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► **To cite this version:**

Isabelle Dahman, Nicolas Jeannin, Philippe Arbogast, Bouchra Benammar. Attenuation Forecasts Model Exploiting Short Range Probabilistic Weather Forecasts. 8th Advanced Satellite Multimedia Systems Conference and 14th Signal Processing for Space Communications Workshop , Sep 2016, PALMA DE MAJORQUE, Spain. hal-01385528

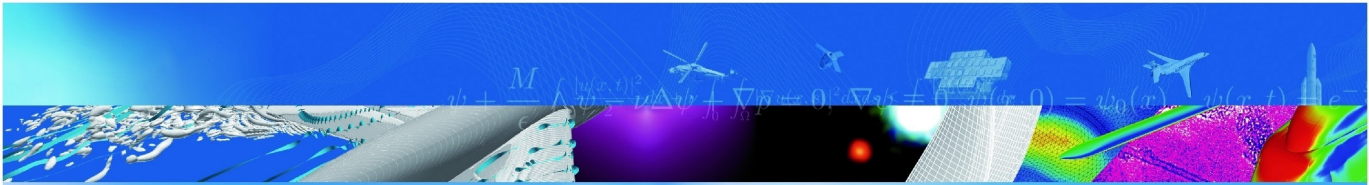
HAL Id: hal-01385528

<https://hal.science/hal-01385528>

Submitted on 26 Oct 2016

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COMMUNICATION A CONGRES

**Attenuation Forecasts Model
Exploiting Short Range Probabilistic
Weather Forecasts**

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ASMS/SPSC
PALMA DE MAJORQUE, ESPAGNE
5-7 septembre 2016

TP 2016-618

70 2016
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Attenuation Forecasts Model Exploiting Short Range Probabilistic Weather Forecasts

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Abstract—This paper proposes a method to control the data rate of an Earth Space link using VCM at Ka band based on the use of meteorological forecasts. Specifically, a probabilistic model of propagation impairments forecast has been developed from the analysis of rain rate measurements and outputs of the Météo-France short-range probabilistic forecast model. The approach is validated against propagation data acquired on a GEO to ground link and applied to the case of a LEO data down link using VCM, where it is shown to outperform significantly the data rate achievable using a purely statistical margin, while keeping the same availability target.

Keywords— *adaptive satellite communications, attenuation meteorological forecasts.*

I. INTRODUCTION

High resolution satellite imagery programs require ever increasing data rates for data download links which are no longer compatible with the limited bandwidth available at X band (8-10 GHz), the frequency band usually used to retransmit data on Earth. In order to increase the capacity of such links, the use of higher frequency bands, for which larger bandwidths are available, becomes a necessity for future Earth observation satellites. It is therefore envisaged to operate communications between satellites and ground stations at Ka band (around 26.5 GHz) and in later future at Q band (around 40 GHz). A counterpart to the large bandwidth available at those frequency bands is a higher sensitivity of radiowaves to rain, with rain attenuations reaching potentially several tens of dB some tenth of percent of the time. In addition, considering the fluctuations of the elevation angle during the visibility period, the magnitude of the propagation impairments is strongly varying. To avoid the severe constraints set by the use of a single modulation and coding for the link in terms of power margins required disregarding the elevation angle, different techniques can be used. Firstly, the power margin to fulfill a given availability objective can be adapted by conditioning it to the elevation angle. This technique is called variable coding and modulation (VCM [1]) and requires an adaptation of the physical layer depending on the elevation of the data download link. No feedback on the state of the link is required and the on-board modulator is programmed based on orbital data. This mechanism still require potentially high

margin to cope with rather infrequent propagation conditions. To increase the efficiency of the link, the adaptation in quasi real time of the waveform to the state of the channel through adaptive coding and modulation is extremely efficient [2], but requires a quasi-instantaneous feedback of the state of the channel to be sent to the modulator through a return channel. The existence of this return channel raises various issues in terms of payload complexity, security of the telecommand (TC), and required infrastructure. It will need significant development before entering in operation. An intermediate solution would be to adapt the waveform for the next contacts with the ground station network each time the satellite is in visibility of the network control center through standard TC link. This requires a probabilistic forecast of the state of the propagation channel for the following contact periods with the receiving ground station network. This forecast can be sent at each contact period by the network control center to program the on-board modulator for the next visibility period for which data have to be downloaded on ground stations.

