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Sizing and Optimization of High Throughput Radio-Frequency Data Down Link of Earth Observation Satellite

Nicolas Jeannin, Isabelle Dahman

Abstract

This paper analyses the sizing of networks of radio-frequency ground stations operating at Ka band or above for the reception of data acquired by Low Earth Orbit observation satellites. In particular, the way to account for the use of adaptive transmission schemes, to cope with the high propagation impairments in the troposphere is detailed. A solution to size optimally the ground stations relying on propagation channel simulations is also proposed. The resulting performances are assessed in a latter stage using simulated propagation time series.

Index Terms

Propagation, Earth observation satellite, on-board memory, data down-link.

I. INTRODUCTION

FUTURE Earth observation satellite programs are targeting the acquisition of an ever increasing amount of data due to the finer resolution, wider swaths, longer duty cycles and the larger number of on-board sensors. Even if significant progresses are made on on-board compression hardware and algorithms, the amount of data to transmit on Earth will grow significantly [1]. Two solutions are currently developed to transmit those data on Earth, namely the direct transfer of data to ground when receiving stations are in visibility of the satellite and the transfer through a relay geostationnary satellite like EDRS [2] (European Data Relay System) and TDRSS [3] (Tracking and Data Relay Satellite System). This latter option will not be addressed in this study that focuses only on the direct data transmission to ground. The data transfer to ground in current generation of Earth observation satellites is generally made through a X (8-10 GHz) band link. The bandwidth available for this service at this frequency band is limited and sets a bound on the maximum data download rate that is not compatible with the targeted acquisition rates of future missions. Thus links at frequency bands in which larger bandwidth are available for this service have to be used. At radio frequency (RF), Ka (15-30 GHz) [4] and more prospectively Q/V (40-50 GHz) band are to be considered. The use of a downlink in the optical domain [5] is also an envisaged possibility but will not be tackled.

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in this study. A common point to those transmission bands is their sensitivity to the propagation conditions in the troposphere. In presence of clouds and especially of rain EM waves at Ka and Q/V bands are severely attenuated reducing the signal over noise ratio of the link. As for fixed broadband satellite system, it is inefficient to cope with those variable propagation impairments with fixed power margins. Therefore, the use of a set of modulation and coding to maintain the link below the operating bit or frame error rate function of the actual or alleged SNR is more efficient as shown in [6].

One of the obvious consequence of the use of several modulation and coding is that the evaluation of system performances becomes more complex than with constant coding and modulation, as the capacity of the link is varying in time and may depends on the propagation channel properties. Thus an optimal trade off to size on board and on ground elements of the transmitting chain requires a strong knowledge of the propagation channel. Few actual propagation measurements of LEO (Low Earth Orbit) to ground channels at Ka band are available up to now at the noteworthy exception of [7] and [8]. Therefore, to mitigate this lack of data, the modelling of this kind of propagation channel has been recently investigated in [9], [10], [11] or [12]. The methodology proposed in this paper for the sizing of the transmission chain of data downlink relies extensively on those simulated propagation conditions.

In the first part of the paper the two transmission schemes scenarios addressed namely variable and adaptive modulation and coding are detailed with a particular emphasis on the performance metrics. It will be shown that the optimal sizing of the transmission system amounts to the optimal sizing of a queuing network whose service rate depends on link budget and transmission schemes. Then the proposed methodology to size and evaluate the performance of the data transfer system is described and illustrated on an example representative of the requirements for future Earth observation satellite missions. The corresponding figures of merit of the system are also presented.

II. SYSTEM SCENARIO AND PERFORMANCE METRICS

The main function of the data transfer link on-board of observation satellite is the transmission of data acquired by the observation sensors without loss, as quickly as possible to the end user. To this aim, in the case of direct to ground data download link, acquired data are temporary stored in a mass memory as long as a ground station is not in visibility of the satellite. Data stored in the memory are then successively transmitted to the ground when the link with a ground station can be established. Thus considering the main function of the data download link, two performance metrics can be defined for the link:

- the duration between data acquisition and reception of data on ground usually referred as data-timeliness,
- the fraction of data successfully transmitted on-ground or equivalently data availability.

The data-timeliness depends on various parameters such as satellite ephemeris, data acquisition rate, the capacity of the link, the position of the ground station(s)...

