Assessment of Practical Smart Gateway Diversity Based on Multisite Measurements in $Q$-/$V$-Band

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Abstract—Next generations of high throughput satellite (HTS) systems operating a $Q$-$V$-band network of gateways (GWs) for the feeder link need to apply some form of smart gateway diversity (SGD) to ensure they meet the demanding availability targets. However, most of the published research on SGD usually resorts to ideal assumptions that are not realistic for an operational system. To evaluate in more depth the performance of practical SGD, this article exploits for the first time multisite propagation measurements for a network of six measurement sites (GWs) at 40 GHz. Based on this, it studies the performance of SGD in terms of feeder availability and number of switches between GWs taking into account the climatic region, the switching processing delay, the clustering of GWs, and the impact of downlink versus uplink frequency in $Q$-$V$-band. Along the course, the interplay between propagation aspects and SGD operational aspects is highlighted.

Index Terms—Millimeter-wave propagation, propagation losses, radio communication countermeasures, radiowave propagation, satellite ground stations, spatial diversity, telecommunication network topology.

I. INTRODUCTION

FOR EXPLOITING extremely high-frequency (EHF) bands beyond 10 GHz in the RF feeder links of high throughput satellite (HTS) networks, it is necessary to rely on some sort of smart gateway diversity (SGD) [1]–[3] since this technique ensures the high availability targets required. The spectrum needs resulting from HTS systems lead to already deploying multiple gateway (GW) stations for nominal service. This is the reason why, in recent years, the cost of the HTS ground segment is absorbing a much larger part of the overall mission cost, a source of growing concern. SGD enables the cooperation between the already existing GWs and ensures the target availability by potentially adding only a few extra resources (GWs) for cold redundancy. This is in sharp contrast with traditional site diversity where each ground station needs to be paired with a redundant one, which leads to a doubling of the number of GWs.

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SGD exploits the geographical spatial diversity provided by interconnecting multiple GW stations in different feeder beams in order to increase the ground network availability. Two main flavors of SGD have been proposed [1]: the N active GWs and the N active + P redundant GWs. They both operate under the same fundamental premise of rerouting data from a faded GW to a different GW site of another feeder beam. Instead, with traditional site diversity, a secondary antenna is placed within the same beam kilometers away from the faded GW site. Their difference is that, in the first scheme (N), each GW is oversized in terms of resources to handle part of the traffic of a faded GW in the network, whereas, in the second scheme (N + P), the N nominal GWs are fully loaded so that when one falls in outage, one of the P redundant ones completely takes over its traffic. Both techniques require substantial ground-based connectivity and the associated spacecraft RF routing mechanisms; as such the choice of SGD has an impact on the satellite payload architecture [4], [5]. For ensuring very high feeder link availabilities (99.9% or even 99.99%), an active GW under heavy fading needs to switch to another one. Such a switching event1 risks the loss of end user demodulator synchronization due to the land-based delay in rerouting data between GWs.

It is clear that the spatial and temporal characteristics of all the feeder propagation channels are driving the performance of the SGD technique and that its effectiveness in the system performance depends on both. Hitherto, with the exception of few recent works (see [6], [7]), most of the contributions on the topic of SGD have made ideal assumptions, such as perfect decorrelation of fading amid the GW locations, ideal knowledge of the fading and ideal prediction of its evolution, as well as instantaneous switching between the GW sites. In practice, the practicalities in operating SGD may play a detrimental role in the performance of SGD in terms of offered availability. Such practicalities include the switching/handover dynamics under practical constraints (e.g., the frequency of GW switching/handover or the criterion when to switch), the switching characteristics between GWs, and the related channel estimation.

There is a clear gap of such studies and models due also to the fact that existing concurrent and synchronized time series of attenuation measured from a network of experimental sites (such as the ALPHASAT propagation experiment [8]) have never been analyzed toward this goal. The existing propagation models (ITU-R Study Group 3 Recommendations, mainly ITU-R P.618 [9]) are statistical prediction models aiming

Switching and handover are interchangeably used in the rest of this article.
mainly at the specification of the fade margin (FM) or at the
description of the fade dynamics (e.g., fade duration and fade
slope) both inconclusive in determining either the performance
of the real systems or how to optimize its operation.

