Performance Analysis and Optimization of Site Diversity Techniques for EHF Satellite Links

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Abstract— In this work authors investigate the use of Propagation Impairments Mitigation Techniques (PIMTs) based on site-diversity for Extremely High Frequencies (EHF) satellite links. This work has been performed in the frame of the joint European/Italian satellite scientific payload named Alphasat TDP#5; this scientific payload will be used to perform experimental analysis on the use of Q/V band frequencies to support satellite telecommunication services. Because of the highly variable attenuation experienced at these frequencies, PIMTs have to be adopted. Site diversity techniques could provide great benefit to EHF satellite communications, dramatically increasing the percentage of operational time of the links. As a matter of fact, through these techniques a large number of services could be supported by EHF satellite links. Different site diversity configurations are analyzed and optimized, through a software simulation tool, in order to obtain the best performance for different service scenarios.  

The large bandwidth availability in Q/V and W-bands allows conceiving and proposing many advanced and innovative services that need high-volume data transfers without tight interactivity constraints for future scenarios. Another aspect that makes EHF (in particular “beyond Ka-band” frequencies) especially attractive is the integration of components (e.g. small antennas).

One of the most important issues for the exploitation of such high frequencies is the knowledge of the satellite propagation channel; in fact, some important limitations could arise from the high propagation impairments. In this frame, techniques able to improve system availability and throughput have to be developed. These techniques are called propagation impairments mitigation techniques (PIMT).

In Q/V-band frequencies important propagation experiments have been performed (i.e. ITALSAT F1 [1]) together with the development of technologies; therefore Q/V-band can be considered as a current industrial research topic for the short term implementation of satellite operative systems.

Furthermore the European Space Agency (ESA) is developing a satellite GEO platform named Alphabus [2], and will use this platform to offer Operators, Service Providers and Industrial Groups the possibility to fly their payloads on board of the proto-flight model.

ESA has selected Inmarsat Global Ltd geomobile mission for the first flight opportunity in 2012.

ESA is also funding the development of four Technology Demonstration Payloads (TDPs) to be launched on the Alphasat. Among these payloads, TDP#5, named “Q/V band payload”, will be devoted to the experimentation of Q/V band satellite propagation and communication. The main goals of the Q/V Band TDP#5 mission are:

• to establish the effectiveness of Adaptive Coding and Modulation (ACM) techniques as defined in the DVB-S2 standard at Q/V bands;
• to test and establish the effectiveness of other PIMT, complementary to ACM, like:
  o site diversity;
  o up-link power control;
• to improve the knowledge of propagation impairments at Q/V band, which is a fundamental step for the design of satellite communication systems adopting PIMTs. In particular, a better characterization of 2nd-order statistics is currently required to better exploit PIMTs;

1 978-1-4244-7351-9/11/$26.00 ©2011 IEEE.
2 IEEEAC paper #1062, Version FINAL, Updated Jan. 10, 2011
• to test the technologies required for implementing a new communication payload in Q/V band, verifying in-flight performance of innovative hardware.

In this work, authors investigate the use of a PIMT based on site-diversity for EHF satellite links considering the previously introduced Alphasat TDP#5 Mission.

In Section 2 a brief introduction on propagation impairments in Q/V-band is reported; in Section 3 the main characteristics of PIMT are presented. Section 4 is devoted to the description of simulation scenario. In Section 5 implementation of site diversity is analyzed and optimized while in Section 6 simulation results are reported and discussed. Finally in Section 7 the conclusions are drawn.

2. PROPAGATION IMPAIRMENTS IN Q/V BAND

The higher the frequency, the stronger the impact of the atmosphere on the radiowave propagation. In particular, the impairments due to the presence of the atmosphere cause a time variant signal attenuation (referred to as “additive attenuation”), which has to be added to the free space loss and carefully taken into account in the system design. Generally a “worst case” approach is considered to introduce a large system margin. The margin is related to the time percentage of system outage that is acceptable for service provision.

The additional attenuation on the Earth-Satellite path is the sum of different contributions as follows:

• absorption of atmospheric gases (oxygen and water vapour);
• absorption, scattering and depolarization due to rain and other precipitations;
• attenuation due to clouds;
• fast fading, scintillation and others related to variations of refraction index.