Data may not be successfully transmitted on ground, either if data are overwritten in memory due to a memory overflow or if data have been transmitted with a too high bit error rate (BER).
To evaluate those performance indicators for a given transmission chain, it is necessary to assess properly the capacity of the link and to perform some link budget assumptions. In the present case there are noticeable changes with regards to link budgets established with GEO satellites. Firstly, due to the motion of the satellite the link between the satellite and a ground station can be established intermittently due to the lack of line of sight path between the ground station and the satellite. Secondly, the variations of the length of the link cause fluctuations in the link budget during the visibility period.

For X band telemetry, the link can be designed assuming a worst case link budget corresponding to the lowest elevation angle suitable for transmission. The modulation and coding rate are chosen to operate the link below a target BER as long as the elevation angle is over the limit defined to establish the link. The link operates thus at a fixed bit rate. Even at low elevation angle, the magnitude of the propagation impairments at X band is low and can be accounted as a fixed margin in the link budget corresponding to an availability that can be evaluated using ITU-R Rec P.618-10 [13].

At Ka band this design procedure becomes inefficient as the propagation margin required to match a given availability at low elevation may be of several tens of dB over the one required at a high elevation, resulting thus in the use of a particularly inefficient modulation and coding (modcod) during the whole visibility period. Therefore, the use of adaptive transmission schemes enabling the use of higher efficiency modcods in favourable conditions (low attenuation or high elevation) increases significantly link capacity as underlined in [6].

Two main options transmission schemes can be considered for the data downlink. The first is the use of variable coding and modulation (VCM) for which the modcods are adapted according to the elevation angle of the link. It can be implemented without feedback provided by a return channel. If feedback can be provided and that the instantaneous estimation of the quality of the channel is possible, an adaptive coding and modulation (ACM) transmission scheme for which the modcod are adapted in real time to the channel conditions can be implemented. The additional complexity introduced by the presence of the return channel has to be balanced against the gain in terms of spectral efficiency resulting from the adaptation to the actual channel conditions.

A. VCM

The driving idea behind VCM ([6] or [14]) is to condition the modulation and coding of the link during the visibility period of one ground station to its elevation angle. Considering a targeted availability for the link \( p \), the modcod used for a given elevation angle \( \theta \) is the modcod that closes the link budget for a propagation margin computed for \( \theta \) and \( p \) for instance using ITU-R Rec P.618-10. The carrier over noise ratio \( (C/N)_{dB} \) expressed in decibels, corresponding to a simplified link budget can be expressed by (1):

\[
\left( \frac{C}{N} \right)_{dB}(p, \theta) = EIRP_{dB} - 10 \log_{10}(k_B) - FSL_{dB}(\theta) - 10 \log_{10}(B) - A_M(p, \theta) + (G/T)_{dB} \tag{1}
\]

In (1) the \( EIRP_{dB} \) denotes the Equivalent Isotropic Radiated Power transmitted by the satellite. The \( FSL_{dB} \) (Free Space Losses) are depending on the elevation as the distance between the satellite and the ground station.
depends on it. $B$ represents the bandwidth of the link, and $k_B$ the Boltzmann constant. $A_M(p, \theta)$ represents the attenuation not exceeded for a fraction $p$ of the time considering a link whose elevation is $\theta$. This attenuation margin accounts for the various atmospheric phenomena causing propagation impairments. The term $(G/T)_{dB}$ denotes the figure of merit in clear sky of the ground station. It has to be noticed that the degradation of this figure of merit due to the increase of the sky noise temperature in case of adverse propagation conditions can be integrated within the propagation margin term $A_M(p, \theta)$. The required $(C/N)_{req}$ (including additional losses and backoff) to operate various modcods in a quasi error free link is given in table I.

