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Smart gateways for terabit/s satellite — Source link

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Smart gateways for terabit/s satellite

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SUMMARY

To reach the terabit per second of throughput, telecommunication satellites cannot make use of frequency below Ka band only. Therefore, the use of broad portion of the spectrum available at Q/V (40/50 GHz) band is foreseen for the feeder link. This study presents the evaluation of performances of different macro-diversity schemes that may allow mitigating the deep fades experienced at Q/V bands by introducing cooperation and a limited redundancy between the different gateways of the system. Two different solutions are firstly described. The performances resulting from the use of those assumptions are derived in a second stage.

KEY WORDS: terabit; Q/V bands; frequency multiplexing diversity; propagation channel

1. INTRODUCTION

The development of very high-capacity multimedia Satcom system approaching the Tb/s will be conditioned to the use of a broad portion of the spectrum that cannot be found at Ka band only where 3 GHz of bandwidth are dedicated to the fixed satellite service [1–3]. Therefore, the use of Q/V band for the feeder link is foreseen for those systems. Hence, large bandwidths may be available for the feeder links as 4 GHz are available at Q band (likely used for the return link) and 5 GHz at V band (likely used for the forward link). If it offers a sufficiently large bandwidth to reach competitive capacity levels, the use of those bands appears as challenging for different reasons:

- The low level of maturity of space-qualified radio frequency components at those frequency bands.
- The sharing of this portion of spectrum with terrestrial services leading thus to an interference-challenging environment.
- The magnitude of the attenuation caused by the troposphere at those frequency bands (due to rain but also to gases and clouds) can reach very high levels even in favorable climatic areas. It will result in a low availability of gateway links, even using a wide range of coding and modulations. This issue, if not properly tackled, may prevent the development of commercial payloads at those frequency bands as the quality of service may be significantly decreased with regards to usual standards.

To increase the availability without significant losses of capacity, the use of classical site diversity is not seen as very efficient as it implies to duplicate the ground segment and the underlying costs. As the number of gateways foreseen to reach the Tb/s is most probably around a few tens [3], a multiplication by two of the number of gateway sites is likely also to cause significant logistical problems. In addition,

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the increase of availability induced by site diversity is bounded by the limited distance between the two sites (as they usually belong to the same spot beam to avoid pointing losses). Therefore, the decorrelation of the impairments is only partial, and the improvement of the availability may not be sufficient in some climatic areas.

As a consequence, other techniques have to be found to increase the availability of the feeder link at a reasonable cost. One of the solutions can be the introduction of cooperation between the gateways as proposed in [4]. The basic principle is that a user terminal can be assigned to different gateways depending on the propagation conditions and on the traffic load, so that when the gateway to which the user is assigned experiences strong impairments, the user terminal can be connected to another gateway. To achieve this, different system architectures can be considered. With regards to conventional bent-pipe broadband multi-beam satellite design, they require the introduction of an additional flexibility at the network and at the radio frequency levels. Two different designs are discussed in this paper:

- The first design consists in serving each user beam with carriers from different gateways; it will be shown that this mechanism enables to preserve a high availability without impacting significantly the payload architecture.
- The second design relies on the use of some additional capacity on the gateway side that is activated to replace the capacity lost by gateways that are experiencing a too-high attenuation level.

Those two diversity schemes will in the following be referred as the $N+0$ and the $N+P$ macro-diversity schemes, respectively. The aim of this paper is to present the two architectures in a first stage and to evaluate the performances resulting from the use of those solutions, considering assumptions of growing complexity.

2. $N+0$ OR FREQUENCY MULTIPLEXING DIVERSITY

2.1. Principle

The basic principle of the frequency multiplexing diversity or $N+0$ diversity is to serve the different beams by carriers from different gateways. In case of propagation impairments on one of the gateway as illustrated in Figure 1, each user beam is still served by carriers from the other gateways to which it is connected. Hence, the outage or reduced capacity of one gateway has an impact on all the user beams. As a counterpart, a complete unavailability of the service within one beam due to gateway outages becomes unlikely as it requires the outage of all the gateways that are serving the beam. Users connected to carriers with a too-low signal level due to fading on the feeder link need to be re-allocated on carriers from gateways that are not experiencing deep fades.

On the payload side, this architecture is fully compatible with a transparent bent-pipe satellite and does not require any additional switch or additional control system for the payload. Nevertheless, it may lead to some technical difficulties as the overall number of channels can be extremely high (the number of gateways involved in the diversity multiplied by the number of user beams) and the transponders are therefore likely to operate in multi-carrier mode.

It will be shown in Section 4 that the availability improvement depends on the number of gateways involved in the diversity and that, therefore, a trade-off between performance improvement and complexity of the payload has to be made. To avoid a too large increase of the complexity, different independent clusters of gateways and beams can be operated for the same system.

2.2. Handover procedure

The handover of the users to different carriers and gateways can be decomposed in three stages:

- The first stage is the detection of impairments on the gateway-satellite link that is routinely performed.
- The second stage is the decision to commutate users to other carriers, to be taken by the network control center (NCC) to which all the information concerning the state of the channel for all the gateways has been previously forwarded.