In this article, the authors try to fill this gap by emulating for
the first time the performance of the SGD technique employing
real multisite data (measurements) of the propagation channels in
Q-/V-band. For easier reading of the results, the N + P
variant of SGD is adopted throughout this article, although
this is expected to have small impact on the main results and
conclusions. The main novelty of this article is that the emu-
lations are based on measurements of the Q-band (40 GHz)
propagation signal transmitted by the Aldo Paraboni payload
(TDP5) from the Alphasat satellite. Although a specific set
of measurements should not be directly used for designing
any HTS system, the exercise offers great insights into the
SGD technique.

The measurements are the results of a joint propagation
campaign at pan-European level, which was coordinated across
five countries [10]. Although measured data have been used
in the past to assess aspects of SGD [6], in this article, six
different sites are considered a number which in terms of GWs
of a feeder network would already match a medium-sized HTS
system of about 100 Gb/s. Section II presents the experimental
sites of the measurements and the climatic patterns which were
found to be closely related to the SGD technique. Section III
describes SGD key parameters and Section IV reports on the
results of the emulations for different system requirements and
system scenarios including among others the impact of switch-
delay, impact of payload connectivity restrictions, as well as
the impact of carrier frequency (downlink frequency versus
uplink frequency). The conclusions are drawn in Section V.

II. EXPERIMENTAL AND PROPAGATION
CHARACTERISTICS

The data used in the SGD emulations are collected using
the Q-band experimental configuration of the ASALACA
experiment [10] at the following locations: [U.K.: (Chilbolton,
Chilton), Spain: (Vigo), Portugal: (Aveiro) and Greece:
(Athens, Lavrion)] with corresponding elevation angles [U.K.: (26.40°, 26.07°), Spain: (30.60°), Portugal: (31.80°), and
Greece: (45.97°, 46.26°)]. The observation period of the used
measurements is of 12 months: from January 1, 2018 to
December 31, 2018 and the concurrent valid data availability
for all locations is greater than 90% which guarantees the
reliability of the results. Data were concurrently unavail-
able between 6th and 12th of July because of issues with
Aldo Paraboni payload. The distances between Chilbolton–
Chilton, Vigo–Aveiro, and Athens–Lavrion are 47.9, 173.3,
and 36.31 km, respectively. For the other pairs of the experi-
mental sites, the distances are longer than 1000 km.

The terminals of the measurement network are time
synchronized (using GPS) to ensure the applicability of
measurements for temporal and spatial correlation studies
and measure excess attenuation, i.e., the variation of signal
that can be ascribed mainly to rain and cloud attenuation.
This means that because of the absence of radiometric
measurements, the attenuation time series are derived based
on the identification of “clear air” signal periods (i.e., when
there is no major rain or cloud attenuation), which are used to
extract the slowly varying signal component presumably due
to system effects (the so-called 0 dB reference level or “clear
air” signal template). The excess attenuation, which should
represent the rain and cloud attenuation and signal scintillation
during the event, is then derived as the difference between the
estimated 0 dB reference level and the measured signal level.
Regarding the consequence of the gaseous attenuation on the
system, measurements and studies [11] have shown that the
gaseous attenuation has a small degree of variation around its
mean value compared with rain or cloud attenuation fluctuation
and can be considered as fixed. This value can be obtained
from the ITU-R Rec. 676 [12]. Furthermore, the initially
derived attenuation time series were further processed to make
sure they are harmonized to a common time resolution of 1 s.