One of the difficulty related to the practical implementation of such a strategy that is referred to as dynamic VCM in [3] (D-VCM) is to develop a probabilistic forecast model of the state of the channel as this information is not directly related to the information contained for instance in numerical weather forecasts. In addition, the accuracy of the weather forecast has to be taken into account. One of the issues is also to get an evaluation of the order of magnitude of the achievable improvements in terms of performance with regards to conventional VCM approach.

Although the presence of cloud, water vapor and oxygen also alters the radiowave during its propagation into atmosphere; this study is focused as a starting point on the forecast of rain attenuation that causes the higher impairments.

In this work, a model to forecast rain attenuation on an Earth space channel for a time horizon of a few hours or days is presented. It makes use of a probabilistic weather forecast data from a model developed by Météo-France named PEARP, and is parameterized using propagation data collected in the south of France by ONERA and using the support of rainfall estimates given by rainfall radar measurements.

In a first stage of this paper, details on the proposed model are given. Then it is validated against fixed Earth space propagation data with a GEO satellite as no propagation data are available for the LEO to ground channel. In a later stage, the performances of D-VCM technique are assessed on a typical Ka band data download link of LEO satellite.

The main originality of this work lies on the use of concurrent and independent data sources for the propagation and weather forecast data and it can thus be representative of the performance of a system actually using those models.

II. ATTENUATION FORECAST MODEL

A. Approach

The proposed model aims at computing the probability to exceed a given rain attenuation threshold, knowing rain meteorological forecasts. This information is then used to deduce the power margin required to match a given availability level.

The learning process of the model requires rain forecast, rain rate measurements and rain attenuation measurements.

Meteorological Forecasts

The accuracy of the attenuation forecasted by the model mainly depends on the quality of the meteorological forecasts.

Deterministic models are the most common type of meteorological models: analysis of initial conditions result in a single forecast such as the forecast of a rain fall rate. There is no assessment of the uncertainty of the prediction. However, knowing the trustworthiness of data used to predict the impairments of the propagation channel could greatly help to limit false alarms and non-detection cases.

Preference is given to probabilistic approach: the probabilistic models PEARP compute 35 realizations of the forecast in order to characterize both of uncertainty on initial conditions and error in the modelization. The closest the forecasts of the ensemble are, the more confidence one might have in the forecast.

PEARP [4] benefiting of a global coverage with a horizontal resolution of 10 km over France (60 km on the opposite side of the globe) and forecast up to 36 h with a step of 3 hours, it appears to be suitable for studies presenting variables requirements such as different spatial locations.

In the whole study, a good compromise between the granularity of the forecasts and the possibility to offer a statistic link between rain rate and rain attenuation has been found selecting an area of 100 km around the receiving station

(latitude 43.5 °N and longitude 1.5 °E) and averaging PEARP data on it.

Rain Measurements

Rain rate measurements are also provided by MétéoFrance in the form of radar quantitative precipitation estimates, called PANTHERE [5]. PANTHERE product has a spatial resolution of 1 km² over France and a temporal one of 5 minutes. An illustration is given on figure 1.