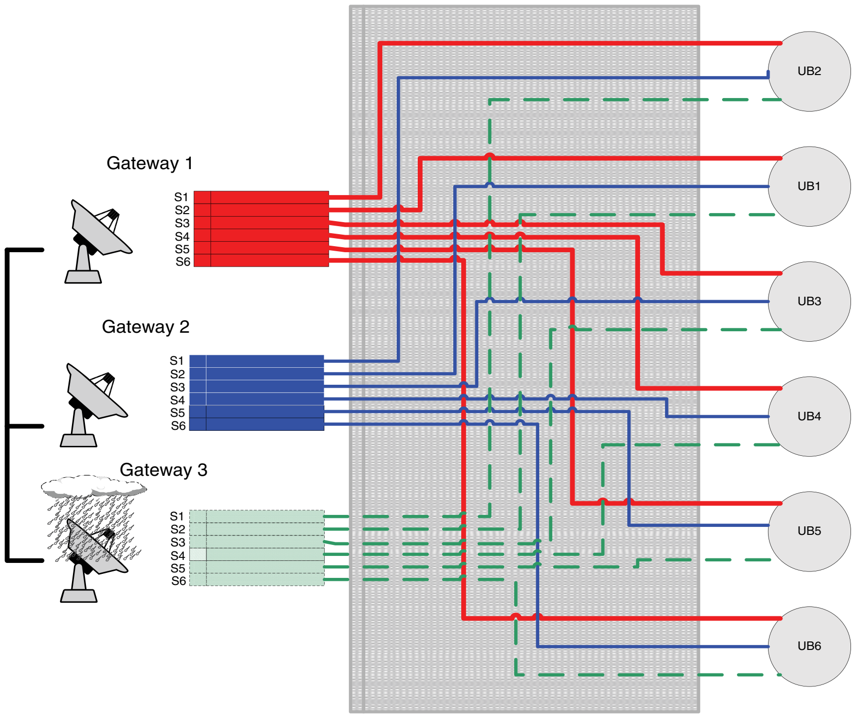

Figure 1. Principle of the $N+0$ diversity.

- The third stage is the execution of the change that will consist in the signaling to the user of the carrier to be changed and, simultaneously, in the update of the routing tables for the terrestrial network.

The handover in those kinds of systems is extremely similar to what can happen in a terrestrial mobile network, or in a mobile satellite network when one terminal has to change of cell or of beam [5]. Therefore, many procedures and concepts developed for those kinds of applications could be used. The main difference is that the handover will not be triggered at the level of the receiver but at the level of the NCC. Ideally, a make-before break handover should be performed. The state of transmission of the gateways has to be monitored during the detection phase. The monitoring can be made through downlink beacon measurements, as for Up-Link Power Control (ULPC). The gateways have to transmit to the NCC the state of their carriers that can be as follows:

- Whether their carriers will be available in a near future or not (without Adaptive Coding Modulation (ACM)).
- The most efficient modcod that can be transmitted by their carriers (with ACM) (requires some knowledge of the instantaneous link budget).

Considering that the channel state will not change considerably, the rate of refreshment of this information can be of some seconds. The decision has to be taken at the NCC. A table containing the list of connected users within one beam and the carrier/gateway they are currently using has to be constructed. The information about the state of transmission of each carrier/gateway has also to be considered. A cost function that involves a large number of parameters among which

- the achievable throughput,
- the number of re-routed users, and
- the number of real-time services switched

has to be minimized, knowing the state of the transmission of each of the gateways, the priorities and fair user policies status.

Two main actions have to be taken to execute the handover:

- to signal and execute the change of carriers, by signaling it in the overhead of the protocol, and
- to update the routing tables in the terrestrial network.

Those aspects have not been tackled within this study and require to be studied in details to achieve all the expected benefits from the implementation of the smart gateway diversity solution.

3. $N+P$ DIVERSITY

3.1. Principle

An alternative mechanism can be implemented to reduce the impact of the propagation impairments on the feeder link. The major change with regards to the $N+0$ diversity design is that P additional gateways with regards to the number of gateways normally required to achieve a given throughput are needed. This implies some additional costs due to the higher number of ground stations.

Each gateway can serve a cluster of k user beams. If P additional gateways with the same characteristics can be connected to the N clusters of user beams, a cluster of user beams served by one gateway that experiences outage can be served by one of the redundant gateways as illustrated in Figure 2. One of the obvious consequences of this architecture is that it requires $N+P$ beams for the gateways and that switches are required inside the payload to connect the additional gateways to one cluster of beams or another.

Similar to the $N+0$ diversity case, it may be required to split the gateways of one system into a few clusters of gateways that are operating independently one from the others to reduce the connectivity complexity.

3.2. Handover procedure

As for the $N+0$ diversity, a prerequisite to implement the diversity solution relies on the monitoring of the state of the channel for each gateway to trigger the handover. If the quality of the channel is too low for one gateway, the decision to use one of the redundant gateways can be taken. Once the NCC has taken the decision of commutation, it should inform the user terminal and send the command to change the state of the switches of the payload. At the network level, the handover can be managed using a similar procedure to the one used for the $N+0$ diversity. During the handover, all the users connected to one gateway have to be re-allocated to another carrier of another gateway. It may lead to congestion problems at the network level as a large number of users need to be reconnected at the same time and to significant recovery times.

4. ASSESSMENT OF THE PERFORMANCES OF THE DIVERSITY SCHEMES

To get a preliminary assessment of the performances induced by the use of those macro-diversity solutions, the issues related to imperfect handover, modcod switching, are neglected. Therefore, the results provided in this section can only be seen as upper bounds as those issues will inevitably lead to a degradation of the performances.