This achievable coverage area is representative of the
fringe of a typical satellite covering Europe and encompass-
passing several climatic zones (from north Atlantic to the
southern Mediterranean areas). The experimental sites can
be clustered into three distinct climatic regions in terms of
radio propagation: Southern U.K. (Chilton, Chilbolton);
Spain–Portugal (Vigo, Aveiro); and Greece (Athens, Lavrion).
Hence, the experimental sites encompass both macro- and
mid-scale diversity effects. This allows us to extrapolate also
some conclusions for a feeder network within even a higher
number of GWs across Europe, with a denser distribution.
Fig. 1 shows the annual attenuation statistics measured at the
six locations at 39.4 GHz (for brevity, we will be rounding
the beacon carrier frequency to 40 GHz), whereas Table I
lists the measured fading time and total number of fades for
fades exceeding 5 and 10 dB. The choice of these fading
margins will be motivated in the following sections. Fig. 2
shows the distribution of fading time versus the fade duration
at 10 dB. The distinct propagation characteristics of the three
regions are clearly visible. In general, it seems that the sites
in Spain, Portugal, and Greece experience severe fades than
in Southern U.K. Regarding the number of fades, the largest
numbers observed in Vigo and the lowest in Greece. This is
reflected in the mean fade duration values listed in Table I (i.e.,
fading time over total number of fades at a given threshold);
the longest mean fade duration values observed in Greece and
the shortest in U.K.
TABLE I
MEASURED FADING TIME OF 40 GHz EXCESS ATTENUATION AT CHILTON, CHILBOLTON; VIGO, AVEIRO; ATHENS, LAVRION

| Location          | dB | Fading Time (%) |Fade Time (minutes) | No. of Fades | Mean Duration (sec) |
|-------------------|----|-----------------|--------------------|--------------|---------------------|
| Chilton           | 5  | 0.695           | 3652.6             | 5726         | 36.73               |
|                   | 10 | 0.203           | 1069.0             | 1802         | 34.16               |
| Chilbolton        | 5  | 0.985           | 5178.1             | 8648         | 34.77               |
|                   | 10 | 0.234           | 1229.0             | 1689         | 42.26               |
| Vigo              | 5  | 1.955           | 10276.0            | 12264        | 48.60               |
|                   | 10 | 0.515           | 2707.3             | 3393         | 46.28               |
| Aveiro            | 5  | 1.199           | 6301.8             | 7249         | 50.57               |
|                   | 10 | 0.367           | 1930.5             | 2122         | 52.92               |
| Athens            | 5  | 0.810           | 4259.4             | 4241         | 58.14               |
|                   | 10 | 0.278           | 1459.6             | 1249         | 67.66               |
| Lavrion           | 5  | 0.446           | 2346.0             | 2155         | 63.29               |
|                   | 10 | 0.129           | 677.0              | 453          | 86.89               |

Fig. 2. Measured Fading time due to fades exceeding 10 dB with duration longer than X-axis value for all the locations. The fading time is normalized to the outage at 10 dB.

Regarding the spatial characteristics of the radio channels, Table II lists the joint statistics that is the time the attenuation at both sites (GWs in the following assuming SGD) exceeds 5 and 10 dB. For the application of the SGD technique, it is interesting to note that the time an attenuation threshold is exceeded on both GW links is not strictly related to the distance between the two GWs, but rather to meteorological characteristics of the GW locations (e.g., weather front). That is, shorter distances do not always imply higher exceedance time. As expected, for the pairs with GWs in the same climatic region, the joint exceedance time is much higher than the other GW pairs, i.e., there is a stronger correlation of the propagation impairments. This is clearly illustrated in Fig. 3 which depicts annual joint attenuation statistics for six pairs of GWs—three pairs with GWs from the same climatic region. For example, the joint attenuation statistics between Vigo–Aveiro is comparable with joint statistics between Chilton–Chilbolton and Athens–Lavrion regardless of the long separation of 173.3 km between Vigo and Aveiro.

III. SGD METRICS AND PARAMETERS

The primary metrics for the SGD assessment is the achievable feeder network availability and number of required switches over a period of interest T (e.g., a year, a day). At any instant, the feeder network is available if N (or more) GWs out of the N + P GWs are not in outage. Over a period of interest T, the feeder network availability is defined as the percentage of T the system is available.

Assuming that the vast majority of HTS are transparent and employ adaptive coding and modulation (ACM), it is undesired that fading over the (oversized) feeder link triggers a change to a lower (more robust) modulation and coding option because that would penalize the throughput of a large user population.
Strictly speaking, ACM should be only triggered when particular user terminals undergo fading. However, in practice, there may be satellite operators who wish to trade throughput for Chilton, Athens, and Vigo on May 24, 2018. A GW location is active when the time series is red, it is in standby when it is blue. The number of switches at Chilton, Athens, and Vigo is six, two, and four, respectively, whereas the network number of switches is $6 = (12/2)$.