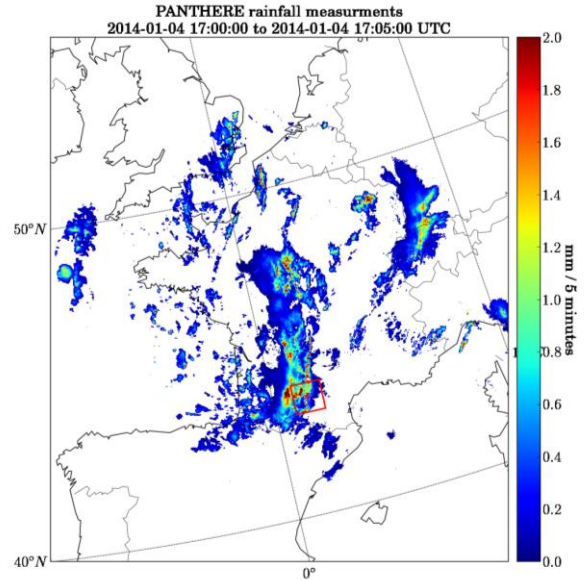


Figure 1: Example of PANTHERE rainfall measurement. The red square represents the study area

Rain Attenuation Measurements

Ka band attenuation measurements have been obtained by ONERA analyzing power fluctuation of the Ka band beacon of Astra 3B geostationary satellite. The link between Astra 3B and the receiving site has an elevation angle of 35°. Although attenuation data are available with a temporal resolution of 1 second for the full year 2014, data have been averaged on 5 minutes to save computational resources.

Errors in weather forecasts are firstly characterized analyzing the correspondence between rainfall radar measurements PANTHERE and the rain forecasts PEARP. In a second stage, a relationship between PANTHERE data and the Ka band rain attenuation measurements is established.

The expression of the probability of exceeding a given rain attenuation threshold A^* knowing the rain meteorological forecast F is then given by (1).

$$P(A > A^*|F) = \sum_j P(A > A^*|c = c_j)P(c = c_j|F) \quad (1)$$

With A , the attenuation due to rain, c the rainfall measurements Panthere and F rain forecasts PEARP.

The probabilistic forecast model of the state on the channel is therefore based on the computation of two conditional probability distributions:

- The rain attenuation distribution conditioned to rainfall radar measurements.
- The rain fall measurements distribution conditioned to rain forecasts.

B. Rain rate distribution conditioned to rain forecasts

To allow a comparison between PANTHERE data and PEARP outputs, PANTHERE data have been averaged on space time domains covering 100 km² and 1 hour. The cumulative distribution functions of rain fall measurements conditioned to PEARP rain forecast is presented in figure 2.

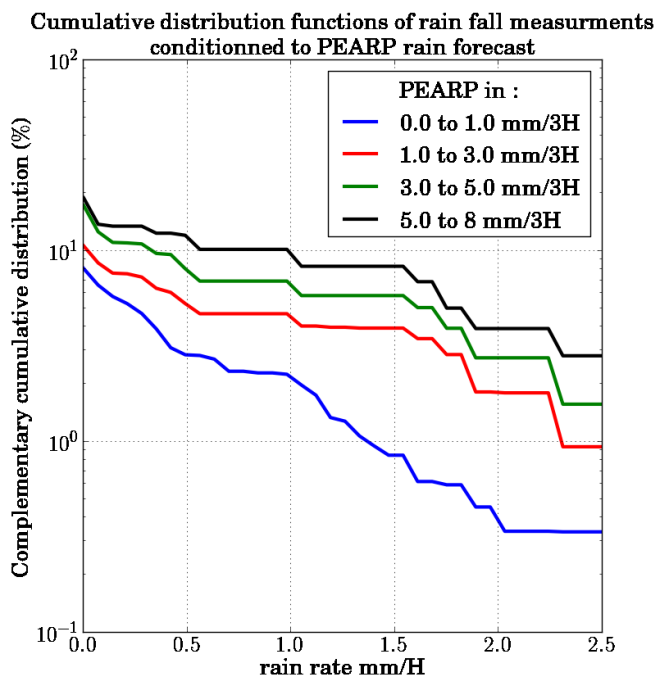


Figure 2: Rain fall measurement cumulative distribution conditioned to rain forecasts from PEARP

The PANTHERE rainfall probability distributions conditioned to PEARP demonstrates unsurprisingly that the higher the forecasted rain rate, the greater the probability to have a high rain rate.

