ASSESSMENT OF A GATEWAY SWITCHING ALGORITHM FOR Q/V-BAND SMART DIVERSITY SYSTEMS IN THE Q/V-LIFT PROJECT

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Abstract

The exploitation of Q/V-band will boost the capacity of High-Throughput Satellites (HTS) but, on the other side, it will prompt the adoption of innovative techniques, such as Smart Gateway Diversity (SGD) to cope with heavy propagation impairments. In this paper, feeder link operation is simulated assuming that an $N+P$ SGD system (i.e. N active gateways and P backup gateways) is adopted to mitigate rain fades. Due to the non-negligible latency (~30 s) involved by gateway handover, a linear predictor of rain attenuation has been designed to operate before the switching decision block. In a gateway cluster ($N = 9$ and $P = 1$) with mid-latitude gateway stations, the above SGD set-up leads to a feeder link availability of about 99.66% of time with a small degradation compared to the case in which the attenuation is exactly known (99.79%). However, the number of predicted handovers significantly increases to an average of about 1200 events per year, which may result in critically short separations between consecutive events. The crucial trade-off involved is between number of handovers and probability to miss a fade.

1. Introduction

The competitiveness of future TLC High-Throughput Satellites (HTS) will rely on their capacity to provide broadband services especially in those areas poorly covered or not covered at all by terrestrial networks. Moving the feeder link from the actual Ku/Ka-band up to the Q/V band (40-50 GHz), where a (non-exclusive) 5 GHz spectrum is available [1], would significantly boost system capacity with the beneficial side effect of reducing the number of gateways. However, as rain fading at Q/V-band dramatically increases the probability of link outage with respect to lower bands, advanced fade mitigation techniques have to be implemented to meet the availability targets required by TLC services. In this frame, the QV-LIFT H2020 project, funded by European Commission with the Grant Agreement No. 730104 (H2020-COMPET-2016; https://www.qvlift.eu/), which kicked-off in November 2016, aims at developing hardware and network technology for Q/V-band exploitation. In particular, a Q/V-band smart gateway management system is being designed and implemented and will be subsequently validated through simulations and measurements. The QV-LIFT demonstrator implements fade mitigation based on the concept of Smart Gateway Diversity (SGD). In general, SGD techniques make use of redundant ground segment resources (i.e. idle gateways and/or spare bandwidth) that are shared among the user beams. The gateways are interconnected and the resources are allocated by a network management system. The effect of rain fading is mitigated by spacing the gateways far apart enough to reduce the probability that deep fades occur at the same time across different feeder links (space diversity) [2].

In principle, gateway handover can be carried out by sounding the propagation channel in real time and by using a threshold related to the quality of data transmission across the link. For instance, in [3], the handover starts when a 10% drop in link capacity is detected. However, the process takes a certain time, namely it involves a latency, which takes into account satellite configuration switching and traffic handover delay introduced by the ground segment. Therefore, a different approach is adopted here: a channel predictor has been designed and integrated into the QV-LIFT smart gateway management system and the switching decision is taken according to the predicted value of rain attenuation along the Earth-to-satellite path.

The QV-LIFT channel predictor and decision algorithm are described here and subsequently used to simulate the operation of an $N+P$ SGD scheme. The feeder link propagation channel at V-band is modelled through a time-series generator.

2. Methods

Fig. 1 sketches a high-level flow diagram of how the QV-LIFT smart gateway management system accomplishes SGD. The feeder link will be emulated by the Alphasat experiment beacons in Tito Scalo and Matera [4]. Alternatively, the demonstrator operation can be assessed by loading the time series of rain attenuation provided by a Multi-site Time series Synthesizer (MTS) that simulates the rainy propagation channel [5]. The channel predictor is based on a linear filter. The gateway switching decision is taken after comparing the predicted time-series of rain attenuation with a threshold during a certain observation time interval. Finally, the network management system implements all the actions necessary for completing the gateway handover process.