The choice of SST in a real system is very much system specific and reflects a number of tradeoffs. As for the existing ground technology for offering such margins, $Q$-/V-band antennas can range from 1.2 up to 13.5 m antennas (simply reusing $K_a$-band reflectors) and V-band HPAs from 20 W up to at least 160 W exist. In addition, power combining of the HPAs can also be considered if necessary, the limit being the antenna power handling capability. All this parameter space results in an offered V-band EIRP ranging from about 65 to 92 dBW. In the rest of this article, two SST values of 5 and 10 dB are selected to somehow reflect a small, low cost GW, and a large, more expensive GW, respectively, based on the rough premise that more than 10 dB of margin renders the GW quite expensive.

IV. SGD ASSESSMENT

The six experimental sites enable the assessment of a 4 + 2 SGD technique. In addition, in order to assess the SGD technique if only one GW within the same cluster can be selected in the event of an outage, the total number of (4 + 2) GWs is split into two subsets, each containing (2 + 1) GWs. This situation may result from connectivity restrictions between GWs and user beams at the satellite payload or between GWs on ground. The assessment is performed for ideal switching (i.e., without considering any switching process delay), as well as for a switching process delay of 2 and 30 s. A common dimensioning has been adopted for each GW and, hence, a common SST which is either 5 or 10 dB. Although this leads to a different single GW availability in each location, it is a practical hypothesis based on the assumption that all GWs will be equipped with the same equipment (antennas, HPAs). In any case, the results can be easily expanded for any choice of frequency and SST per GW.

A. (4 + 0) Without SGD Deployment

In general, in an $N + P$ SGD network, the number $N$ of active GWs is determined by the required HTS system capacity, whereas the deployment of $P$ redundant GWs is to increase the network availability. In this section, we discuss the availability of feeder networks consisting of four active GWs without deploying the SGD technique, i.e., without redundant GWs. This serves as a reference for judging both the technical need and cost effectiveness of deploying the SGD technique. The network availability is assessed for each of the 4 GWs utilizing 5 and 10 dB of PM (as there is no switching involved), respectively.

For the selection of the four GWs out of six GWs, there are 12 combinations provided that each combination has three GWs from different climatic regions. This selection of GWs gives the highest possible values of availabilities bearing in mind the joint exceedance time discussed earlier in Section II. Table III shows the measured network annual availability for each combination. The availability values range from 95.3497% to 96.9567% at 5 dB and from 98.6269% to 99.0769% at 10 dB with average values 96.1692% and 98.8586%, respectively. On average, the networks which include the GWs at Vigo and Aveiro have the worst availability.
In conclusion, regardless of the combination of GWs, the achieved availability cannot reach the demanding availability requirements of feeder links (e.g., 99.99%) and, consequently, the HTS systems cannot meet their service specifications.

B. (4 + 2) Without Switching Process Delay

The network of this section consists of four Active and two Standby stations. As discussed in Section III, the choice of initial combination of Active/Standby GWs makes no difference in the network availability due to fades. Furthermore, the random selection of the Active GW from the available standby GWs ensures the unbiased statistical estimation of the number of switches. Also, the network includes three pairs of GWs with each pair within the same climatic area. Therefore, the results are considered a worst case scenario (see Section II).

The measured SGD performance is listed in Table IV. For SST = 5 dB, the feeder network annual availability is 99.9645% which is achieved via 813 ideal switches (without a switching process delay) on 175 days out of the 365 days of observation. The daily network availability is 100% except for 20 days for which the availability values range from 99.1273% to 99.9965%. For SST = 10 dB, the network availability is 99.9992%, which is achieved via 280 ideal switches on 110 days. All days have daily network availability 100% except for two days with availabilities 99.7442% and 99.9857%. Therefore, thanks to the SGD technique, there is a significant increase from 96.1692% to 99.9645% and from 98.8586% to 99.9992% of the feeder network availability at SST = 5 dB and SST = 10 dB, respectively.

Despite the long distance, 173.3 km, between the two GWs compared with the distances between Chilton–Chilbolton and Athens–Lavrion.

In conclusion, regardless of the combination of GWs, the achieved availability cannot reach the demanding availability requirements of feeder links (e.g., 99.99%) and, consequently, the HTS systems cannot meet their service specifications.