Each of these contributions has its own characteristics as a function of different parameters such as frequency, geographic location and elevation angle.

For analysis purpose, in this paper three main prediction algorithms, developed by ITU, have been used in order to evaluate the total additional attenuation: ITU-R P676 (“Attenuation by atmospheric gases”), P840 (“Attenuation due to clouds and fog”) and P618 (“Propagation data and prediction methods required for the design of Earth-space telecommunication systems”) [3][4][5].

In Figure 1 the estimated total additional attenuation (y-axis, dB) not exceeded for a time percentage (x-axis, %) is shown for a ground terminal located in the area of Rome (Italy), a central frequency of 38 GHz and an elevation of 40°. In this situation PIMTs have to be introduced in order to dynamically adapt the link characteristics to channel propagation conditions. In this frame, in order to design effective PIMTs, adaptive systems have to be designed with the aim to react in real-time to the different changes in propagation conditions. These techniques will be introduced and discussed in Section 3.

ITU models are useful to obtain first order statistics for additional attenuation but, as a matter of fact, part of the propagation losses are time-variant. In particular precipitations (mainly rain) and scintillations can be considered the two main contributions to the time-variant part of additional attenuation, while absorption due to atmospheric gases can be considered fixed as a first approximation.

The procedures to obtain information regarding second order statistics of rain attenuation and scintillations has to be identified in order to simulate channel variations and optimize PIMTs.

In literature there are different methodologies used for rain and scintillations attenuation time-series synthesis for EHF satellite links [6]; the most important are: spectral model, synthetic storm techniques, ITALSAT data based model, two-sample model, second-order Markov chain and N-states Markov chain models. These models can be used for links operating in Ka and Q/V bands, being obtained for the empirical measurements performed during scientific satellite missions (i.e. ITALSAT F1).

In this work the ITALSAT data based model, developed by Riva et al. [7], will be used for simulation purposes; the model main characteristics will be briefly introduced in Section 4.

3. EHF FADE MITIGATION TECHNIQUES

In order to counteract atmospheric attenuation, high system static link margins could be used to minimize the duration
of the service outage. Fixing high static link margins is in contrast with the technology limitations, both on space and ground segments, and with the efficiency of the system; in fact, due to the large additional attenuation variations (mainly due to the presence of rain), fixing static link margins brings to a tremendous waste of resource of the system. In this frame PIMTs have to be used which allow the design of systems with rather small static margin, while overcoming (both in real-time or in post-processing) cloud attenuation, a fraction of rain attenuation, scintillation, and depolarization events.

These techniques aim to compensate for the fade by using different types of diversity techniques in different domains. In the space domain, we can send the information on a different route with respect to the one that is suffering an high fade. In the time or frequency domain, we can transmit at a different time slot or in a different frequency band, respectively.

These techniques are designed to statistically uncorrelate the probability for each signal transmitted on a different time slot, frequency band or location.

Diversity techniques are usually adaptive with the channel conditions. Adaptive techniques change some parameters of the system set-up to compensate for the current fade. For instance, in adaptive up-link power control, the ground transmit power is increased to compensate for the effects of a fade.

Adaptive Coding and Modulation technique aims at compensating the fade by changing coding and/or modulation scheme with respect to the propagation channel conditions.

Layer 2 techniques, such as Automatic Repeat reQuest (ARQ), do not mitigate the fade event but rely on the retransmission of the data packets when the conditions of channel are less error prone.

4. Simulation Scenario

The scenario used for the simulations is based on a geostationary satellite link. The satellite orbit is GEO 25° East, the two receiving stations, connected by a terrestrial link for signaling Exchange, are located in the area of Rome (Italy); o.s.l. altitude of 20 m, 42° latitude N, 12° longitude E, elevation of 40°, circular polarization. The up and down central frequencies are 48 and 38 GHz respectively.

The following service has been considered in order to evaluate site diversity performance: High Definition TV broadcasting, supporting 160 HD channels, FDM, having 12.256 adaptive source coding (3.5-7.5 Mbps) and using both data rate reduction and ACM (following DVB-S2 standard). The target BER is $10^{-5}$.

In this frame it is not possible to guarantee service availability higher than 99% of the time without the use of site diversity technique.