C. Rain attenuation distribution conditioned to rain measurements

The estimation of rain attenuation based on PEARP forecasts is obtained coupling the rain fall measurements

distribution presented above with the rain attenuation distribution conditioned to PANTHERE measurements.

The ccdf of Ka band rain attenuation conditioned to PANTHERE derived rain amount presented in figure 3.

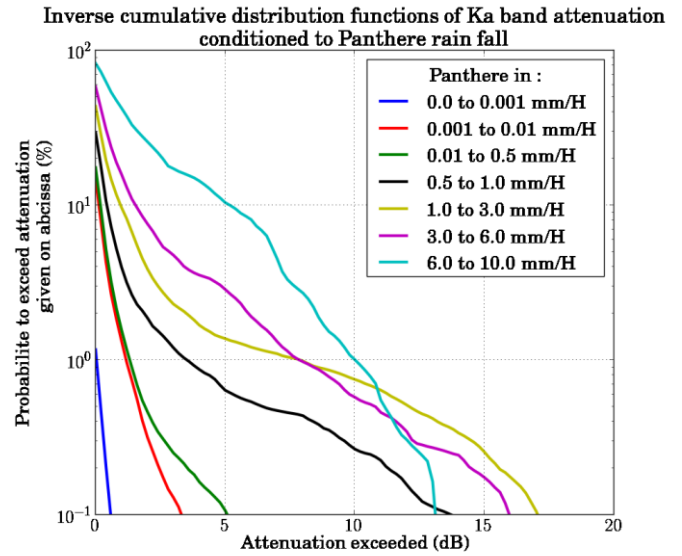


Figure 3: Ka band (20 GHz) attenuation measurements cumulative distribution conditioned to PANTHERE measurements. The elevation

D. Rain attenuation distribution conditioned to rain forecasts

As described by equation (1), the above conditional probability distributions leads to the computation of the probability to exceed a given rain attenuation threshold, knowing rain meteorological forecasts. The result is illustrated on figure 4.

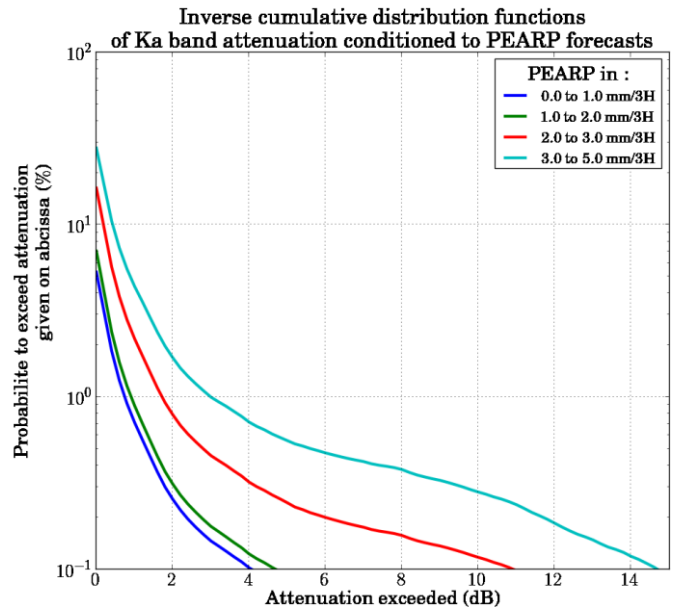


Figure 4: Ka band attenuation measurements inverse cumulative distribution conditioned to PEARP rain forecasts. The elevation angle of the link is 35 °.

For each realization of the forecast computed by the PEARP model, an estimation of the attenuation not exceeded p% of the time can be deduced from the previous graph. The mean of the attenuation forecasts thus obtained gives us a good estimation of the power margin that shall be provided to fulfill availability equal to 1-p % of the visibility duration. This information will allow optimizing the transmission adapting the waveform to the state of the channel.