TABLE III

| GW from Region | GW from Region | GW from Region | GW at Region | Network annual availability (%) |
|----------------|----------------|----------------|-------------|-------------------------------|
| Chilton        | Vigo           | Athens         | Chilbolton  | 95.8664 98.7911               |
| Chilton        | Vigo           | Lavrio         | Chilbolton  | 96.2361 98.9402               |
| Chilton        | Aveiro         | Athens         | Chilbolton  | 96.5357 98.9258               |
| Chilton        | Aveiro         | Lavrio         | Chilbolton  | 96.9249 99.0769               |
| Average Availability of Networks including Chilton and Chilbolton GWs | 96.3908 98.9335 |
| Chilton        | Vigo           | Lavrio         | Aveiro      | 95.8920 98.7819               |
| Chilbolton     | Vigo           | Athens         | Aveiro      | 95.3497 98.6269               |
| Chilbolton     | Vigo           | Lavrio         | Aveiro      | 95.7229 98.7815               |
| Chilton        | Vigo           | Athens         | Aveiro      | 95.5146 98.6300               |
| Average Availability of Networks including Vigo and Aveiro GWs | 95.6214 98.7051 |
| Chilton        | Vigo           | Athens         | Lavrio      | 96.2305 98.8675               |
| Chilbolton     | Vigo           | Athens         | Lavrio      | 96.0725 98.8715               |
| Chilbolton     | Aveiro         | Athens         | Lavrio      | 96.9567 99.0112               |
| Chilbolton     | Aveiro         | Athens         | Lavrio      | 96.7224 99.0017               |
| Average Availability of Networks including Athens and Lavrio GWs | 96.4956 98.9378 |
| Average of all 4+0 Networks | 96.1692 98.8586 |

TABLE IV

| Switching process Delay | 0 sec | 2 sec |
|------------------------|-------|-------|
| SST 5 dB               |       |       |
| Network Availability (%) | 99.9645 99.9992 | 99.9591 99.9971 |
| Network Fade Outage (minutes) | 166.23 3.88 | 165.83 3.88 |
| Network Switching Outage (minutes) | N/A  N/A | 25.07 9.63 |
| Network Total Outage (minutes) | 166.23 3.88 | 191.9 13.51 |
| Number of Network Fades | 514 21 | 502 21 |
| Number of days with Outages | 20 2 | 20 2 |
| Network Mean Fade Duration (sec) | 19.4 11.1 | 19.8 11.1 |
| Number of Switches | 813 280 | 782 291 |
| Number of days with Switches | 175 110 | 177 115 |

| Switching process Delay | 30 sec | 5 minutes |
|------------------------|--------|----------|
| SST 5 dB               |       |         |
| Network Availability (%) | 98.8841 99.9687 | 99.2204 99.7075 |
| Network Fade Outage (minutes) | 158.32 3.80 | 99.92 1.18 |
| Network Switching Outage (minutes) | 385 143 | 3555 1370 |
| Network Total Outage (minutes) | 543.32 146.8 | 3654.92 1371.18 |
| Number of Network Fades | 404 19 | 184 12 |
| Number of days with Outages | 20 2 | 17 2 |
| Network Mean Fade Duration (sec) | 23.5 12 | 32.6 5.9 |
| Number of Switches | 770 286 | 711 274 |
| Number of days with Switches | 176 110 | 177 114 |

(a)

(b)
Fig. 5. Daily number of network switches for the $4+2$ network with SST = 5 dB. (a) Number of switches per day. (b) Distribution of the number of days with switches classified according to the number of switches occurred during the day.

**TABLE V**

NUMBER OF SWITCHES OF THE $4+2$ NETWORK

| Location   | Number of Switches |
|------------|--------------------|
|            | SST=5 dB | SST=10 dB |
| Chilton    | 338       | 103       |
| Chilbolton | 358       | 118       |
| Athens     | 203       | 50        |
| Vigo       | 346       | 146       |
| Lavrion    | 126       | 50        |
| Aveiro     | 255       | 93        |
| Total      | 813       | 280       |

Figs. 5(a) and 6(a) show the daily distribution of switches for SST = 5 dB and SST = 10 dB, respectively. The frequency table of the number of switches per day in the network, i.e., the number of days with one switch or number of switches within [2,4), [4,6), …[38,40), is shown in Figs. 5(b) and 6(b). The number of days with more than four switches a day drops steeply with the increasing number of switches per day. This is more apparent as the SST increases.