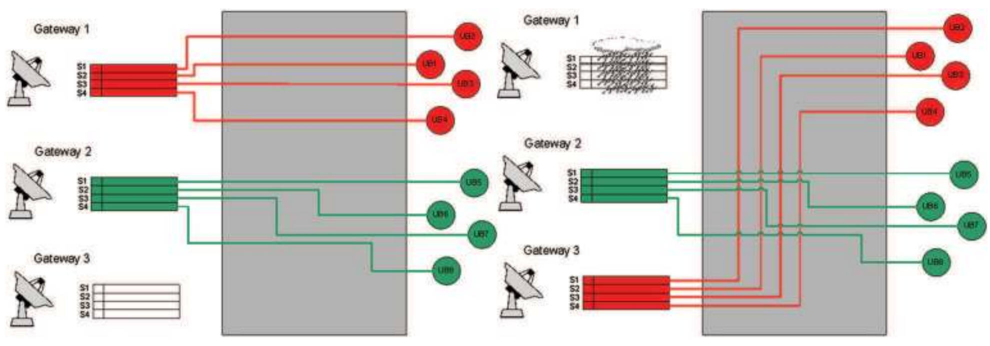

Figure 2. Principle of $N+P$ diversity.

4.1. Use of simple probabilistic assumptions

To get a very rough idea of the availability improvement induced by the use of the two macro-diversity architectures discussed in the previous sections, a simple combinatory analysis is performed. Even if the results cannot be used as such for system dimensioning, they enable to draw some trends on various parameters. To isolate the impact of the macro-diversity, it is assumed that there is no ACM so that either the link is available at full capacity or it is unavailable. It is moreover assumed in a first stage that there is no impairment within the user beams. The analysis is conducted for N gateways involved in the diversity scheme that all have an individual probability of outage p due to the deterioration of the propagation channel. The outages on the gateway side are supposed to be independent and uncorrelated. The impact of this assumption will be discussed more in details in Section 4.3.

4.1.1. $N+0$ diversity. In the case of $N+0$ diversity, one user beam will be served by N gateways. If N_{out} gateways out of N are in outage at a given time, the maximum capacity delivered to one user beam is a fraction $T = 1 - \frac{N_{\text{out}}}{N}$ of the nominal capacity. Hence, the complete outage will be reached only if all the gateways are simultaneously in outage. Considering the simple assumptions taken on the occurrence of outage, the probability to have n out N gateways in outage is given by

$$P(N_{\text{out}} = n) = C_N^n p^n (1-p)^{N-n} \tag{1}$$

where $C_N^k = \frac{n!}{(n-k)!k!}$ is the binomial coefficient.

Hence, the CDF of the fraction of the nominal throughput that can be delivered to one beam can be estimated by

$$P\left(T \geq \frac{k}{N}\right) = P(N_{\text{out}} \leq N-k) = \sum_{i=0}^{N-k} C_N^i p^{N-i} (1-p)^i \tag{2}$$

Evaluating this CDF for different values of N and p yields to the results presented in Figure 3.

It can be observed in Figure 3 that as long as a sufficient number of gateways N is involved in the diversity, the probability of total outage becomes negligible even considering a relatively high value of single site outage p. With 10 gateways in the diversity scheme, a significant fraction of the nominal capacity can still be provided more than 99.99% of the time.

The average fraction of capacity that can be deduced from Equation (1) is independent of N and equal to $1-p$. The use of the $N+0$ diversity does not enable to increase the average capacity, as no extra resources are included, but enables to reduce the fluctuations of capacity provided to the user beam. As what can be noticed from Figure 3, the increase of the number of gateways decreases the probability of occurrence of provision of low fraction of nominal capacity as well as the probability of occurrence of nominal capacity.

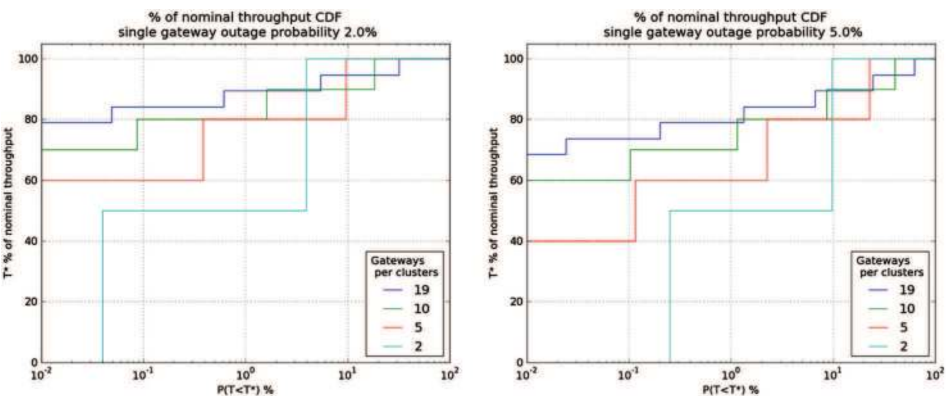

Figure 3. % of nominal capacity CDF for various $N+0$ diversity configurations.