A method to increase the efficiency of the link selecting the most suitable modulation and coding based on the attenuation forecasted is presented in the next section.

III. SYSTEM SCENARIO

Communications with LEO satellites are constrained by the visibility periods of the receiving stations. The deterioration of propagation conditions during this time window, especially for systems using Ka bands or above, may result in transmission outage and consequently in loss of data. The requirements in terms of minimum availability can be satisfied by applying to the link a couple modulation/coding that close the link budget for the given propagation margin that corresponds to the requested availability.

The ModCods considered in this study are presented in Table 1.

ModCods	Modulation	Code rate	η (b/s/Hz)	C/N_{required} (dB)
1	Q-PSK	0.36	0.72	0.3
2	Q-PSK	0.43	0.86	1.1
3	Q-PSK	0.51	1.02	2.4
4	Q-PSK	0.60	1.20	3.6
5	8-PSK	0.47	1.41	4.7
6	8-PSK	0.54	1.62	6.0
7	8-PSK	0.62	1.86	7.2
8	8-PSK	0.70	2.10	8.7
9	8-PSK	0.79	2.37	10.2
10	16-APSK	0.66	2.64	11.3
11	16-APSK	0.73	2.92	12.5
12	16-APSK	0.80	3.20	14.0
13	16-APSK	0.88	3.52	15.7
14	32-APSK	0.76	3.80	17.2

Tab. 1: Set of ModCods selected for the study, associated spectral efficiency η and required carrier to noise ration C/N . From DVB-S2X[7].

The idea is to select the ModCod leading to the higher efficiency η while keeping an error free transmission. To achieve this, the carrier to noise ratio of the link must exceed a preset threshold C/N_{required} .

The expression of the Carrier to Noise Ratio of the link not exceeded for p% of the visibility time and an elevation angle θ is given by equation (2).

$$\left(\frac{C}{N}\right)_{dB}(p, \theta) = EIRP_{dB} - 10\log_{10}(k_B) - FSL_{dB}(\theta) - 10\log_{10}(B) - A(p) + \left(\frac{G}{T}\right)_{dB} \quad (2)$$

With EIRP the equivalent isotropic radiated power, expressed in dB. B is the Bandwidth of the link. G/T represents the figure of merit in clear sky conditions of the receiving station. k_B is the Boltzmann constant. FSL represents the Free Space Loss which are function of θ . A is the power margin required to ensure an availability p% of the time for an elevation θ .

The most effective strategy is to adapt in real time the transmission scheme to propagation conditions. A detailed description and an evaluation of the limits of this solution, called ACM (for Adaptive Coding and Modulation solution), are available in [2] and [6].

As illustrated in the figure 5, the choice of the ModCod is made at the level of the receiving station on the actual instantaneous attenuation A converted into effective carrier to noise ratio. The satellite is then informed of the most efficient ModCod usable under current propagation conditions. The communication between the satellite and the Earth stations is optimized and much higher mean capacities are offered by the link.

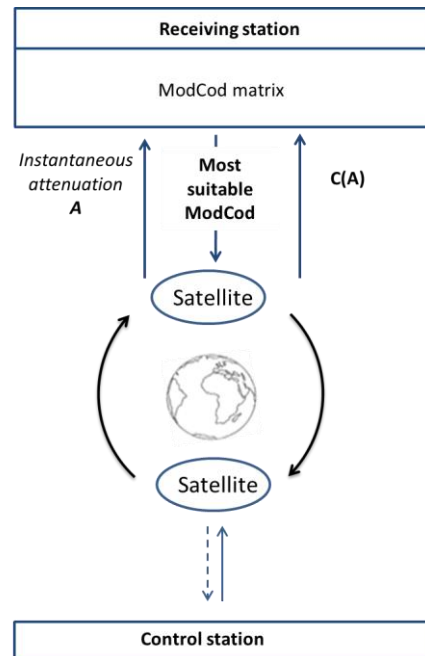


Figure 5: ACM system principles

However, a return channel, from the receiving station to the satellite, is required to transmit the state of the channel to the on board modulator. This ACM is not yet operational and requires further developments. Therefore, in absence of a return link, a pre-programming of the ModCod for the next orbit is necessary.