The number of switches for each GW for the whole observation period is given in Table V. It seems that the number of switches of each GW is related to the climatic area where it is located. As was mentioned in Section II, the lowest numbers of fades were observed in Athens and Lavrion along with the longest on average duration compared with the other locations. This results in the smaller number of switches for the GWs at these two locations.

Fig. 7 shows the measured annual network availability and the required number of switches versus the SST, which ranges from 5 to 14 dB. There is a clear increase of the feeder network availability and decrease of the number of switches, respectively, as the SST increases. However, beyond 10 dB, there is a saturation to almost 100% availability, whereas the number of switches continues to decrease. This is exactly the type of plot that allows a ground network operator to decide how to trade between the cost of the individual GW (expressed by the SST) and the number of GWs.

For a significant fraction of the observation time (a year in this article), when a GW is on standby mode, the attenuation on the feeder link is less than that of the SST. This means that the propagation impairments could be compensated by the GW’s FM and the GW could be operational. This time spans from 19.90% to 39.77% and 16.03% to 44.44% at SST = 5 dB and SST = 10 dB, respectively.

C. ($2+1$) Without Switching Process Delay

Next, the $4+2$ feeder network, i.e., six GWs, is split into two subnetworks each containing ($2+1$) GWs.
The (2 + 1) feeder networks are structured considering the propagation dependence of the locations of the GWs and are classified into two categories: the category 1 where all the three GW pairs of the network are from different climatic regions and the category 2 where the network includes a GW pair from the same climatic area. The latter configuration may be representation of a scenario where there is a large number of GWs that can no longer be distributed in remote enough location to claim perfect weather decorrelation. However, not only the clustering of the total population of GWs into subnetworks but also the pairing of the GWs within each subnetwork may be dictated by the satellite payload connectivity between feeder beams and user beams. For example, the sites in the same climatic region may be too close to each other to be simultaneously active and still allow an adequate uplink carrier-to-co-channel interference ratio.

For the given 4 + 2 network, there are four pairs of subnetworks with each containing (2 + 1) GWs from category 1 and six pairs of subnetworks containing (2 + 1) GWs from category 2. The performance evaluation of each pair of subnetworks is given in terms of the following.

1) The availability and number of switches for the individual (2 + 1) networks of the pair.

2) The pair availability and the sum of the number of switches of the two (2 + 1) networks. The pair availability is defined as the average of the two (2 + 1) subnetworks availabilities.

For all the subnetworks pairs, the availability is less than the availability of the (4 + 2) network. A pair of (2 + 1) subnetworks has, in total, equal number of active and standby GWs, i.e., 2 and 1 + 1, respectively. However, within each subnetwork, there is the option of switching only to one GW compared with the option of switching to two GWs for the (4 + 2) network. This results in a better availability for the latter.

The listed values in Tables VI and VII indicate that the four pairs of networks from category 1 are statistically similar and perform much better than the subnetworks from category 2. In particular, the availability of subnetworks from category 1 is greater than 99.9% and 99.99% for SST = 5 dB and SST = 10 dB, respectively. On the other hand, the subnetworks from category 2 cannot reach availabilities greater than 99.87% and 99.986% for SST = 5 dB and SST = 10 dB, respectively. This is expected based on the earlier rationale about joint exceedance statistics for GW pairs.

Regarding the number of switches of each GW for the subnetworks from category 1, similar conclusions are drawn as for the (4 + 2) network (see Section IV-B). However, for the subnetworks from category 2, the smaller number of GW switches occurs always at the GW which is located in different climatic region with respect to the other two GWs.

D. Impact of Switching Process Delay

Let w be the time interval required for a switching from one GW to another to be completed. The following approach is adopted in the evaluations of this section: when a switching is initiated at the time instant t, the whole network is frozen during the switching process delay window w. The network is operational and, consequently, a decision for a following switch can be made, from the time instant t + w onward. The switching delay introduces an additional network outage.