4.1.2. $N+P$ diversity. In addition to the N gateways from the baseline design, P redundant gateways able to replace any of the N gateways, as illustrated in Figure 2, are also considered with the same probability of outage p. Unlike the $N+0$ diversity, the capacity delivered is either the nominal capacity or 0. If less than P gateways are simultaneously in outage, all user beams can still be served. If $P+i$ gateways are in outage simultaneously, a fraction i/N of the user beams will not be served by any gateways. From a user terminal point of view, it results in a probability i/N of outage if $P+i$ gateway are unavailable, as it can be assumed that the redundant gateway can be allocated randomly to any of the i gateways in outage. Another alternative could be to give the priority to the gateway that serves the user beams with the highest traffic load, but this will not be considered in the following.

The probability to have $P+i$ out of $N+P$ gateways in outage assuming a decorrelation of the outages is given by a binomial distribution:

$$P(N_{\text{out}} = P + i) = C_{N+P}^{P+i} p^{P+i} (1 - p)^{N-i} \tag{3}$$

Therefore, the probability of outage due to the feeder link experienced in one of the user beam is given by the summation of the possible cases:

$$p_{\text{outage}} = \sum_{i=0}^{N} \frac{i}{N} C_{N+P}^{P+i} p^{P+i} (1 - p)^{N-i} \tag{4}$$

An illustration of this result for different values of p and N is given in Figure 4 where the overall outage experienced in one user beam function of the probability of outage for a single gateway is plotted.

It can be noticed in Figure 4 that the availability of the feeder link is improved by at least one order of magnitude with a low level of redundancy. Hence, considering an individual availability of the gateway links of 98%, the overall feeder link availability can reach 99.99% adding two redundant gateways to eight needed from a strict bandwidth point of view. This overall availability of 99.99% can also be reached adding three redundant gateways for 20 in the initial design (with the same availability of 98% for individual gateway links).

This diversity scheme is clearly more advantageous when considering large clusters of gateways as it enables to limit the proportion of redundant gateways. In fact, the use of a larger N will decrease the variation coefficient of the distribution of the number of gateways simultaneously in outage given by Equation (3). This is achieved through a more frequent use of the redundant gateways, than in the case of clusters of gateways of lower cardinal.

4.2. Application on design foreseen for reach the Tb/s

If the previous section has clearly highlighted the potential interest of the $N+0$ and $N+P$ diversity schemes in terms of improvement of availability on an idealized case, it is interesting to evaluate the performances using more realistic assumptions, implying the use of ACM as well as different climatic

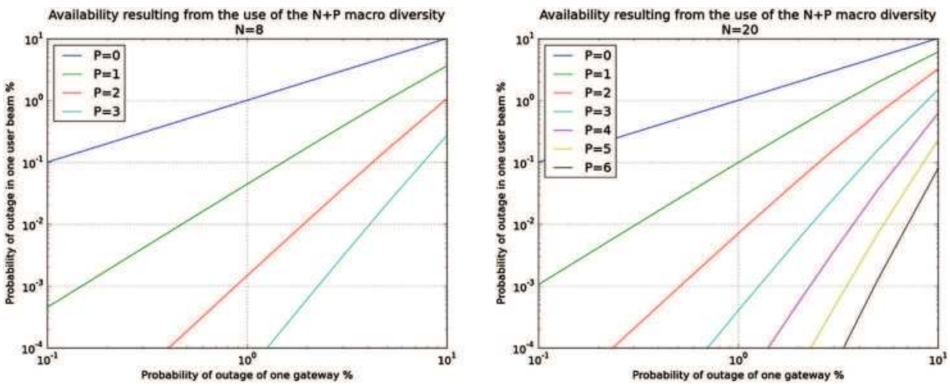

Figure 4. Probability of outage of the feeder link in one user beam.

conditions over the gateways. Nevertheless, the performances are assessed without taking into account the imperfections of ACM control loop or the traffic pattern. To simplify the computations, it will be assumed that the same resources are allocated to every terminal and that the satellite is fully loaded.

Using those assumptions, the spectral efficiency or throughput CDF using one of the given diversity scheme is assessed in this section. The system parameters proposed in [3] to achieve the Tb/s are used for this example. The basic link budgets parameters of Table 1 are considered for the forward up and down links.

The $C/(N+I)$ and usable modcod function of the up and down link attenuation are summarized in Figure 5, assuming a DVB-S2 [6] like air interface.

As illustrated in Figure 5, the propagation margins on the up and down links are approximately the same on the feeder and the user link. Therefore, the feeder link operating at 50 GHz against 20 GHz for the user link will be the most constraining on the availability. It also shows that the clear-sky modcod that is assumed to correspond to the nominal spectral efficiency is the 16APSK5/6.

As illustrated in Figure 5, the spectral efficiency s can be defined as a function of the uplink and downlink attenuation A_{up} and A_{down} through the following:

$$s = \mathrm{f}\left(A_{\mathrm{up}}, A_{\mathrm{dn}}\right) \tag{5}$$

Six gateways whose position is detailed in Table 2 are considered in the analysis. A user terminal located near Rome is also considered.

Table I. Considered link budget parameters. Interference levels are given assuming no propagation losses.