Free space losses significantly grow with decreasing elevation angle. The simplest strategy to guarantee the required availability is to assume a worst case link budget corresponding to the lowest elevation suitable for transmission. Assuming that a minimum elevation angle of 5° is required to operate the transmission, the power margin $A(p)$ is equal to the attenuation not exceeded $p\%$ of the time at 5° of elevation. The ModCod selected is thus the most efficient that fulfill the required $\left(\frac{C}{N}\right)_{dB}(p, \theta = 5^\circ)$.

A first degree of adaptation consists in associating to each elevation angle the most efficient ModCod that close the link budget.

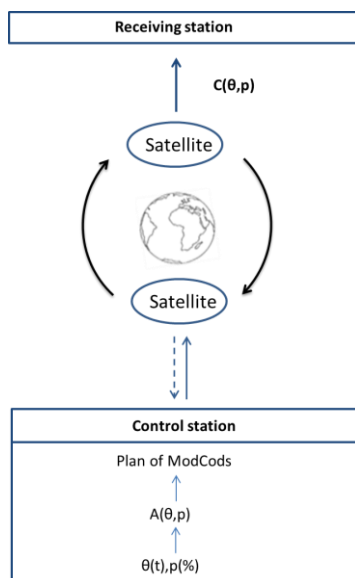


Figure 6: VCM system principles

A schematic representation is given in figure 6. At the level of the control station, a plan of ModCods that statistically fulfill, for each elevation angle θ , the required availability $p(\%)$ is established and communicated to the satellite. During the visibility period of the receiving station, the satellite applies to the transmission the pre-programmed ModCods. Compared to CCM, this technique called Variable Coding and Modulation (VCM[1][6]) allows operating the link more efficiently but still do not allow any flexibility with regards to weather conditions and limits the throughput of the link.

A good trade-off between performances and complexity could be to program in advance the transmission scheme, according to weather forecast. A method to predict the attenuation on the link from probabilistic weather forecasts has been developed in the previous section. This Dynamic VCM offers the ability to adapt the link to propagation impairments without the need of a return link.

The figure 7 summarizes the steps involved in the implementation of D-VCM strategy. Each day, the control station is informed of the current PEARP forecasts which allow the calculation of the attenuation forecasts $A(p, \text{PEARP})$ for the next communication with the receiving station. This information can be exploited at the level of the control center to build a plan of ModCods for the next visibility period of the receiving station. This solution allows a first degree of adaptation to weather conditions optimizing the capacity of the link $C(p, \text{PEARP})$ to weather forecasts.

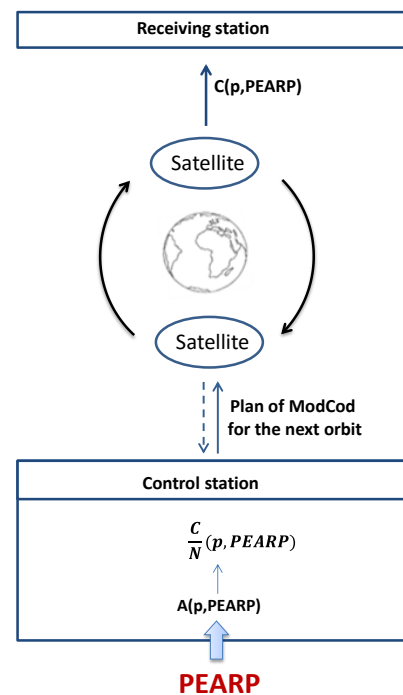


Figure 7: D-VCM system principle

A comparison of VCM, ACM and D-VCM strategy is proposed in the next part, first for a fixed Earth space link, second simulating a data download link with a LEO satellite.

