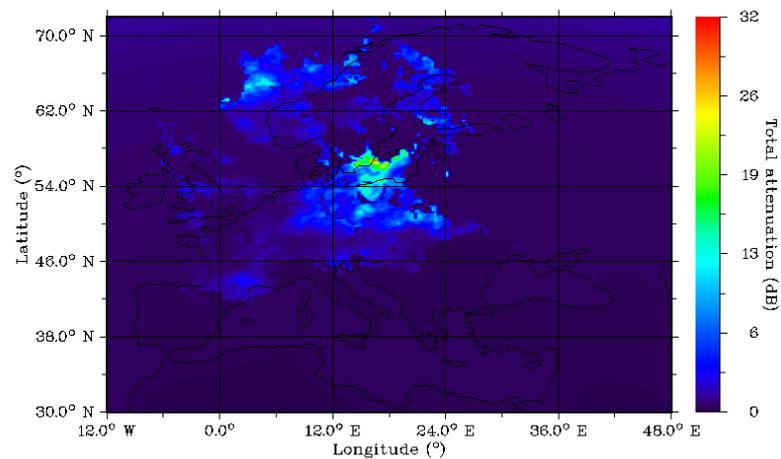
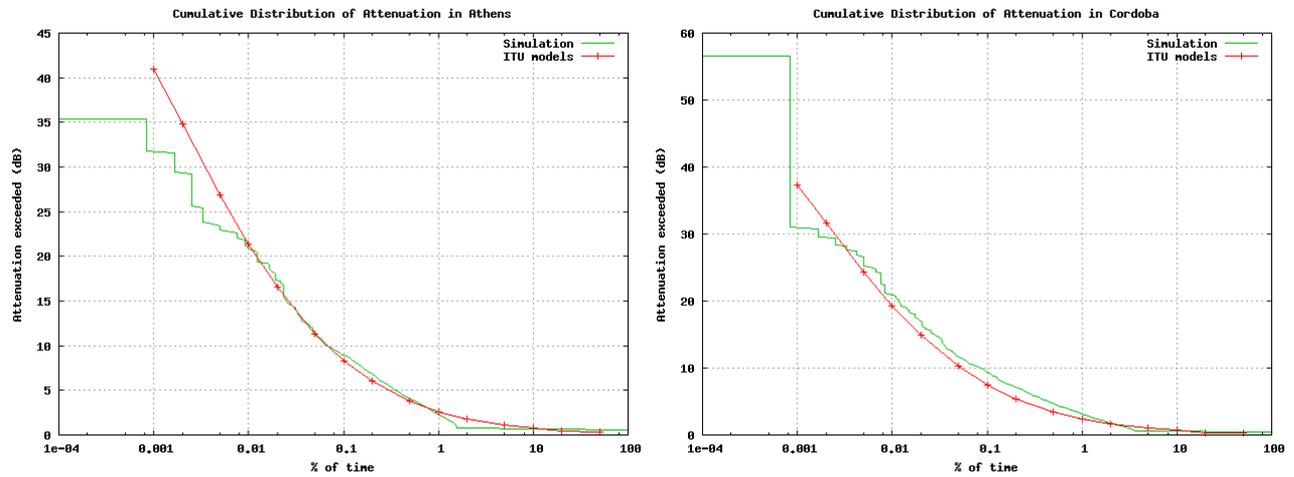


Figure 7 : Example of rain map

This model have been validated for several locations including Athens and Cordoba for which the cumulative density function of total attenuation is given below according to the ITU models and to the generated maps.



A good compliance between both curves can be observed.

A more accurate description of the model will be given in a paper soon.

6 CONCLUSION

In this paper, the authors have presented link budget computation and new systems based on adaptivity. They have shown the limitation of the use of a classical link budget for such system validation. A new philosophy for system design having to be elaborated, the paper has described the new software developed in this context, the MALTE package. The latter analyses accurately link budgets to ensure a high capacity and availability of the transmission links, when adaptive modulations and codes are used. Moreover, new results have been obtained by this tool for a future satellite system for telecommunications providing multimedia services in Europe.

The next step for the authors is to propose a GUI for MALTE package and to allow a direct use for system designers.

The T-shirt is dry now (see [7]).

7 REFERENCES

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