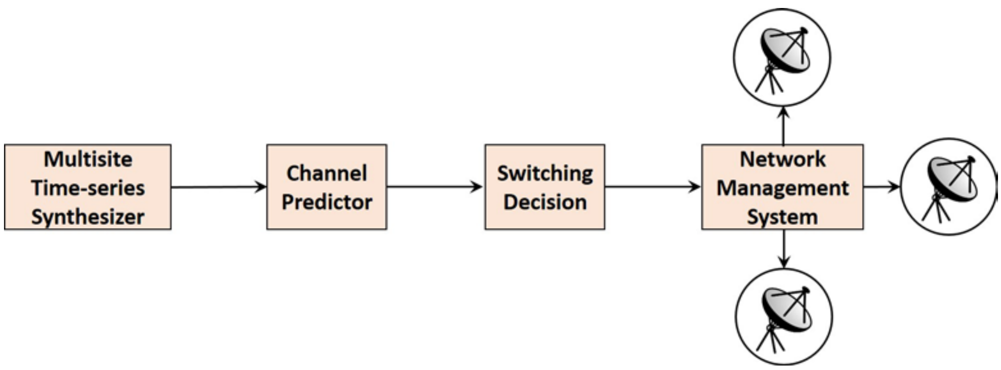

Fig. 1 High-level sketch of the QV-LIFT gateway handover process.

In the following, the operation of the first three blocks in Fig. 1 is assessed by a MATLAB simulation. An $N+P$ SGD scheme is assumed, i.e. there are N active gateways during system operation under ideal channel conditions and P back-up gateways. When an active gateway is shadowed by a deep rain fade, it is replaced by a back-up gateway, provided the latter is free from heavy rain and not already used to replace another gateway. The system performance is evaluated in statistical terms by generating one-year time-series that fit the climatologic CCDF of rain attenuation in each gateway site. The performance index considered is the percentage of time the system is fully operational, that is, the number of active gateways equals the one in ideal propagation conditions. It is assumed that a gateway link either works at full capacity (when attenuation is below the threshold) or it is in outage. The simulation is limited to the feeder link operation. Hence, system aspects involving user beam operation are not taken into account here (e.g. adaptive feeder link capacity in response to variable traffic loads on the user link side or the way gateway resources are allocated among the user beams).

There are few crucial simulation parameters:

- M_R = power margin available on each link to counteract rain attenuation (dB). When rain attenuation A_R across a link exceeds M_R, the link is in outage.
- Δt_1 = system latency introduced by gateway switching operation (s).
- $\Delta t_2 > \Delta t_1$ = duration of the prediction: when working at time t_0 the predictor is able to estimate channel attenuation up to $t_0 + \Delta t_2$. The switching decision is taken comparing the predicted attenuation from $t_0 + \Delta t_1$ to $t_0 + \Delta t_2$ with M_R.

In this paper, it is assumed that link outage is produced by rain attenuation, which is reasonable at Q/V-band. Despite contributions due to oxygen, water-vapor and clouds are not negligible, they can be compensated by simple strategies such as a static margin. On the other side, V-band rain fades at mid-latitude can be in excess of 10 dB in 0.5% of yearly time and 20 dB in 0.1% of yearly time, respectively.

3. Multi-site Time-series Synthesizer (MTS)

Time series of rain attenuation are generated for a given site by combining rain events measured during propagation experiments, hence having the characteristics of real signals. The CCDF calculated from the time series fits the corresponding climatologic CCDF as provided by one of the standard models (e.g. ITU-R, ExCell, etc.). Finally, spatial correlation between rain in different sites is taken into account.

As an example, Fig. 2 plots three CCDFs of V-band rain attenuation for two of the gateway sites considered in the simulations (Cagliari and Paris, respectively). The magenta line is the climatologic CCDF (objective curve), whereas the cyan line is obtained from the MTS when all the database events (i.e. about 2387 rainy hours) are used. Finally, the black line corresponds to a one-year long time series (i.e. about 378 rainy hours in Paris and 133 in Cagliari, respectively).

The time series are sampled every 1-s and are generated as follows: the events in the database are divided into classes according to their peak attenuation and duration. Then, the objective CCDF is approximated by a linear combination of the CCDFs of each class of events. Finally, one-year time series of rain attenuation are obtained by picking up events from each class. The process must fulfill two constraints: 1) the sum of the durations of the selected events of each class is proportional to the corresponding coefficient and 2) the events fit into the rainy segments of a binary time series of rainy/dry states that has been generated in advance. The time series represent an average year with respect to the occurrence and intensity of rain.