As previously introduced, in order to perform the simulations, the variation of rain attenuation has to be modeled. The model developed by Riva et al. [7] has been selected. This model is based on the large attenuation database collected through the ITALSAT F1 mission. This model can generate different classes of rain attenuation time-series; the time-series class is a function of peak attenuation. For simulation purposes 134 time-series have been generated, on the basis of geographical location of ground stations (Rome, Italy) and considering an antenna having a diameter of 1.5 m and an efficiency of 0.65; Table 1 summarizes the characteristics of generated rain attenuation time-series.

<table>
<thead>
<tr>
<th>Class</th>
<th>Attenuation Range (dB)</th>
<th>Number of generated time series</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 0.3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.3 - 0.6</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.6 - 1.0</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>1.0 - 1.6</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>1.6 - 2.8</td>
<td>65</td>
</tr>
<tr>
<td>6</td>
<td>2.8 - 4.7</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>4.7 - 7.9</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>7.9 - 13.3</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>13.3 - 22.5</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>22.5 - 38</td>
<td>10</td>
</tr>
</tbody>
</table>

In order to use the different series for site diversity simulation purposes, data on the time-concurrent presence of two different series on the two sites are needed. These data are not available from the time-series simulator therefore “case studies” have been defined; through these case studies it is possible to simulate time-concurrent weather conditions at ground stations sites.

In order to define the case studies three propagation conditions have been identified:

- **Clear sky** - this is the propagation in the absence of rain; the attenuation is mainly due to gas, clouds and fog and the sum of these contributions is lower than 2 dB.

- **Stratified rain** - this is the most external part of a precipitation event spatial structure; rain intensity is variable and is in inverse proportion to its spatial size (typically from 5 to 50 km). The attenuation is mainly
due to rain and to wet scintillation.

- Convective rain - this is the inner part of a heavy precipitation event spatial structure; its spatial size is very low (typically few kilometers) as well as its time duration (typically less than one hour). Clearly the attenuation is mainly due to rain and it can be very high (tenth of dB).

Case studies have been created coupling two of the previously defined propagation conditions (one for each site) and identifying two of the generated attenuation time-series that can be classified into the previous definitions. The first case study is “convective-rain/convective-rain”. Various combination of class 8, 9 and 10 attenuation time-series have been used for this test case. As previously described there is a high mean attenuation difference between series of classes 8, 9 and series of class 10; therefore the coupled time-series have been selected in order to have similar mean attenuation.

The second case study is “convective-rain/clear-sky”. For the area of Rome this is a typical summer situation and its probability of occurrence grows as the spatial separation between ground sites grows. Time-series of classes 8,9 and 10 have been used to model convective rain while time-series of classes 3 and 4 have been used to model clear sky conditions.

The third case study is “convective-rain/stratified-rain”. This case represents the typical situation of a rain cell passing above the two sites, therefore its probability of occurrence is very high. Time-series of class 10 have been used to model convective rain while time-series of classes 8 and 9 have been used to model stratified rain. The classes used are the same considered for the first test case but in this context the two selected series does not have similar mean attenuation.

5. **Site Diversity Management**

Site diversity management is performed by a network node device, referred as Control Unit (CU), based on satellite beacon measurements at each site. The CU manages a control loop based on three essential functions:

- real-time fade detection, through the simultaneous monitoring of attenuation evolution on both sites using 1 Hz sampled beacon data. Real time data are received from each Earth Station (ES).
- short-term prediction of total attenuation, based on dynamics previously observed.
- decision on the activation of diversity technique, selecting each sample time the receiving ES for useful data (i.e. signal for further processing “source”). Data stream transmission from that ES, if remote, is enabled.

The control loop reference model is reported in [8], whose logic diagram is shown Figure 2.

Delay issues deriving from different physical path lengths are supposed to be solved by equalization, so CU operates on time aligned signals (no switchover data loss has been considered). Since prediction of propagation impairment is performed at the same frequency of monitored beacon, no frequency scaling is needed. Rain fade is predicted, using the last two filtered samples, through four different possible algorithms:

- **Persistence**: the attenuation (two stored samples mean) is assumed to be constant during prediction interval (time instant at which prediction is referred to);
- **Slope invariance**: attenuation slope (calculated from two stored samples) variation is assumed to be invariant during prediction time;
- **ITU-R based model**: implemented following ITU-R Recommendation P.1623-1, [9], on fade slope statistics;
- **Van de Kamp 'two samples' model**, based on theory developed by M. Van de Kamp [10].