The set up and validation of the model requires Ka band attenuation measurements. No data are available for LEO satellites. It prevents the direct validation of the attenuation forecast model in this context and fixed Earth space propagation data are first considered. In a second step, a comparison of D-VCM over VCM is proposed to demonstrate the interest of such method in case of downlink LEO transmission.

A. Application to GEO satellite:

To assess the performances of the D-VCM strategy, one year of transmission between the geostationary satellite Astra 3B and a receiving station located in Toulouse, France, at latitude 43.5 °N and longitude 1.5 °E has been simulated, using measured attenuation data for the channel. The EIRP of the satellite is assumed to be 50 dBW, the G/T of the receiving station 30 dB/K. A bandwidth of 540 MHz is also considered for the link.

The PEARP forecasts of 2014 have been used as input of the D-VCM decision algorithm. The ACM one was based on the Ka band measurements of the same year assuming no switching losses or margins. The throughputs obtained have been compared to the ones provided by CCM link.

The table (2) illustrates the mean capacities associated to each of these methods for an availability of 99.9 %.

	CCM	D-VCM	ACM
Mean capacity	648 Mbps	963 Mbps	1410 Mbps

Tab 2: Mean capacities obtained for a target availability of 99.9% and considering a GEO satellite. Comparison of CCM D-VCM and ACM strategies.

As expected, the best performance is obtained for an ACM strategy. Due to the limits of the weather forecasts, the D-VCM strategy proposed is not able to offer the same level of mean spectral efficiency. It is nevertheless clear that, with an increase of more than 48 %, this technique highly improve the throughput ensured by constant coding and modulation without any prior on the instantaneous state of the propagation channel.

Despite these achievements, the D-VCM is not of great interest in case of a geostationary satellite since either a return is available making it possible to applied ACM, or the absence of communication between the control center and the satellite impose a constant coding and modulation. However, to study the application of D-VCM in the context of a LEO satellite allowed testing the algorithm from end to end.

B. Application to LEO satellite:

It has been shown that opting for D-VCM rather than CCM strategy in context of GEO satellite allows a significant gain in terms of capacity. However, the main application of such method is certainly the case of LEO satellites for which the communication with the control station is occurring once every few hours and for which propagation prediction between those contacts may be needed. A comparison of D-VCM and VCM system is now proposed.

The attenuation probability distribution conditioned to PEARP (figure 4) has been computed from Astra 3B beacon measurements and is thus only representative of the attenuation expected for an elevation angle of 35 °. However, since propagation attenuation increases with decreasing elevation angles, the attenuation probability distribution must be available for the full range of elevation angle.

From the simplification given in equation (3) the attenuation probability distribution conditioned to PEARP and to the elevation angle θ of the link is generated.

$$A(\theta) = \frac{A(\theta = 90^\circ)}{\sin(\theta)} \quad (3)$$

The elevation time series using for the simulation has been obtained considering a LEO satellite with an altitude of 800 km. Figure 8 illustrates the power margins computed for both systems and the resulting capacities. The forecast of a rain event followed by a lull has been isolated (8-a). A forecasted rain amount equal to 2 mm leads to a power margin (8-c) closes to the one obtained for VCM system (8-b). By contrast, in clear sky condition, the power margin of the D-VCM system is substantially lower that the VCM one, resulting in a better capacity (8-e). The peaks visible for both systems are the result of the evolution of the elevation angle of the satellite.