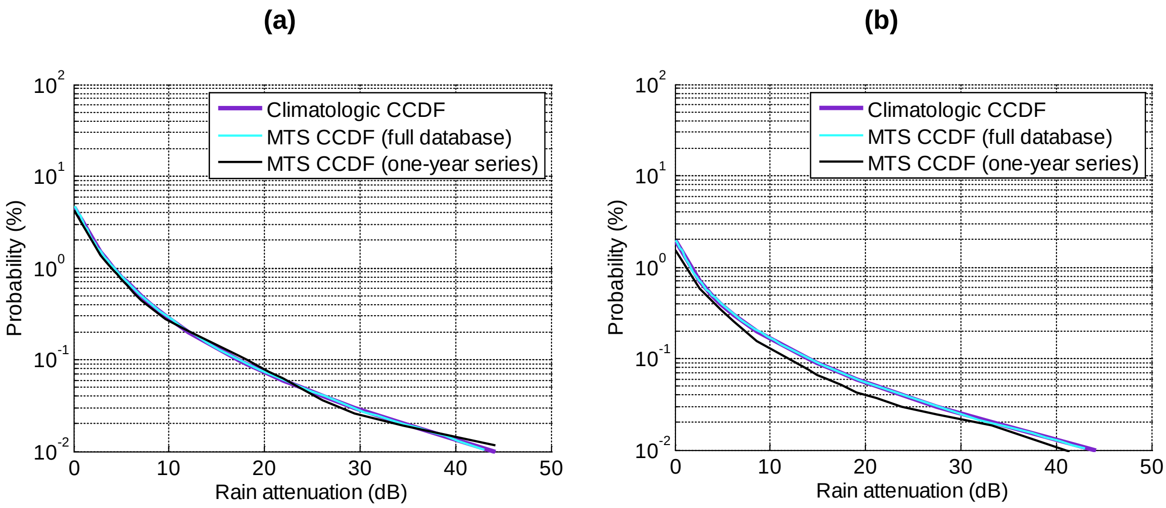

Fig. 2 V-band CCDFs of rain attenuation across an Earth-to-GEO satellite path. (a) Paris and (b) Cagliari. Satellite position: 9°E.

4. Channel attenuation predictor

As gateway switching has a latency, it is necessary to predict channel attenuation to begin the process before a rain fade has occurred. In general terms, let $y_p(i+L)$ be the prediction (made at discrete time i) of a quantity y at time $i+L$, which is computed using the information available in an $(W+1)$-sample window from i-W to i. A classical method based on linear regression is the following:

$$y_p(i+L) = c_0 y(i) + c_1 y(i-1) + \ldots c_W y(i-W) = \sum_{k=0}^{W} c_k y\left(i-k\right) \quad (1)$$

where $y(i\text{-}k)$ is the instantaneous channel measurement at time i-k and c_k is a coefficient that can be computed using several different approaches. Eqn. (1) represents a FIR filter of order W, called Linear Prediction Filter (LPF) as the prediction is a linear combination of past samples. The LPF proposed here considers the first and the last element of the $(W+1)$-sample window, i.e.

$$y_p(i+L) = c_0 y(i) + c_W y(i-W) \quad (2)$$

and the predictor is based on the slope of the straight line passing through i-W and i, i.e.

$$c_0 = 1 + \frac{L}{W}$$
$$c_W = -\frac{L}{W} \quad (3)$$

Fig. 3 shows an example of LPF operation. The time axis has been normalized so that the prediction is produced at $i = 0$, whereas the decision window is comprised between $\Delta t_1 = 30$ s (latency time) and $\Delta t_2 = 60$ s. The LPF operates considering the first and the last rain attenuation samples of the window between -50 s and 0 (hence $W = 50$ s) and calculates the slope of the straight line passing through the above two points. The prediction is due at 60 s (black star).

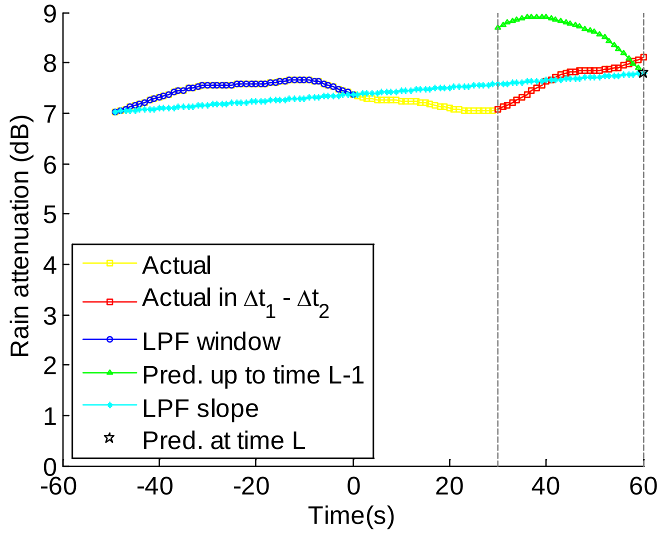

Fig. 3 Example of LPF operation.