As scintillation decorrelates too fast (unpredictable), its envelope is estimated by moving standard deviation calculated on last 21 filtered samples, then the fluctuation amplitude not exceeded for a fixed percentage (standard Gaussian model, ONERA tool sets $\alpha$ to 1.96, 95th percentile) is calculated and added to predicted rain attenuation.

The selection of receiving station is based on these results (total predicted attenuation), computed for each site signal. Decision on path selection can be realized through three different algorithms based on different diversity management logics:

- **Master-slave**: a main station working as master is selected until the predicted attenuation is lower than the fixed threshold (propagation margin, PM) on that site. If this is not verified, and the attenuation on slave station channel is estimated lower than its own threshold, a switch is performed and the slave station becomes the reference terminal for useful data path. Otherwise switching is avoided, since a link outage occurs anyway. When the slave station is currently selected, the
system tries to restore the primary link (the one with master station) as soon as the predicted attenuation returns under the set threshold.

- **Dual active**: Earth station selection is solved comparing the two predicted attenuations, identifying the path which is less affected by the impairments. In order to manage configurations with ES having different PM, the predicted values of attenuation for the two sites are respectively multiplied for the other station PM before comparison (Modified Dual Active).

- **Combined or Alternate prime**: the currently active station acts exactly as a master station in master-slave algorithm. As a switch is performed due to propagation condition, the selected station behaves as the former one. The role of master station is practically exchanged, the logic figure of slave terminal does not exist.

Furthermore, in order to prevent erroneous decision deriving from errors in detection/prediction functions, the following parameters are introduced in the decision process:

- Detection margin (DM): this value is subtracted to PM, carrying out a more “conservative policy” whose goal is to avoid link outage. In SD this is considered a priority with respect to the drawback of a certain occurrence of “false alarms” and consequent useless switching between stations. It obviously increases switch number and frequency.

- Hysteresis margin (HM): this value is subtracted to PM, preventing from too early station switching when it is coming out from unavailability conditions. It guarantees a proper attenuation stabilization under PM before considering “safe” that site. It decreases switch number and frequency.

- Hysteresis delay (HD): it has the same goal of HM, once attenuation is estimated to be under PM, a fixed time interval is waited before performing station switching. It doesn’t impact on switch number.

In order to search for optimal site selection decision, the prediction algorithm performance have to be carefully evaluated. It is important to underline that performance evaluation is not centered on conventional criterion, such as prediction accuracy RMSE [11], [8], but actually on suitability for site diversity requirements, i.e. the ability of reading in advance attenuation time profile.

Figure 3 shows graphically that, although Van de Kamp predictor is surely the best in fitting actual attenuation (minimum RMSE, ≈ 0.75 dB²), slope invariance seems clearly to better play the outlined role. Despite its high RMSE (≈1.2 dB²), it guarantees the earliest forecast of attenuation trend. This is fundamental for signal fade or enhancement prompt detection, in order to avoid link outages as well as allow restoration when needed. Once slope invariance predictor has been selected, prediction time was optimized by simulations. Best performance are achieved for 10 seconds (trade-off accuracy/advance properties).

Before analyzing the differences among the proposed algorithms, we have to deal with a preliminary correction made in the control loop. First, site diversity simulations gave evidence that a reduction in availability performance (with respect to ideal case), was due to a not suitable fit between predicted and actual total attenuation. This effect has been achieved reducing coefficient $\alpha$ that multiplies moving standard deviation (see Figure 1) for the signal predicted to experience lower rain attenuation. Performance improvements seems to saturate for $\alpha$=0.65. Furthermore this new configuration behaves perfectly in master-slave and combined logic, assisting effectively site diversity management in critical situations, so increasing overall link availability.