Feeder link			User link		
Parameter	Value	Units	Parameter	Value	Units
GES EIRP max	76.5	dBW	EoC EIRP	72.5	dBW
Frequency	50	GHz	Frequency	20	GHz
FSL	218.3	dB	FSL	210.3	dB
Propagation loss	?	dB	Propagation loss	?	dB
G/T sat	31.45	dB/K	G/T ut	20.3	dB/K
C/I co-channel	20	dB	C/I co-channel	21	dB
$C/$Ixpd	23	dB	C/I adj-channel	25	dB
C/I adj-channel	25	dB	C/I imod	25	dB

GES, Ground Earth Station; FSL, Free Space Loss.

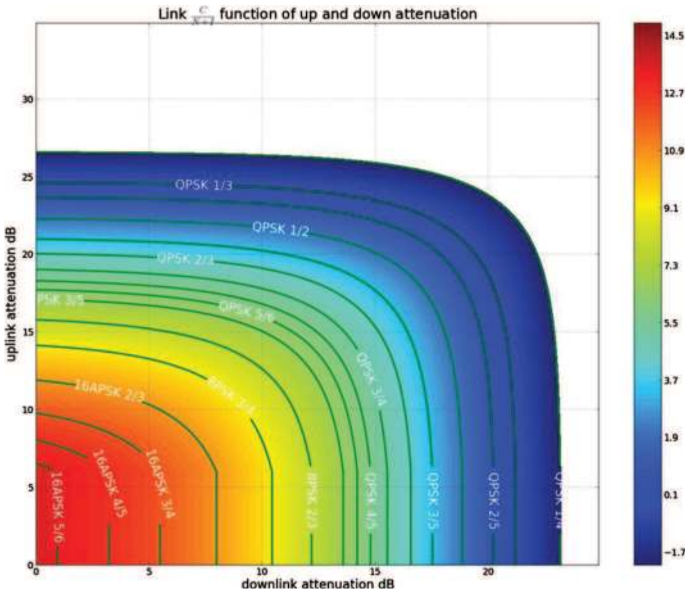

Figure 5. Link $C/(N+I)$ and modcod of maximum spectral efficiency allowed considering system parameter of table 1.

Table II. Position of the gateways considered in the analysis.

Location	Latitude	Longitude
Krakow (Poland)	50.15	19.45
Belgrade (Serbia)	44.88	20.02
Kuopio (Finland)	61.93	27.43
Bucaresti (Romania)	44.22	26.72
Kiev (Ukrain)	50.43	30.52
Mogilev (Belarus)	54.48	29.76

The attenuation complementary CDF ϕ_i for each of the gateways can be derived from International Telecommunication Union Radiocommunication sector (ITU-R) *P* Recommendations [7, 8]. Therefore, attenuation samples for the feeder link of the *i*th gateway can be simulated using $A^i_{\text{up}} = \phi_i^{-1}(U)$ where U is a sample from a random variable with a uniform distribution between 0 and 1. Similarly, attenuation samples for the downlink can be computed using $A_{\text{dn}} = \psi^{-1}(V)$ with V being a draw from a uniformly distributed random variable between 0 and 1.

Therefore, the spectral efficiency CDF of the link between the *i*th gateway and the user terminal can be computed using a Monte Carlo simulation [9] as follows:

$$P(s < s^*) = E\left[I_{[0,s^*[}(s)\right] = \lim_{M\to\infty} \frac{1}{M} \sum_{k=1}^{M} \mathrm{I}_{[0,s^*[}\left\{\mathrm{f}\left(\varphi_i^{-1}(U_k), \psi^{-1}(V_k)\right)\right\} \tag{6}$$

where I is the indicator function, and U_k and V_k are realizations from independent uniformly distributed random variable between 0 and 1. In practice, as the variance of the Monte Carlo evaluation decrease as the square root of M, a number of samples of 10^6 give a relative standard deviation of less than 1%.

4.2.1. N + P diversity. In the case of $N+P$ diversity, the considered user terminal will be connected randomly to any of the N gateway experiencing the lowest attenuation among the $N+P$ considered gateways. Therefore, Equation (6) need to be changed to compute the spectral efficiency CDF of the link:

$$P(s < s^*) = E\left[I_{[0,s^*[}(s)\right] = \lim_{M\to\infty} \frac{1}{M} \sum_{k=1}^{M} \mathrm{I}_{[0,s^*[}\left\{\mathrm{f}\left(A_k^{\text{up}}, \psi^{-1}(V_k)\right)\right\} \tag{7}$$

where A_k^{up} is randomly chosen among the N lowest values of $\left\{\varphi_i^{-1}\left(U_k^i\right)\right\}_{i=1,\ldots,N+P}$ where the U_i^k are independent uniform random draw within [0;1]. The hypothesis of independence between the samples implies that there is no correlation between the samples.

To assess the efficiency of the diversity scheme, the spectral efficiency CDF considering the use of the 5 + 1 diversity is compared with the spectral efficiency without any kind of diversity and also with an ideal case without rain impairments on the feeder link. The comparison is illustrated in Figure 6.

As what can be noticed in Figure 6, the use of $N+P$ diversity is extremely efficient as the obtained performances are close to the ones obtained without impairments on the feeder link. The performances of the link are hence strongly limited by the user link, whereas they are strongly limited by the feeder link without diversity.

4.2.2. N + 0 diversity. For the evaluation of the performances of the $N+0$ diversity, the spectral efficiency of the link does not constitute a good performance indicator of the link as several carriers coexist in the same user beam and that a maximization of the spectral efficiency would require having all the users on the carrier of maximum spectral efficiency.