5. Switching decision algorithm

The decision algorithm proposed here assumes that the $N+P$ system gateways are identical and that there is no limit to the number of allowable gateway handovers. Again, let us assume a discrete time axis i. The switching decision is taken at time $i = 0$ based on predicted channel attenuation $A_{R,p}$ between i_1 and i_2, where $i_1 = \Delta t_1$ and $i_2 = \Delta t_2$, respectively. Moreover, gateways from 1 to N are active at $i = 0$, whereas the ones from N+1 to $N+P$ are back-ups. The status of each gateway in the time interval between i_1 and i_2 is checked and the following indicator is calculated:

$$X(m,0) = \sum_{i=i_1}^{i_2} (A_{R,p}(m,i) > M_R) \tag{4}$$

where $m = 1, 2, \ldots, N+P$ is the gateway index. If $X(n, 0) \geq X^*$, where $n = 1, 2, \ldots, N$, the gateway is predicted to move into outage at a certain time between i_1 and i_2. For each active gateway with $X(n,0) \geq X^*$, the system checks whether there is a spare gateway available, i.e. one with $X(p,0) < X^*$, where $p = N+1, \ldots, N+P$. Two conditions shall be fulfilled before switching is allowed: a) no switching process is already going on at the gateway that will move into outage, and b) no switching process is already going on at the selected spare gateway.

6. Simulation scenario

An 9+1 SGD configuration has been simulated. Table 1 lists the ten gateway stations, their coordinates, altitude and link elevation angle. The satellite is orbiting at 9° E. 9+1 is a realistic configuration for one gateway cluster of a larger system made of several clusters and providing continental coverage. Clustering the gateways reduces the complexity, hence the cost of the ground segment. On the other side, when a single large cluster is used, SGD operation is more efficient.

Table 1 Gateway configuration

ID	Site	Latitude (deg)	Longitude (deg)	Altitude (m)	Elevation (deg)
1	Helsinki	60.192059	24.945831	17	20.4
2	Berlin	52.520008	13.404954	37	29.8
3	Amsterdam	52.357044	4.950124	-2	30.0
4	Udine	46.0693	13.23715	108	36.8
5	Catania	37.49223	15.07041	40	46.1
6	Warsaw	52.237049	21.017532	111	29.2
7	Turin	45.097848	7.628667	265	38.0
8	Paris	48.864716	2.349014	36	33.6
9	Madrid	40.416775	-3.70379	648	41.5
10	Cagliari	39.23054	9.11917	41	44.6

Table 2 shows the values of the simulation parameters. Please note that $X^* = 1$ represents a conservative choice: if $A_{R,p} > M_R$ at least once in the prediction window $\Delta t_1 - \Delta t_2$, the gateway is flagged as in outage.

Table 2 Simulation parameters

Parameter	Description	Value
$N+P$	Gateway diversity scheme	9+1
M_R	Link power margin against rain attenuation	8 dB
Δt_1	Latency time due to the switching process	30 s
Δt_2	Duration of channel prediction	60 s
W	LPF window width	50 s
X^*	Threshold on minimum number of link outages in $\Delta t_1 - \Delta t_2$	1

7. Results

First, the decision algorithm has been tested over a one-year simulated period, assuming an ideal channel predictor as a benchmark (i.e. link attenuation is known in advance or, which is equivalent, the channel is deterministic). The following results have been obtained:

- The system is fully operational for 99.85% of time (i.e. at least 9 gateways are operational and exactly 9 are active) assuming the system works during a switch. If the system is not operational during the 30-s latency time, the above figure reduces to 99.79%. On the other side, a 9-gateway system with no diversity would feature a 96.42% of availability.
- The number of gateway handovers in a year is 673.

When the system is not fully operational, the number of active gateways is less than 9 (usually 8). This turns into a reduction in the number of users served and/or in user link data rates depending on how the gateway resources are allocated to the user beams.