The modcods to be used during any transmission are preprogrammed considering satellite ephemeris and the simplified link budget given by (1). Data are transmitted regardless of the actual propagation conditions. Thus, once the performances of the emitter and receiver are known, the instantaneous capacity of the channel $c$ depends only on the current elevation of the link $\theta(t)$. The link is operated with a too low $C/N$ with regards to the required $(C/N)_{req}$

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Code rate</th>
<th>$\eta$ b/s/Hz</th>
<th>Required $\frac{C}{N}$ dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-PSK</td>
<td>0.36</td>
<td>0.72</td>
<td>0.3</td>
</tr>
<tr>
<td>Q-PSK</td>
<td>0.43</td>
<td>0.86</td>
<td>1.1</td>
</tr>
<tr>
<td>Q-PSK</td>
<td>0.51</td>
<td>1.02</td>
<td>2.4</td>
</tr>
<tr>
<td>Q-PSK</td>
<td>0.60</td>
<td>1.20</td>
<td>3.6</td>
</tr>
<tr>
<td>8-PSK</td>
<td>0.47</td>
<td>1.41</td>
<td>4.7</td>
</tr>
<tr>
<td>8-PSK</td>
<td>0.54</td>
<td>1.62</td>
<td>6.0</td>
</tr>
<tr>
<td>8-PSK</td>
<td>0.62</td>
<td>1.86</td>
<td>7.2</td>
</tr>
<tr>
<td>8-PSK</td>
<td>0.70</td>
<td>2.10</td>
<td>8.7</td>
</tr>
<tr>
<td>8-PSK</td>
<td>0.79</td>
<td>2.37</td>
<td>10.2</td>
</tr>
<tr>
<td>16-APSK</td>
<td>0.66</td>
<td>2.64</td>
<td>11.3</td>
</tr>
<tr>
<td>16-APSK</td>
<td>0.73</td>
<td>2.92</td>
<td>12.5</td>
</tr>
<tr>
<td>16-APSK</td>
<td>0.80</td>
<td>3.20</td>
<td>14.0</td>
</tr>
<tr>
<td>16-APSK</td>
<td>0.88</td>
<td>3.52</td>
<td>15.7</td>
</tr>
<tr>
<td>32-APSK</td>
<td>0.76</td>
<td>3.80</td>
<td>17.2</td>
</tr>
<tr>
<td>64-APSK</td>
<td>0.69</td>
<td>4.14</td>
<td>18.5</td>
</tr>
<tr>
<td>64-APSK</td>
<td>0.74</td>
<td>4.44</td>
<td>19.8</td>
</tr>
<tr>
<td>128-APSK</td>
<td>0.69</td>
<td>4.83</td>
<td>20.9</td>
</tr>
<tr>
<td>128-APSK</td>
<td>0.74</td>
<td>5.18</td>
<td>22.5</td>
</tr>
<tr>
<td>256-APSK</td>
<td>0.69</td>
<td>5.52</td>
<td>23.7</td>
</tr>
<tr>
<td>256-APSK</td>
<td>0.74</td>
<td>5.92</td>
<td>25.8</td>
</tr>
<tr>
<td>256-APSK</td>
<td>0.79</td>
<td>6.32</td>
<td>28.0</td>
</tr>
<tr>
<td>1024-APSK</td>
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<td>6.90</td>
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</tr>
<tr>
<td>1024-APSK</td>
<td>0.74</td>
<td>7.40</td>
<td>31.6</td>
</tr>
<tr>
<td>1024-APSK</td>
<td>0.79</td>
<td>7.90</td>
<td>34.0</td>
</tr>
<tr>
<td>1024-APSK</td>
<td>0.85</td>
<td>8.50</td>
<td>37.1</td>
</tr>
</tbody>
</table>

TABLE I: Required $\frac{C}{N}$ and spectral efficiency for various DVB-S2X modcod used in the study [15]. Additional losses due to pre-distorsion and additional Output Back Off (OBO) included.
with a probability $1 - p$ by construction of the link budget. Thus a fraction $1 - p$ of data is lost in average. This happens when the actual attenuation $A(t)$ on the link is greater than the attenuation margin $A_M(p, \theta(t))$ designed to match the availability target at the current elevation angle $\theta(t)$.

The transmission part of the payload in the case of VCM can be modelled by the queue process illustrated on Figure 1.

![Fig. 1: Queuing network in the case of VCM transmission.](image)

The acquisition rate, corresponding to the client arrival rate is denoted as $a(t)$. The occupation of the on-board memory corresponding to the occupation of the queue is $M(t)$. This on-board memory is assumed to have a size $M_{\text{max}}$. The capacity of the link corresponding to the service rate of the queue is $c(\theta(t))$. The amount of properly downloaded data is $D(t)$ whereas the amount of lost data is $L(t)$. It has to be noticed that if the memory is completely occupied $M(t) = M_{\text{max}}$, data are lost at a rate $\max(0, a(t) - c(\theta(t)))$. Those kind of losses can be avoided if the memory is sufficiently large.