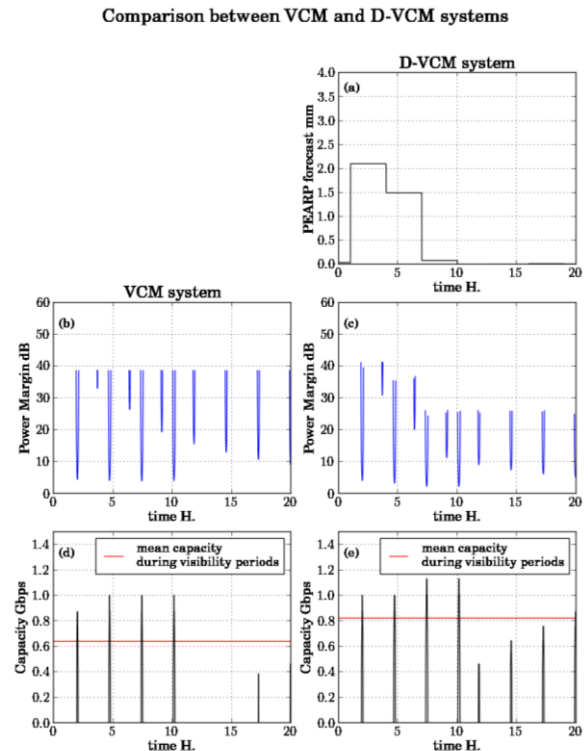


Figure 8: VCM (a) and D-VCM (b) power margin and resulting capacity time series (c) and (d) computed for a LEO satellite and a target availability of 99.9%. The red lines show the mean capacities obtained for each system.

On average over the year, D-VCM allows to reach a mean capacity of 821.9 Mbps against 638.8 Mbps for VCM (Tab 3), representing an increase of more than 30 %.

	VCM	D-VCM
Mean capacities	638.8 Mbps	821.9 Mbps

Tab 3: Mean capacities obtained for a target availability of 99.9% and considering a LEO satellite. Comparison of VCM and D-VCM strategies.

V. DISCUSSION

It has been shown that the implementation of an attenuation prediction system based on probabilistic weather forecasts could constitute an appropriate response to the problematic of the Ka band transmissions operated in the context of Low Earth Orbit satellites. An increase closes to 30% in the mean capacity of a LEO system has in fact been obtained using D-VCM instead of VCM strategy. With some adjustments, these already encouraging results could be improved. First, the model, currently limited to the rain attenuation forecast, could as well include the forecast of cloud, water vapor and oxygen attenuation, that are much more accurately predicted by weather forecasts model and for which the link between the attenuation on the link and the forecasted quantities is easier.

Similarly, a better use of the probabilistic weather forecasts PEARP could be foreseen. As an example, the standard deviation of the members of the ensemble gives us a good estimation of the realizations confidence that can be placed in the forecasted attenuation. This information would allow adapting the choice of ModCods, not only to the weather forecast, but also to its likelihood.

Finally, it would be interesting to study the impact of the spatial resolution of weather forecasts on the performances of the model proposed. Finest resolution allows locating in a more accurate way the rain cells but in a same time and potential error in the weather forecast become thus more penalizing. A tradeoff between resolution and error of forecasts must be found.

The major drawback of the model is probably its lack of flexibility to meet different receiving stations localizations and orbits parameters. In fact, the development of the model is based on beacon measurements, on rain fall measurements and on weather forecasts which characterize the situation around a given receiving station. Furthermore, the rain fall measurements are radar images which often present a limited reliability, in particular due to measurement artifact. A further study will address the use of supervised learning techniques to avoid the use of radar measurements.

Once the model is developed, the only precondition for the implementation of the model is the availability, on a daily basis, of weather forecasts.

Perspectives of such study are numerous and far from being limited to the specific case of LEO satellite. As developed in [8] and [9], Deep space Ka Band link also suffers from the propagation impairments and their anticipation, based on weather forecasts, would allow more frequent updates and an increase in the rain rate available on the link during a pass.

Another potential application is the Ka band broadcasting reconfigurable satellites antenna [10]. Known in advance thanks to weather forecasts, the area with risk of rain could benefit from a greater concentration of power obtained with an appropriate redirection of the power flux.

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