This empirical result can be explained on theoretical bases. In fact, even if beacon frequency is 38 GHz, the employed low pass filter cut off frequency is equal to 0.025 Hz, optimal value for filtering out scintillation at 19.77 GHz [12]. As spectral properties of rain attenuation and scintillation depends on frequency too, filter operation here performed would have required a proper scaling of cut off frequency for optimal frequency domain phenomena separation (around 0.05 Hz) [13], [14]. So an increased statistical correlation between artificial defined phenomena deriving from inaccuracy in their actual separation can be noticed. More precisely, the slow varying component will include a not negligible part of information on the so identified fast fluctuation (a lot of power due to rain erroneously associated to scintillation). So it seems reasonable to increase weigh on predicted rain attenuation.

The proposed modified control loop works properly. Remaining gap with ideal case is due to occurrence of very different scintillation power associated to the same attenuation level. Nevertheless this event can be neglected, as dependence of scintillation variance on rain attenuation makes its occurrence probability very low.

In the following, the main features of decision algorithms are outlined. Dual active fully takes advantage of having two different signals to select. It’s conceived to minimize attenuation suffered by the overall link, ensuring for further processing the best SNR achievable. So it aims at maximizing link availability (outage more difficulty occurs on best propagation channel with respect to a single path) and user throughput.
Combined algorithms allow to stabilize communication path, holding current configuration until possible. It offers solid SD management, relaxes system requirements in term of switchover frequency, minimizes terrestrial signaling traffic.

Master-slave supposes to have whatever reason to prefer an ES (quite common issue). The other one is fully activated only when primary channel is experiencing severe (with respect to PM) signal degradation. This logic presents critical switching decision (always near ES PMs), so needs HM and DM to achieve reasonable performance and it’s very sensitive to their set. HM is always set equal to DM (otherwise switch number hardly increases) but is zero whenever slave attenuation is predicted to be higher than master one (otherwise HM becomes a switch harmful impairment). HD was also tested, but it showed lower performance than HM for link availability, and did not compensate critical switch dynamics induced by DM. Adequate HM and DM impact on link performance, can be resumed in term of mean gain: + 1.03% availability on event duration, + 1.64% relative user throughput, only + 4.9 switch/h.
6. Simulation Results

Site diversity performance relationship with site separation was carried out. This was achieved considering difference in simultaneous attenuation time series mean and standard deviation and, when they result comparable in such terms, studying cross correlation coefficient influence. Furthermore, site diversity impact dependence on PM is estimated and a solution with a second receiving station with lower PM (2.5 dB) is evaluated (very likely because of terminal cost).

HM and DM for margin are empirically optimized for each case study. Too low or high HM and DM lead in fact to performance degradation.

“Convective rain / convective rain” case study
The large variety characterizing the highest three classes of attenuation time-series provides a consistent standard deviation in the following data. Relevant mean availability (about 21% on event duration, 1006 seconds) and relative user throughput (around 16%) gain is noticed, even if mean diversity gain is rather low (0.9 dB). This case study, extremely useful for testing algorithm and underlining their differences, is in fact the less significant for diversity concept (i.e. to take advantage of two different propagation conditions). Simultaneous occurrence of convective rain at both sites is a situation that a proper site separation should avoid as far as possible.

Simulation results are provided in Table 2. HM and DM are set to 1 dB.

| Table 2: Convective rain/convective rain case study – algorithms performance comparison. |
|---------------------------------------------------------------|----------------|-----------------|-----------------|
| Master-slave | Availability (% on event duration) | 56.77 | 41.38 | 25.12 /h |
| Dual Active | | 56.85 | 42.04 | 24.5 /h |
| Combined | | 56.81 | 40.47 | 3.12 /h |
| No site diversity | | 35.53 | 25.19 | - |

Experimental relationship between availability gain and cross correlation coefficient seems to follow an exponential law (aligned to exponential traditionally estimated dependence between diversity benefits and distance separation). Linear fit shows angular coefficient -0.194 (Fig.5). It was -0.035 in stratified rain /stratified rain case study and -0.016 in clear sky/clear sky case study.

Site diversity performance, as a function of variable PM is reported in Table 3.