To evaluate the performances and to size a VCM system, the queue process schematized in figure 1 is analyzed in section III.

### B. ACM

ACM for data download link is likely to operate in a similar fashion as what is done for fixed Satcom links [16]. The ground station will monitor the quality of the link and feedback to the transmitter the modcod of highest spectral efficiency that can be used considering the monitored or expected $C/N$. Unlike the probabilistic link budget established for VCM in (1), the modcod used in the case of ACM is the modcod that closes the instantaneous link budget given by:

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

In (2), the main difference with (1) is the use of the actual state $A(t)$ of the channel at time $t$. In addition, a margin to account for the evolution of the channel during the latency in the ACM feedback loop has to be considered. The rate of fluctuations of the channel can be expected to be higher for a link with a varying elevation angle than for
a link with a GEO satellite as demonstrated in [9]. However considering the low link latency, the safety margin to anticipate the evolution of the propagation channel can remain at a reasonable level. In case of strong propagation impairments, no modcod can close the link budget, no data is sent and the memory is not emptied. No direct loss of data results from outage of the link. Thus, the queue process to model the transmission system using ACM can be modelled as illustrated on figure 2.

![Queueing network](image)

Fig. 2: Queuing network in the case of ACM transmission.

### III. LINK SIZING

The data transmission part of the Earth observation satellite has to comply with mission requirements but should not be significantly oversized to spare mass, power and cost for mission instruments. Thus it seems interesting to start from mission parameters to design optimally the link. One obvious requirement on the data download link is to have an average capacity $\bar{c}$ of the link (possibly considering several ground stations) greater or at least equal to the average data acquisition rate $\bar{a}$. This can be turned into the constraint:

$$\bar{c} \geq \bar{a} \tag{3}$$

If the condition (3) is not fulfilled, at least a fraction $(\bar{a}/\bar{c} - 1)$ of the data will be lost as the queue of the data to download will grow infinitely, and the on-board memory size is limited. This constraint is used to size the minimum EIRP and $G/T$ of the link.

The performances of the system in terms of data timeliness and data availability can not straightforwardly be related to system parameters. They can however be evaluated by simulation of the queue processes illustrated for VCM and ACM on figures 1 and 2 respectively. Indeed the availability $p_d$ of data can be evaluated as:

$$p_d = \lim_{t \to \infty} \frac{D(t)}{D(t) + L(t)} \tag{4}$$

Relation 4 just denotes that the data availability is the ratio of the downloaded data over the download plus lost data after a very long period of time.

The time spent in memory by data acquired at time $t$ assuming a memory usage $M(t)$ will be, assuming a first in first out (FIFO) policy for the memory:
\[ w(t) = \arg \min_{\tau} |M(t) - [(D + L)(t + \tau) - (D + L)(t)]| \] (5)

In (5) The waiting time \( w(t) \) corresponds to the time needed to empty the memory given its state at time \( t \). Constraints in terms of data timeliness can be translated in terms of constraints on the waiting time distribution.

In the following of this section starting from mission parameters and requirements, a method to size the transmission chain elements and to evaluate the resulting performances is proposed considering the use of VCM and ACM.

A. Mission parameters

To illustrate the methodology for link sizing, some generic mission parameters will be considered in the following. The baseline scenario will be a sun-synchronous quasi-polar satellite with an inclination of the orbital plane of \( i = 98.5^\circ \) and an altitude of \( h = 800 \text{ km} \), yielding to an epoch time of approximately 100 min. It is assumed that the satellite has a constant acquisition rate \( a(t) = 21 \text{ Tb/day} \), this kind of scenario could correspond to future meteorological sensors continuously scanning the atmosphere. For some missions, this acquisition rate may be variable for instance for observation satellites that have several acquisition modes and a limited duty cycle or targeting the acquisition of data in particular regions of the world. It may impact the numerical results presented in this study but if the acquisition rate pattern is known the sizing methodology can be applied in a similar fashion. It is assumed that a bandwidth of 540 MHz available at Ka band around 26.5 GHz for data downlink is used without polarization reuse.