From the user point of view, the data rate that will be received will depend on how all the users within the same beam are allocated to the various carriers. It will be assumed that if there is no impairment on the feeder link, all the user terminals are allocated the same data rate. This can be carried out intuitively by allocating fewer users to carriers of low spectral efficiency than on the carriers with the highest spectral efficiency. Therefore, if there is no impairment on the user link, the fraction of the maximal data rate that can be served to the beam and to each individual user is

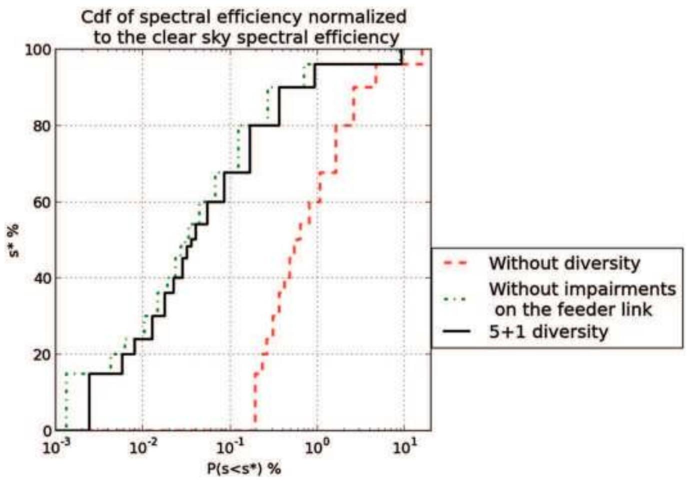

Figure 6. CDF of fraction of spectral efficiency normalized to the clear sky spectral efficiency considering 5 + 1 diversity, no diversity and a feeder link without rain impairment.

$$\tilde{t} = \frac{\sum_{i=1}^{N} \tilde{s}_i}{N s_{CS}} \tag{8}$$

where N is the number of carriers serving one beam (assuming the same bandwidth for all the carriers), $\tilde{s}_i = \mathrm{f}(A_i^{\mathrm{up}}, 0)$ is the maximum throughput for the ith carrier knowing the fading on the feeder link, and $s_{CS} = \mathrm{f}(0,0)$ is the clear sky modcod. It has to be noticed that with the use of this kind of heuristic to allocate the users on the carriers, a degradation of the spectral efficiency of one carrier will have an impact on the throughput of all the users within the beam.

The impairments on the user link will also lead to a degradation of the throughput experienced by the user. The link for one user will actually have a spectral efficiency $s_i = \mathrm{f}\left(A_i^{\mathrm{up}}, A^{\mathrm{dn}}\right)$, whereas the spectral efficiency to achieve the fraction $\tilde{t}$ of the maximum throughput is $\tilde{s}_i = \mathrm{f}(A_i^{\mathrm{up}}, 0)$. Therefore, the fraction of the maximum throughput experienced by the user connected to the jth gateway, and experiencing an attenuation A^{dn} on the downlink can be evaluated as follows:

$$t = \frac{s_j}{\tilde{s}_j} \frac{\sum_{i=1}^{N} \tilde{s}_i}{N s_{CS}} = \frac{\mathrm{f}\left(A_j^{\mathrm{up}}, A^{\mathrm{dn}}\right)}{\mathrm{f}\left(A_j^{\mathrm{up}}, 0\right)} \frac{\sum_{i=1}^{N} \mathrm{f}(A_i^{\mathrm{up}}, 0)}{N \mathrm{f}(0,0)} \tag{9}$$

As for the $N+P$ diversity, the CDF of the fraction of the maximum throughput for one user can be evaluated by Monte Carlo integration. This can be carried out simulating M independent draws of the random variables A_i^{up}, A^{dn}, and j (uniformly distributed over the indices ranging from $1,\ldots,N$ where $\tilde{s}_i \neq 0$ as it is assumed that the user terminal can be connected to any of the gateways that provide an available carrier). Here also, the simulation of independent random variables implies that the fading are uncorrelated.

A comparison of the performances induced by the use of the $N+0$ diversity with the performances obtained without the use of diversity and without impairment on the feeder link is presented in Figure 7.

As what can be seen, the effect of the $N+0$ diversity is to mitigate completely the unavailability due to the feeder link at the expense of a slight loss of throughput. The nominal throughput can be maintained a lower fraction of the time than in the case without diversity. The availability is driven by the fading on the user link only.

4.3. Impact of the spatial correlation of the propagation channel

In the previous paragraph of this section, the performances of the system have been assessed assuming a total decorrelation of the propagation impairments over the various locations. It can be motivated by the fact that the gateways involved in the diversity schemes are belonging to different beams and that,

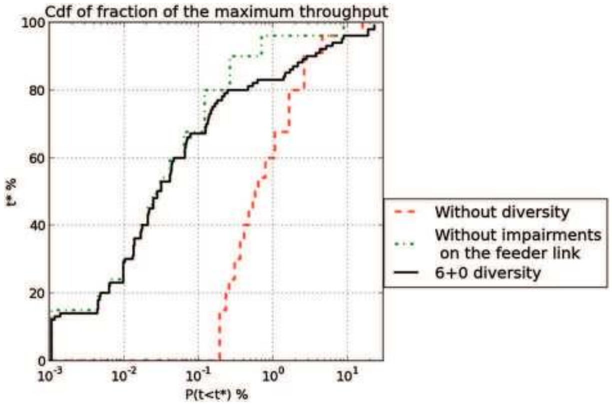

Figure 7. CDF of fraction of the maximum throughput experienced by one user considering the use of the $N+0$ diversity, no diversity, and without impairments on the feeder link.