<p>| Table 3: Convective rain vs. convective rain - site diversity vs. propagation margin |
|---------------------------------------------------------------|----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Prop. marg.</th>
<th>Without site diversity (% avail.)</th>
<th>With site diversity (% avail.)</th>
<th>Absolute gain (sec.)</th>
<th>Divers. Gain (dB)</th>
<th>Avail. gain vs. cross corr. Coeff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.669 dB</td>
<td>21.72 (9.38)</td>
<td>31.1</td>
<td>445.75</td>
<td>1.09</td>
<td>-0.08</td>
</tr>
<tr>
<td>4.9 dB</td>
<td>35.53 (21.32)</td>
<td>56.83</td>
<td>1006.7</td>
<td>0.9</td>
<td>-0.194</td>
</tr>
<tr>
<td>6 dB</td>
<td>44.66 (20.55)</td>
<td>65.19</td>
<td>915.06</td>
<td>1.6</td>
<td>-0.15</td>
</tr>
</tbody>
</table>

Availability gain is at its maximum when PM is a little smaller (ratio around 0.8) than the mean attenuation. Diversity gain is low till this PM value, than becomes to increase, at first slowly, then exponentially. It’s better to increase HM and DM values with PM (0.5 dB for 2.669 dB, still 1 dB for 6 dB).

Simulation result achieved considering a smaller second station (i.e. a station having lover G/T) are shown in Table 4.

| Table 4: Convective rain vs. convective rain – algorithms comparison with one smaller station |
|---------------------------------------------------------------|----------------|-----------------|-----------------|
| Master-slave | Availability (% on event duration) | 38.69 | 31.79 | 3.27 /h |
| Dual Active modified | | 39.3 | 31.66 | 16.73 /h |
| Combined | | 39.21 | 31.86 | 1.65 /h |
| No site diversity | | 35.53 | 25.19 | - |

In order to optimize master-slave logic HM and DM were set 0.5 dB. In terms of availability DAM seems preferable, it is not definitely clear which one is the best algorithm for throughput in this configuration.
“Convective rain / clear sky” case study
This is an important case study, due to the fact that high availability and throughput gain can obtained (mean + 64.47% and + 67.51% respectively). The enormous diversity gain (36.85 dB) means that none PIMT would be by far comparable with site diversity.
HM and DM are set to 1 dB. This choice is rather conservative, but an outage in this context would not be tolerated.
Performance results are reported in Table 5.

Table 5: Convective rain vs. clear sky – algorithms comparison

<table>
<thead>
<tr>
<th></th>
<th>Availability (% on event duration)</th>
<th>Relative user Throughput (%)</th>
<th>Mean switching rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master - slave</td>
<td>100</td>
<td>91.04</td>
<td>5.17 /h</td>
</tr>
<tr>
<td>Dual Active</td>
<td>100</td>
<td>92.7</td>
<td>3 /h</td>
</tr>
<tr>
<td>Combined</td>
<td>100</td>
<td>91.7</td>
<td>0.8 /h</td>
</tr>
<tr>
<td>No site diversity</td>
<td>35.53</td>
<td>32.49</td>
<td>-</td>
</tr>
</tbody>
</table>

Availability gain is inversely proportional to PM (78.68% and 55.90% on event duration for 2.669 and 6 dB).
Results obtained considering a smaller second station are summarized in Table 6.

Table 6: Convective rain vs. clear sky – algorithms comparison with one smaller station

<table>
<thead>
<tr>
<th></th>
<th>Availability (% on event duration)</th>
<th>Relative user Throughput (%)</th>
<th>Mean switching rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master - slave</td>
<td>100</td>
<td>60.12</td>
<td>5.17 /h</td>
</tr>
<tr>
<td>Dual Active modified</td>
<td>100</td>
<td>59.52</td>
<td>3 /h</td>
</tr>
<tr>
<td>Combined</td>
<td>100</td>
<td>59.71</td>
<td>0.8 /h</td>
</tr>
<tr>
<td>No site diversity</td>
<td>35.53</td>
<td>32.49</td>
<td>-</td>
</tr>
</tbody>
</table>

Small throughput variation is the only difference between the diversity management logics. Quickness in restoring primary link, for master-slave, now becomes an advantage (while in the other situation was a drawback).

“Convective rain / stratified rain” case study
A wide range of events forms this case study. Sometimes it can be more similar to a convective rain/clear sky event or to a convective rain/convective rain one. To face these differences, a sort of subclasses were created and analyzed (and finally joined according to their statistical weight).
Mean availability gain is 61.58% on event duration, 54.44% as far as relative throughput concerns. Diversity gain results equal to 17.78 dB. HM and DM set to 1 dB.
Results are reported in Table 7 and 8, considering ground stations with the same characteristics and a second smaller station respectively.