As illustrated on 3, the visibility of those quasi polar satellites is much more frequent at high latitude, fostering the implantation of ground stations in polar areas. In some areas, like Svalbard, the station can be in visibility of the satellite at every epoch. It is assumed that the link can be established if the elevation is over 5\(^\circ\).

![Fig. 3: Position of the ground stations considered for the study and ground track of the satellite. The contour around the ground stations represents the contact area between satellite and ground station.](image)

The main characteristics of the different sites used in the study are detailed in table II.
<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Visibility Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svalbard</td>
<td>78.22°</td>
<td>15.40°</td>
<td>11.1%</td>
</tr>
<tr>
<td>McMurdo</td>
<td>−77.84°</td>
<td>166.67°</td>
<td>11.0%</td>
</tr>
<tr>
<td>Perth (Aus)</td>
<td>−31.57°</td>
<td>115.52°</td>
<td>3.2%</td>
</tr>
<tr>
<td>Matera (It)</td>
<td>40.66°</td>
<td>16.60°</td>
<td>3.0%</td>
</tr>
</tbody>
</table>

TABLE II: Position of the ground stations considered for Ka band data downlink, and fraction of time during which the satellite is in visibility.

**B. Propagation Simulation**

To evaluate the performances of the queue process for VCM as well as for ACM, it is necessary to get propagation time series pertaining to the link with the considered ground stations. Due to the very sparse availability of experimental data, simulated time series are used in replacement. For this study synthetic time series of total attenuation covering a duration of ten years have been generated considering the simulation process described in [11]. It is based on the methodology to generate space time correlated attenuation fields depicted in [17]. The first stage of the simulation process is to generate time correlated attenuation values $A(\theta, \phi)$ for links at any azimuth $\phi$ and elevation $\theta$ around the considered ground station. Then knowing the orbitography of the satellite, the temporal evolution of the azimuth $\phi(t)$ and elevation $\theta(t)$ of the LEO to ground link can be computed and the corresponding time series of attenuation $A(\theta(t), \phi(t))$ can be extracted. This procedure is illustrated on figure 4.

![Attenuation function of antenna pointing direction and satellite path](image1)

**Fig. 4:** Attenuation at a given time generated around a ground station and extraction of the time series knowing the azimuth elevation of the link.

The main interest of this methodology for this application is that the simulation of attenuation fields is driven by a global meteorological archive from ECMWF (European Center for Medium-range Weather Forecast) or NCEP (National Center for Environmental Predictions), allowing to have realistic fluctuations of the meteorological...
conditions for several successive passes over the ground stations and correlated attenuation conditions over the
different ground stations. The model is designed to converge towards ITU-R Rec P. 618-10 attenuation probability
distribution if run over a sufficiently long period. An example of time series for one month is illustrated on figure
5. It illustrates the dependence of the attenuation on the elevation angle as well as on the meteorological conditions.

![Total attenuation time series on a link between Metop-A satellite and a ground station in Perth at 26GHz](image)

Fig. 5: Example of time series generated for one month (top) and zoom on selected timeframes. Attenuation is
computed only when the satellite is in visibility of the ground station.

Attenuation time series with a temporal resolution of ten seconds are used in the following to simulate the queue
processes of figure 1 and 2 respectively.

C. Link sizing for VCM

For VCM as recalled in subsection II-A, the spectral efficiency of the link depends only on the elevation of the
link and on the availability target but not on the actual propagation conditions. The average spectral efficiency $\bar{\eta}(p)$
can be computed for a given site and availability target as:

$$\bar{\eta}(p) = E[\eta(p, \theta)] = \int \eta(p, \theta)P(\theta)d\theta$$

(6)

where the probability distribution of elevation of the link $P(\theta)$ can be obtained from the orbital parameters. The
average capacity $\bar{c}$ can be inferred just by multiplying the average spectral efficiency by the bandwidth $\bar{c} = \bar{\eta}B$. The
average capacity $\bar{c}$ function of the sum of EIRP and clear sky $G/T$ for various link availability target is illustrated
on figure 6 for Svalbard and Matera, using ITU-R Rec P.618-10 for the evaluation of propagation impairments
distribution.