Fig. 4 shows the percentage of yearly time a gateway is active, which is rather uniform. As expected, stations less affected by rain (Madrid and Cagliari) exhibit the highest percentages of activity. Fig. 5 (blue curve) shows the cumulative sum of the duration of time intervals between two consecutive gateway handovers. On the y-axis is the number of times in a year the duration exceeds the corresponding value on the x-axis. In 173 cases the duration is less than 1 h and in 10 cases it is less than 1 min.

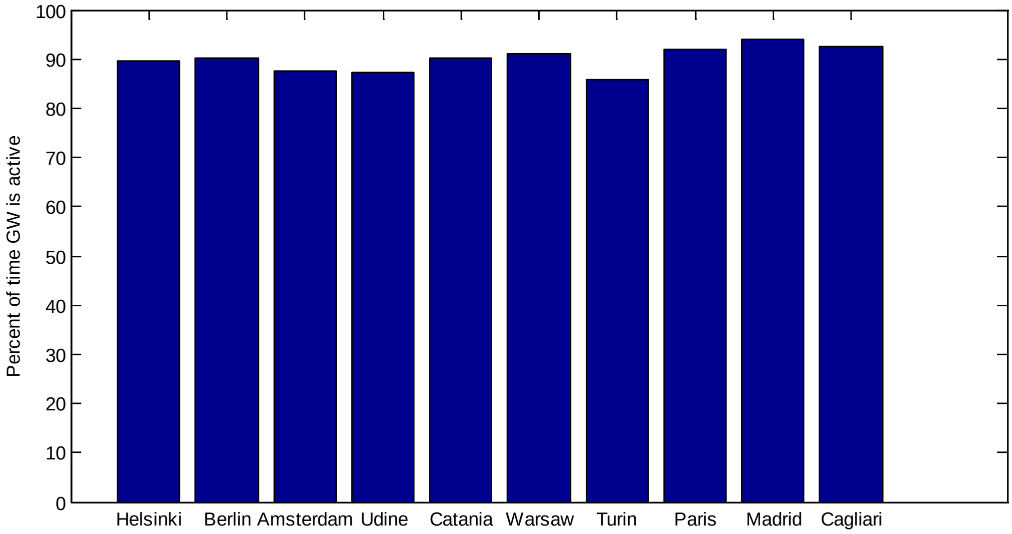

Fig. 4 Gateway activity in the simulated 9+1 SGD scheme.

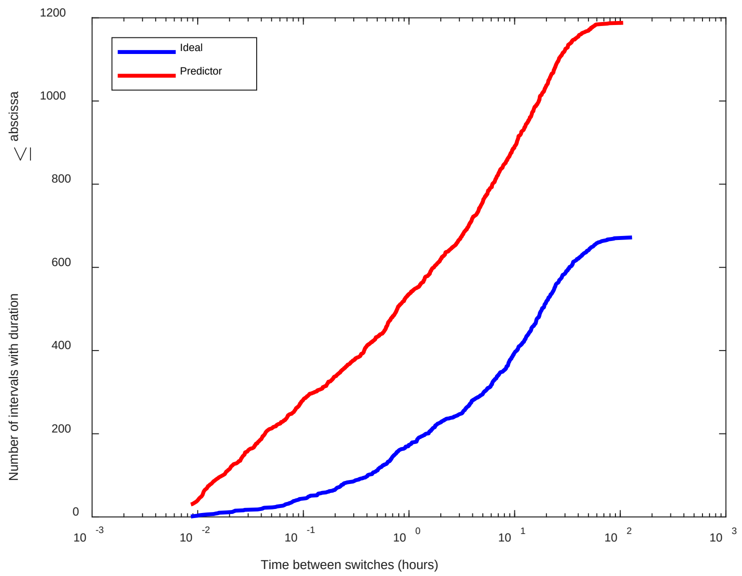

Fig. 5 Cumulative sum of the duration of intervals between consecutive gateway handovers in a one-year time.

Now, let us consider the system performance when the channel attenuation is estimated by the predictor described in Sec. 4. First, let us check the quality of the prediction for each gateway link. Fig. 6 shows the ten scatterplots of predicted against real (i.e. MTS) channel attenuation conditioned to the presence of rain and the best fit straight line. The correlation is fair and the prediction is generally unbiased.