Table 7: Convective rain vs. stratified rain – algorithms comparison

<table>
<thead>
<tr>
<th></th>
<th>Availability (% on event duration)</th>
<th>Relative user Throughput (%)</th>
<th>Mean switching rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master - slave</td>
<td>98.53</td>
<td>78.67</td>
<td>9.68 /h</td>
</tr>
<tr>
<td>Dual Active</td>
<td>98.53</td>
<td>81.72</td>
<td>15.73 /h</td>
</tr>
<tr>
<td>Combined</td>
<td>98.53</td>
<td>80.80</td>
<td>1.33 /h</td>
</tr>
<tr>
<td>No site diversity</td>
<td>36.95</td>
<td>27.28</td>
<td>-</td>
</tr>
</tbody>
</table>

Dual active is more reliable in terms of availability, while master-slave provides more user throughput.

Overall results
An overall performance result was obtained assuming statistical independence between the two interested sites. Strength of this assumption is mitigated by construction events procedure. Results are reported in Figure 6.

Figure 6: Availability & relative throughput – site diversity impact (mean on all events).

Note: fixed PM (4.9 dB). No FMT refers to 160 HD channels with constant source coding (7.5 Mbps) transmission, constant modulation and channel coding scheme (8PSK 9/10); DRR & ACM refers to section 4; blue one refers to site diversity simulation results.
terminal are compared to the reference one and results are reported in Figure 7.

Cost advantages translate in 266.13 availability seconds and 69.96 Mbps user throughput loss.

Statistical consideration on yearly basis approximated estimation is reported in Figure 7.

High switching rate is due to an always ‘active’ behavior in order to select the best signal, while an activation threshold is to be exceeded for master-slave and combined. It means that they remain ‘passive’ for longtime. Master-slave concerning, HM and DM best value is 1 dB. It can be eventually hold at 0 dB for attenuations lower than 2-3 dB to further reduce slave utilization. Anyway, the most important result is the good agreement achieved among these algorithms. So a proper choice can be taken evaluating others issues: protocols or resource management requirements, maximizing a station use or user throughput, minimizing traffic on terrestrial interlink, signaling traffic between ES or switches or similar.

Algorithms final performance comparison results are summarized in Table 9 and 10 for equivalent and different Earth station respectively. Best performance seems to be provided by DA (extremely little availability gain but not negligible throughput one with respect to the others).

DAM well manages intense rain situation, but not the same can be said for light rain (this explains availability losses).
HM and DM are set to 0.5 dB for master-slave. It seems to be the most suitable algorithm in this configuration. However, previous final consideration is completely confirmed.

7. CONCLUSIONS

In this paper a detailed simulation analysis on the use of site diversity technique in EHF satellite link has been performed. Currently site diversity is not widely used to high cost and ground stations synchronization issues. The future transition towards higher frequency bands, as Q/V or W ones could lead the development of this propagation impairments mitigation technique due to the fact that this is the only way to obtain high service availability. The simulation showed the possibility to reach connection availability greater than 99.5% of the total time with the concurrent use of ACM and site diversity techniques. Moreover, in some cases, it could be possible to efficiently schedule and share the use of already existing ground stations in order to decrease the costs and increase the overall systems performance through the use of site diversity techniques.

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[2] European Space Agency web site: http://www.esa.int


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Tommaso Rossi received his University Degree in Telecommunications in 2002, MSc Degree in “Advanced Communications and Navigation Satellite Systems” in 2004 and PhD in Telecommunications and Microelectronics in 2008 at the University of Rome “Tor Vergata” where he is currently an Assistant Professor (teaching Digital Signal Processing). He is a member of the Italian Space Agency WAVE (W-band Analysis and VErification) Project Technical Team, a feasibility study for W-band telecommunication payloads. He is part of the scientific team that is defining TDP#5 payload embarked on ESA Alphasat satellite. He has been a technical member of the ESA research project on Flowers Constellations. He has been involved in European Space Agency “EDRS” (European Data-Relay Satellite System) project. His research activity is focused on Space Systems, EHF Satellite Telecommunications, Satellite and Inertial Navigation Systems, Digital Signal Processing and Satellite
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