The fraction of time during which the satellite is in visibility explains the large differences between the capacity
obtained for ground stations in Matera and in Svalbard. As what could be anticipated higher probability of outage
Fig. 6: Average throughput for various link availability targets and combined EIRP and G/T values for Svalbard and Matera using VCM (the throughput is 0 if the link is not in visibility).

results in lower attenuation margin and thus in lower capacity. Due to the more favourable propagation conditions in Svalbard, the decrease of capacity for increasing availability target is less marked than in Matera where much larger propagation margin are needed to reach high availability levels. The plateau for the highest RF chain performances is due to the limited modcod range considered in table I. In presence of high SNR, the most efficient modcod is almost exclusively used and an additional increase of SNR brings a marginal if not non-existent improvement of the performances.

Then, for a given $EIRP + G/T$ value, knowing the time series of elevation, the capacity time series $c(t)$ can be constructed as $c(t) = B\eta(p, \theta)$ and injected in the queue along with the attenuation time series $A(t)$. This enables to evaluate the amount of lost and downloaded data as well as the distribution of waiting time as illustrated on figure 7 for a memory $EIRP + G/T$ equal to 70 dBW/K with a ground station located in Matera.

Those numbers have voluntarily been chosen to be insufficient to fulfil the requirements in order to illustrate the loss of data due to memory overflow. This evaluation of the queue parameters can be made for longer durations to get statistically sounded results. The various performance criteria for the transmission part using VCM can be computed for different values of availability target and RF performances of the transmission part. In the case of VCM the rate of dumping of the memory depends only on the temporal evolution of the elevation pattern and is deterministic. The size of the memory $M_{\text{max}}$ to avoid memory overflow can thus be evaluated assuming first an
infinite memory and determining the maximum memory usage over time denoted by the dashed line of 7.

This memory size, function of the RF performances and data availability target is illustrated on figure 8 along with the distribution of waiting time of data in memory for a single ground station located in Svalbard and an acquisition rate of 243 Mb/s.

It can be noticed on figure 8 that the memory needed not to loose data decreases with an increasing link average capacity. For VCM this increase of link capacity can be achieved either, decreasing the link availability or for a given level of link availability by an increase of the RF performances. The same trend can be observed for the fraction of data downloaded before a given time after their acquisition. Thus depending on operational constraints in terms of data timeliness a trade-off between the RF chain performances and the link availability has to be found with implications in terms of required memory size. This trade off can be made in the following fashion. Starting from the requirements in terms of data acquisition rate of the sensor, targeted data availability, ground station position, a minimum EIRP+G/T for the selected ground station can be defined to get at least an average capacity equal to the acquisition rate as illustrated on figure 6. It relies on the link budget characteristics, the orbitography and the local propagation conditions. Then, from the selected RF transmission parameters and the targeted availability, capacity time series can be computed and given at input of the queue process depicted on figure 1. The maximum memory occupation simulating the queue process can be deduced alongside with the fraction of data downloaded after a
given duration since their acquisition. Repeating this process for various RF transmission chain performances and availability targets yields to establish the plots of figure 8. Figure 8 gives the RF performance level to fulfill a given data timeliness criterion for a targeted availability objective. It also gives the optimal associated memory size associated to this configuration. Thus with this methodology, mission requirements as data availability and data timeliness figure can be translated into memory size and RF chain performance level of a data downlink using a VCM scheme.

There may be no solution to match data timeliness requirement using only the selected site for the ground station and in this case this figure might be improved considering a network of several ground stations as discussed in section III-E.

It has to be noticed that the propagation time series (except the elevation angle time series) are not completely necessary to perform the analysis. Nevertheless, their use is mandatory to get further information on the characteristics of the outage or on secondary performance metrics. For instance, the average number of days with link outages, the fraction of contacts affected by outages, the maximum duration without transmission or the maximum fraction of data lost per day computed from ten years of simulations are reported in table III.