TABLE VI

| Pairs of 2+1 sub-networks | SST=5dB | SST=10dB |
|---------------------------|---------|----------|
| GW Locations              | Availability (%) | Number of Switches | Availability (%) | Number of Switches |
| 1                         |          |          |                |                |
| Chilton-Vigo-Athens       | 99.9439  | 420      | 99.9952        | 149             |
| Chilton-Aveiro-Laverton   | 99.9660  | 351      | 99.9991        | 114             |
| Pair availability         | 99.9550  | 771      | 99.9972        | 263             |
| 2                         |          |          |                |                |
| Chilton-Vigo-Laverton     | 99.9493  | 362      | 99.9951        | 145             |
| Chilton-Aveiro-Athens     | 99.9595  | 406      | 99.9971        | 127             |
| Pair availability         | 99.9544  | 768      | 99.9961        | 272             |
| 3                         |          |          |                |                |
| Chilton-Aveiro-Athens     | 99.9682  | 337      | 99.9964        | 122             |
| Chilton-Aveiro-Laverton   | 99.9199  | 419      | 99.9910        | 162             |
| Pair availability         | 99.9441  | 756      | 99.9937        | 284             |
| 4                         |          |          |                |                |
| Chilton-Aveiro-Laverton   | 99.9748  | 273      | 99.9979        | 108             |
| Chilton-Vigo-Athens       | 99.9144  | 474      | 99.9911        | 162             |
| Pair availability         | 99.9446  | 747      | 99.9945        | 270             |

Fig. 7. (a) Network availability and (b) number of required switches versus the SST for the (4 + 2) network.
TABLE VII
AVAILABILITY AND NUMBER OF SWITCHES FOR (2 + 1) NETWORKS OF CATEGORY 2 OPERATING WITHOUT SWITCHING DELAY

| Pairs of 2+1 sub-networks | SST=5dB | SST=10dB |
|---------------------------|---------|----------|
| GW Locations              | Availability (%) | Number of Switches | Availability (%) | Number of Switches |
| Chiloe-Chilboton-Vigo     | 99.6769 | 975      | 99.9606 | 326         |
| Athens-Laviron-Aveiro     | 99.8471 | 292      | 99.9787 | 131         |
| Pan performance           | 99.762  | 1268     | 99.9695 | 457         |
| Chiloe-Chilboton-Vigo     | 99.7237 | 917      | 99.9693 | 275         |
| Athens-Laviron-Vigo       | 99.8617 | 278      | 99.9797 | 128         |
| Pan performance           | 99.7927 | 1195     | 99.9745 | 403         |
| Chiloe-Chilboton-Athens   | 99.7694 | 742      | 99.9716 | 237         |
| Vigo-Aveiro-Laviron       | 99.8374 | 858      | 99.9853 | 401         |
| Pan performance           | 99.8009 | 1600     | 99.9785 | 638         |
| Chiloe-Chilboton-Athens   | 99.7687 | 685      | 99.9731 | 236         |
| Vigo-Aveiro-Chilboton     | 99.8383 | 884      | 99.9849 | 406         |
| Pan performance           | 99.8035 | 1569     | 99.9797 | 642         |
| Vigo-Aveiro-Chilboton     | 99.8069 | 1056     | 99.9814 | 466         |
| Athens-Laviron-Chilboton  | 99.8648 | 301      | 99.9814 | 117         |
| Pan performance           | 99.8358 | 1357     | 99.9848 | 377         |
| Vigo-Aveiro-Chilboton     | 99.7755 | 1145     | 99.9781 | 467         |
| Athens-Laviron-Chilboton  | 99.8678 | 309      | 99.9813 | 117         |
| Pan performance           | 99.8216 | 1454     | 99.9797 | 584         |

to fade outage, the switching outage $O_{out \text{switch}}$, which reduces further the network availability and is given by the following equation:

$$O_{out \text{switch}} = N_{\text{switches}} \cdot w$$  (1)

where $N_{\text{switches}}$ is the number of required switches.