therefore, they are located some hundreds of kilometers away the ones from the others. At this distance, the tropospheric attenuation, and especially the attenuation due to rain, becomes strongly decorrelated, but a residual correlation may exist [10]. This correlation may be due to the correlation of gaseous attenuation (especially the one due to water vapor) or to the seasonality of correlation. No experimental data at Q/V band enables to test the validity of those assumptions at least until the deployment of the Alphasat propagation campaign [11]. Therefore, to evaluate the impact of the decorrelation hypothesis made in the previous section, spatially and temporally correlated time series have been simulated using the space–time channel model developed in [12] to describe rain attenuation and extended to total attenuation in [13]. The correlation at long range within this modeling is included through the use of a coarse meteorological database.

One year of time series sampled at 1 s has been generated using this model on the sites of Table 2. The performances of the two diversity schemes have been assessed using those time series by substituting the concurrent samples of the time series to the randomly and independently drawn attenuation samples in Equations (7) and (9) for the $5+1$ and $6+0$ diversities.

The CDF of fraction of spectral efficiency experienced by one user in the case of $5+1$ diversity considering or not correlated time series is illustrated in Figure 8.

The impact of the correlation of the time series is limited as it induces a relatively low degradation of the availability and of the spectral efficiency. In the case of $6+0$ diversity, the effect is even less pronounced as the CDF of maximum throughput is almost unchanged as illustrated in Figure 9.

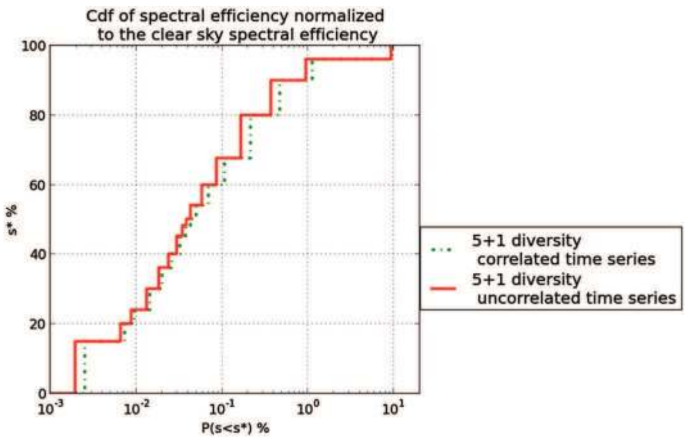

Figure 8. CDF of spectral efficiency considering spatially correlated or uncorrelated time series to assess the performances of the $N+P$ diversity.

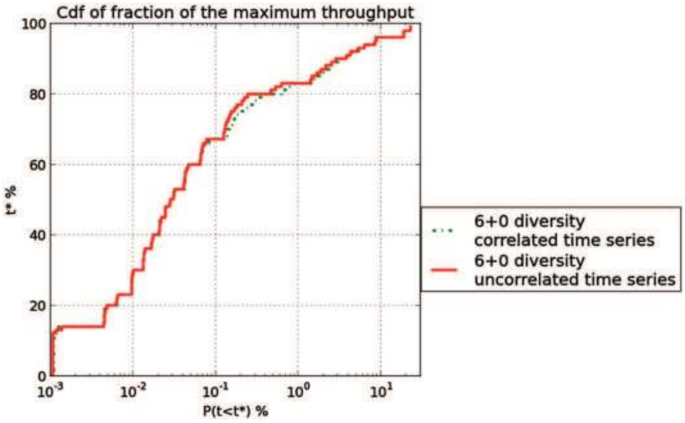

Figure 9. CDF of fraction of the maximum throughput considering spatially correlated or not attenuation samples for the $N+0$ diversity.

Those results, even if relying on simulations, tend to show that the impact of the slight residual correlation of the impairments on the performances of the macro-diversity schemes is relatively low.

5. CONCLUSION

This study has presented some preliminary results on the performances of two diversity schemes that could be applied to maintain a high availability for the feeder links of Q/V band Satcom systems targeting terabit per second. The use of the concept of smart gateways macro-diversity is motivated by the possible mitigation of the frequent outages of the feeder link due to strong propagation impairments at Q/V band while maintaining a high fraction of the nominal capacity, using the spatial decorrelation of propagation impairments. Site diversity solutions are seen as inefficient as they imply a duplication of the ground segment and are therefore prohibitive.

The two different mechanisms that have been considered to mitigate the propagation impairments on the feeder link are as follows:

- $N+0$ macro-diversity that is a frequency multiplexing solution without using any kind of redundancy.
- $N+P$ macro-diversity that makes use of redundant gateways.

Those mechanisms are completely compatible with bent-pipe payloads and assume that the gateways are linked between them by a terrestrial network and have the ability of exchanging some traffic. They also imply that the user beams are no longer connected to only one gateway. After a brief description of the underlying assumption related to the implementation of those schemes, in a rough performance estimation stage, a simplified method has been developed to evaluate the capacity distributions resulting from the use of the macro-diversity solutions.