D. Link sizing for ACM

As for VCM the first element to size is the average capacity of the link. In this case, for a given link design, the spectral efficiency depends on the experienced attenuation and elevation as recalled in (2). The average spectral efficiency $\bar{\eta}$, can be expressed as:

![Image of Fig. 8: System performances resulting from the use of various availability target and various RF chain performance levels for a ground station located in Svalbard and usage of VCM.](image-url)
<table>
<thead>
<tr>
<th>Site</th>
<th>Targeted availability</th>
<th>% of contacts with outages</th>
<th>Number of days per year with outages</th>
<th>Maximum % of lost data per day</th>
<th>Maximum duration without transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svalbard</td>
<td>( p = 1% )</td>
<td>2.12</td>
<td>51</td>
<td>10.8</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>( p = 0.25% )</td>
<td>0.43</td>
<td>10</td>
<td>4.6</td>
<td>1.61</td>
</tr>
<tr>
<td>Matera</td>
<td>( p = 1% )</td>
<td>1.6</td>
<td>17</td>
<td>25.5</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>( p = 0.25% )</td>
<td>0.35</td>
<td>4</td>
<td>14.7</td>
<td>10.5</td>
</tr>
</tbody>
</table>

TABLE III: Characteristics of the outage for VCM transmission assuming an \( EIRP + G/T \) of 80dBW/K, computed using 10 years of time series.

\[
\bar{\eta} = \int \int \eta(\theta, A)P(A|\theta)P(\theta)dAd\theta \tag{7}
\]

This average spectral efficiency and thus the average capacity of the link depends on the joint distribution of elevation and attenuation of the link. It can be evaluated using ITU-R Rec P.618-10 and knowing elevation probability distribution. The average capacity of the link function of the RF transmission chain performances is plotted on figure 9.

Fig. 9: Average capacity of the link using ACM function of RF chain performances for Matera and Svalbard.
In the case of ACM as illustrated on figure 9, the average throughput of the link is still highly dependent on the visibility time of the ground station. The throughput is in any case higher than for VCM for the same performances of RF transmission chain. Here also the plateau of the curves indicates the almost exclusive use of the most efficient modcod above a threshold of RF performances.

As for a link using VCM, the estimation of the required memory and of the waiting time distribution requires the simulation of the queue process. In this case the instantaneous capacity $c(t)$ depends on the experienced attenuation level $A(t)$ and on the elevation $\theta(t)$. An example of the evolution for some days of the memory, the attenuation and the capacity is shown on figure 10.

With ACM, assuming that the transition between the various modcods does not induce loss of data, the losses of data occurs only when the maximum on-board memory is exceeded. In this case the oldest data in memory are replaced with the newly acquired ones. The relation between the memory size and the availability of the data can be established from the simulation of the queue process depicted on figure 2 for various memory size and various RF chain performances. The data availability function of the RF performance chain and the memory size for an acquisition rate of 243 Mb/s and a ground station located in Svalbard is illustrated on figure 11. This figure shows the increase of data availability with increasing memory size. It can also be noticed that due to the random capacity fluctuations, a 100% availability of the data can not be guaranteed whatever the memory size (the unlikely case
Fig. 11: Memory size function of the fraction of lost data objective considering a ground station in Svalbard and the use of ACM.

The fraction of data that is downloaded to the ground within a delay of 90 min after their acquisition is reported on figure 12. It can be noticed that the dependence of this performance indicator on the memory size is very limited.

To summarize the link sizing procedure starts from the knowledge of the position of the considered ground station, the data acquisition rate and the requirements in terms of data timeliness and overall data availability. The first step is to determine the RF performance parameters sufficient to have an average link capacity that exceeds the average acquisition rate from an evaluation similar to the one illustrated on figure 9. Then considering the range of possible performance values for the transmission chain, the data timeliness criterion can be computed from simulations of the queue process as illustrated on figure 12. Finally the optimal on-board memory size that can achieve the targeted data availability can be determined, using results presented on figure 11. It has to be noticed that this sizing process relies strongly on the propagation channel time series as the channel instantaneous capacity used as input in the queue process depends directly on the attenuation on the link.

As already mentioned in the case of VCM, there may be no solution that fulfil system constraints in case of too stringent requirements in terms of data timeliness or data acquisition rate with a single ground station. It is thus required to download data using links with several ground stations. The extension of the presented methodology to the case of a network of ground stations is presented in section III-E.
Fig. 12: Percentage of data downloaded before 90 min after their acquisition for a ground station located in Svalbard, function of the RF chain performances.