The SGD performance of the (4 + 2) network with switching process delay $w$ equal to 2 s, 30 s, and 5 min, respectively, for all the GWs is shown in Table IV for SST = 5 dB and SST = 10 dB. The results can be directly compared with the SGD performance of ideal switching. There are several contributors to the switching process delay such as: configuration and propagation delay of the ground network interconnection, configuration and propagation delay of the satellite payload (e.g., in case a telecommand needs to be send), as well as the level of automation and sophistication of switching control center (SCC). Therefore, 2 s, 30 s, and 5 min represent a very fast, medium, and slow reaction of the SCC, respectively. The differences in the values of network fade outage, number of fades, and number of switches for networks operating without and with switching process delay are rather random and due to the network freeze within the time window $w$. The switching characteristics, e.g., number of switches of each GW, daily distribution of switches, are similar to the switching characteristics without a processing delay discussed in Section IV-B. Similar conclusions are drawn for the impact of switching process delay on the (2 + 1) networks.

E. Impact of Frequency

To portray the SGD technique on the forward link (uplink) and in general to evaluate the impact of the GW operational frequency on the SGD technique, the 40 GHz measured time series of attenuation are scaled-up to their corresponding uplink frequency of 50 GHz. This is of high interest because, typically, a feeder link carries much more traffic in its uplink (forward link) than in the downlink (return link). Therefore, protocol and strategies for SGD should focus on the feeder uplink. The frequency scaling is performed by using the algorithm described in ITU-R P.618 [9, Annex 1, Sec. 2.2.1.3.1].

At 50 GHz, the (4 + 2) network availability over the one year observation period for ideal switching is 99.9932%, 99.9988%, and 99.9997% for SST values equal to 10, 11, and 12 dB, respectively. The corresponding required number of switches is 454, 362, and 292. A comparison of these values with the network availability and number of switches, 99.9992% and 280, for the same (4 + 2) network operating at 40 GHz with SST = 10 dB shows that the performance of the two (4 + 2) networks is similar. This can be explained by the facts that are as follows.

1) The performance of SGD technique depends on the joint exceedance time of a given attenuation threshold, i.e., SST. As the frequency increases, the GW links are more prone to propagation impairments. However, the strong dependence of the joint exceedance time on the spatial distribution of atmospheric phenomena significantly reduces the propagation impairments particularly if the GWs are located in different climatic regions (see Section II). [13]

2) In addition, the increase of (ground and space) antenna gain with the increasing frequency might allow higher levels of SST with the same antenna which reduces further the joint exceedance time. For example, the performance of the feeder network operating at 40 GHz with SST = 10 dB is comparable with the one operating at 50 GHz with SST = 12 dB.

Note, however, that in a practical SGD system, when a switching takes places, this is done for both the forward and the return links.

V. CONCLUSION

The performance of four active +2 redundant SGD technique is assessed based on one year measurements of the Q-band (40 GHz) propagation signal transmitted by the Aldo Paraboni payload (TDPS) of the Alphasat satellite in six European locations. This is a unique type of emulations given the wealth and quality of data from such a large number of locations.

It is found that SGD significantly improves the network availability but at the expense of the additional GWs and required number of switches. There is a steep increase of
the feeder availability and decrease of number of switches, respectively, as the SST increases. However, beyond 10 dB, there is a saturation effect evident to almost 100% availability, whereas the number of switches continues to decrease. A ground segment network design needs to take into account this information to balance the network cost between individual GW and network sizing.

For a significant fraction of the observation time, spanning on average from 16% to 45%, each GW is on standby mode with the attenuation on the feeder link less than SST. This means that during this time, the propagation impairments could be compensated by the GW’s FM and the GW could be operational. This fact maybe lends itself to considering reusing GWs among multiple satellite networks.

When the (4 + 2) network is split into two (2 + 1) networks, the subnetworks pair has always lesser availability than the (4 + 2) network.

As the switching from one GW to another cannot be ideal, i.e., without switching process delay, the network availability is reduced further by the number of switches times the switching process delay. The number of switches is a critical parameter for the implementation of the SGD, not only to reduce the switching outage, but also due to practical constraints of the system (e.g., maximum allowed number of switches a day, time spacing between consecutive switches). However, the required number of switches can be reduced by an optimum switching management scheme, e.g., short-term prediction of the radio channel, long-term planning of switching, selection of standby GW, and selection of SST. Therefore, research activities are proposed in this particular topic to secure the cost and technically effective implementation of the SGD technique.

Finally, for the impact of operation frequency on the SGD performance, it seems that system dimensioning for the application of SGD technique to higher frequencies is not proportional to severity of propagation impairments at these frequencies.

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