Both diversity schemes have been shown to be efficient for preventing outages if a sufficient number of gateways are involved considering spatially uncorrelated propagation impairments:

- In the $N+0$ macro-diversity scheme, no oversizing of the ground segment is required. This scheme avoids outages by balancing the capacity fluctuations of the different gateways among the user beams. The average capacity in time delivered by the system is the same as the same system without diversity (more than 95% of the nominal capacity).
- In the $N+P$ macro-diversity scheme, some redundancy is added (by an oversizing of the ground segment of 10% to 20%), and the nominal capacity can be maintained except for some minutes or hours per year.

With the use of those diversity techniques, the end-to-end performances of the system are likely to be driven by the performances of the satellite user link. Those diversity techniques may also enable a significant reduction of gateway Emitted Isotropically Radiated Power (EIRP) if a sufficient level redundancy is introduced. Hence, the costs induced by the additional gateways can be balanced by the reduction of the costs induced by the reduction of the amplifier power or antenna size. The use of redundant gateways is also advantageous as it enables the impact of hardware failure or outages to be limited, and also relaxes the constraints in the maintenance.

A verification of the hypothesis of decorrelation of the propagation impairments has finally been carried out using a space–time channel model of total attenuation. It has been shown that as long as the gateways are spaced by several hundreds of km, this hypothesis has a limited impact, considering the $N+0$ macro-diversity scheme. It may be needed to consider this correlation, for instance considering the future results of the Alphasat propagation experiment [11] for the $N+P$ macro-diversity scheme to achieve an accurate evaluation of the system performances.

There are numerous points that need to be investigated or extended to assess more in detail the performances of the smart gateways for terabit/s satellite systems and their feasibility:

- The implications and the feasibility of the numerous connections within the payload have to be assessed for the different macro-diversity schemes, as it constitutes a prerequisite to those techniques. It may limit from a practical point of view the overall number of gateways
- The major difficulty of this kind of diversity implementation lies in the control logic to perform the handovers. Its impact on the higher communication layers has to be studied. In particular, the algorithm to schedule the switches will require a particular care as it has to consider a large number of parameters such as possible connections, channel state, priority of the traffic, and fair user policies. The management of the network may be considerably complicated by the use of those techniques.
- The study here was focused on the forward link. No major changes are expected for the return link (except that the gateway-satellite link will be less sensitive to propagation conditions as the co-channel interference level will not depend on the propagation conditions).

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REFERENCES

1. Gayrard JD. Terabit satellite: myth or reality? *First International Conference on advances in Satellite and Space Communications*, Colmar, France 2009.
2. Evans B, Thompson P. System design for a broadband access terabit/s satellite for Europe. *17th Ka and Broadband Communications, Navigation and Earth Observation Conference*, Palermo, Italy 2011.
3. Kyrgiazos A, Evans B, Thompson P, Mathiopoulos T, Papaharalabos S. A terabit/s satellite for european broadband access – feasibility study. *Int J Satell Commun Netw* this issue.
4. Skinnemoen H. Gateway diversity in Ka-band systems. *Fourth Ka Band Utilization Conference*, Venice, Italy 1998.
5. Bolea Alamanac A, Chan PM, Duquerroy L, Hu YF, Gallinaro G, Guo W, Mignolo D. DVB-RCS goes mobile: challenges and technical solutions. *Int J Satell Commun Netw* 2010; **28**:137–155. doi:10.1002/sat.946
6. Alberty E, Defever D, Moreau C, Gaudenzi R, Ginesi A, Rinaldo R, Gallinaro G, Vernucci A. Adaptive coding and modulation for the DVB-S2 standard interactive applications: capacity assessment and key system issues. *IEEE Wirel Commun* 2007; **14**(4):61–69.
7. ITU-R Rec P.837-5. Characteristics of precipitation for propagation modeling. *ITU-R P Series Recommendations—Radiowave Propagation*, 2007.
8. ITU-R Rec P.618-10. Propagation data and prediction methods required for the design of Earth–space telecommunication systems. *ITU-R P Series Recommendations—Radiowave Propagation*, 2009.
9. Rinaldo R, Gaudenzi RD. Capacity analysis and system optimization for the forward link of multi-beam satellite broadband systems exploiting adaptive coding and modulation. *Int J Satell Commun Netw* 2004; **22**:401–423. doi:10.1002/sat.789
10. Barbaliscia F, Ravaioli G, Paraboni A. Characteristics of the spatial statistical dependence of rainfall rate over large areas. *IEEE Trans Antenn Propag* 1992; **40**(1):8–12. doi:10.1109/8.123347
11. Koudelka O. Q/V-band communications and propagation experiments using ALPHASAT. *Acta Astronaut* 2011; **69**(11–12): 1029–1037. doi:10.1016/j.actaastro.2011.07.008.Alphasat
12. Jeannin N, Féral L, Sauvageot H, Castanet L, Lacoste F. A large-scale space–time stochastic simulation tool of rain attenuation for the design and optimization of adaptive satellite communication systems operating between 10 and 50 GHz. *Int J Antenn Propag* 2012. doi:10.1155/2012/749829.
13. Jeannin N, Carrié G, Castanet L, Lacoste F. Space–time propagation model of total attenuation for the dimensioning of high frequency multimedia satcom systems. *17th Ka and Broadband Communications, Navigation and Earth Observation Conference*, Palermo, Italy 2011.

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