E. Decreasing waiting time

In the previous sections, it has been shown that the decrease in waiting time is bounded even increasing the maximum capacity of the channel between a LEO and a ground station. In fact, data can not be downloaded to ground before the ground station is in visibility of the satellite. The waiting time is hence limited by the visibility pattern of the ground stations. If the constrains in terms of waiting times are not fulfilled, the only remaining solution is to use additional or more frequently visible ground stations. This solution should also be used if the average acquisition rate of a satellite is too high with regards to the average capacity of the link with one ground station. To perform an assesment of the performance of the system if several ground stations are used, the capacity time series in the queue processes presented on figures 1 and 2 has to include the contributions of the various ground stations. The queue processes can be simulated in a similar fashion as in previous sections.

1) VCM: The capacity served considering two ground stations is illustrated on figure 13, considering VCM transmission and two ground stations with one in Svalbard and another one in Perth or McMurdo.

the performances in terms of required memory and data timeliness obtained from the simulation of the queue process can be found on figure 14.

It can be observed that the inclusion of an additional ground station with the same RF chain performance improves clearly the data timeliness and reduces the required memory. This effect is all the more sensible than the other ground station is located in a favourable area in terms of propagation and of visibility of the satellite.
Fig. 13: Capacity time series and memory usage for an acquisition rate of 243 Mb/s using VCM and various sets of ground stations.

2) ACM: The same kinds of results can be obtained using ACM as shown on figure 15. In this case, the improvement of the performances is even more noticeable. For instance two ground stations located in Svalbard and McMurdo are sufficient to get the same level of performance as a ground station located in Svalbard with a decrease of 10 dB of the performances of the transmission chain.

IV. CONCLUSION AND PROSPECTS

Direct RF data downlink at Ka band (or above) constitutes one of the possible solution to gather on Earth the huge amount of data acquired by future Earth observation satellites. The efficient use of this frequency band is conditioned to the use of adaptive waveforms like in ACM or VCM schemes. One of the challenge linked to the use of those schemes is the proper sizing of the transmission chain with sufficiently high performances to fulfil mission driven constraints. It has also not to be too oversized to avoid unnecessary mass and costs. Starting from the requirements in terms of data volume to download, data availability and data timeliness, a methodology to size optimally the RF transmission chain and the memory of the satellite has been developed for the case of link using VCM or ACM transmission schemes. It has been demonstrated that the use of time series of propagation channel
Fig. 14: Fraction of data downloaded before 90 min considering a ground station in Svalbard, and an additional one located in McMurdo or Perth. Optimal memory size for the various scenarios using VCM and an availability target of 99.9%.

Fig. 15: Fraction of data downloaded before 90 min considering a ground station in Svalbard, and an additional one located in McMurdo or Perth. Optimal memory size for the various scenarios, using ACM. The $G/T + EIRP$ value to assess required memory size is of 70 dBW/K.
in the atmosphere is indispensable to optimize the system parameters that are RF chain performances and on-board memory through the optimization of a queue process.

The increase of performances resulting from the use of ACM with regards to VCM already widely documented in [6] is clearly visible from the presented analysis. For instance assuming an on-board memory of 3.5Tb and a $EIRP + G/T$ of 75 dBW/K, the data availability is of 99.9% with 77% of the data downloaded 90 min after their acquisition for a link using VCM, whereas the data availability is over 99.98% and 95% of the data are downloaded 90 min after their acquisition for a link using ACM. It has to be noticed that the link capacity is bounded by the spectral efficiency of the most efficient modcodes for large $EIRP$ and $G/T$. Thus the use of constellations over 1024 APSK could lead to an improvement of the performances of the link. Improved VCM solutions making use of a knowledge of the seasonal fluctuations of the propagation channel or of an anticipation of propagation conditions have not been investigated in this study. The efficiency of those solutions could however be assessed using a methodology similar to the one described in this paper if proper models describing those anticipation schemes are available.

The extension of the simulation framework to networks of ground stations has been presented in a latter stage. The evaluation of the performances improvement induced by the use of several ground stations has been performed. It seems particularly interesting for missions targeting extremely large acquisition rate and with stringent data timeliness requirements. The use of several ground stations may allow under some conditions to decrease sensibly the RF performances of the individual link.

The results have been obtained assuming a FIFO behaviour for the memory. For some missions there may be prioritized data streams. In this case the design can rely on simulations of parallel queues with if necessary various data acquisition rate probabilistic patterns.

The simulation framework presented in this study could also be re-used in the future to compare the performance of data downlink operating at different frequency bands including optical data downlink. It may strives to be useful to perform trade-off for the design of future ground station networks.

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