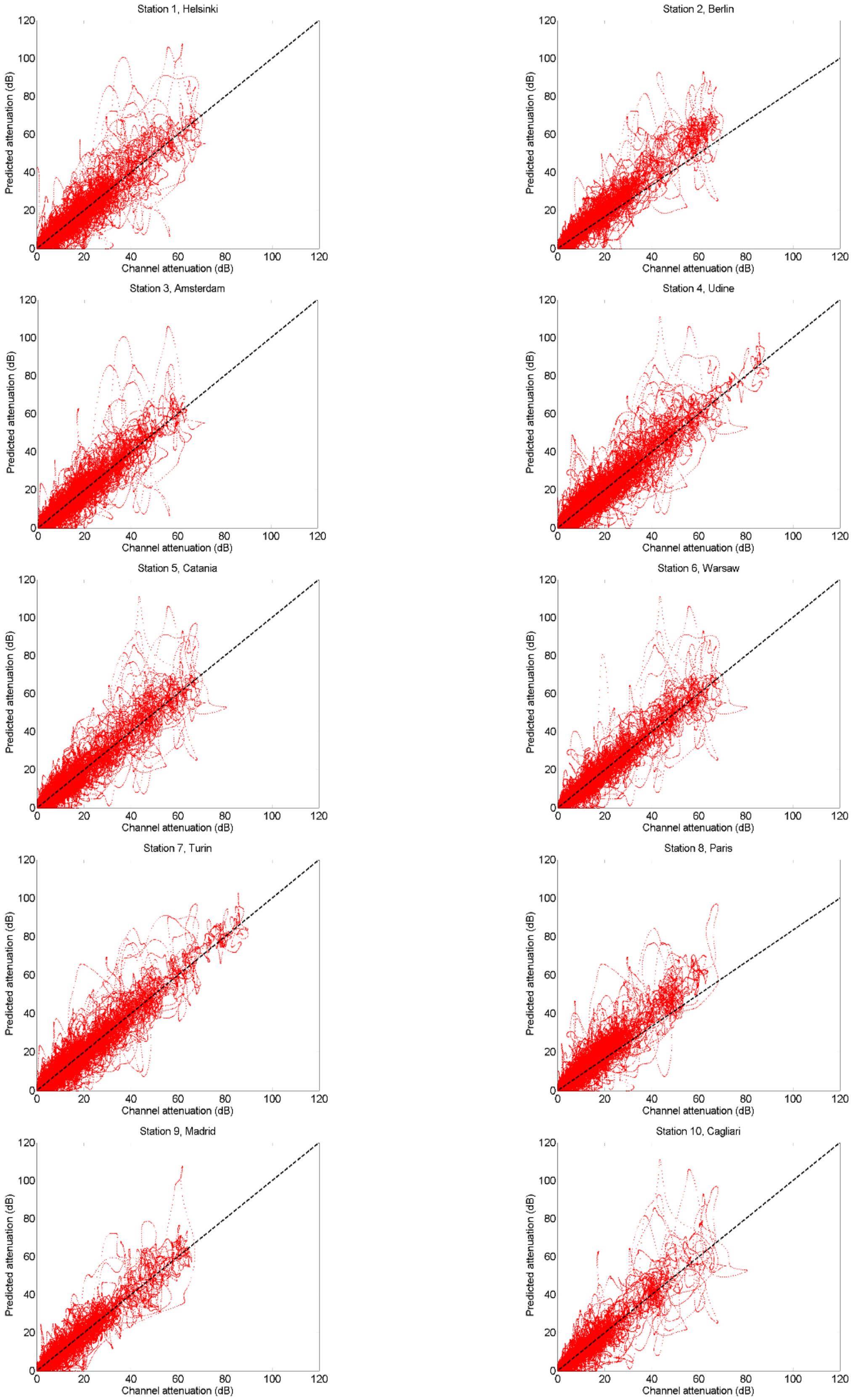

Fig. 6 Predicted against real channel attenuation in every gateway station.

How do we quantify prediction errors? An obvious indicator is the number of “misses”. A missed outage or, shortly, a “miss” occurs when a gateway link is predicted as operational (i.e., $A_{R,p} \leq M_R$) whereas it is actually in outage (i.e., $A_R > M_R$). Fig. 7 shows the percentage of misses, defined as the percent ratio of the number of misses to the actual number of outages. The above percentage is less than 15% for each station. The last bin in the figure is relative to the entire 9+1 system and quantifies the percentage of time the predictor wrongly flags the system as fully operational whereas it is not. The number of false alarms, i.e. the number of wrongly predicted outages (not shown here) is comparable with the number of misses, that is, the estimator is not biased towards either type of error.

The red curve in Fig. 5 shows the cumulative sum of the number of system handovers in the case the LPF is used. An overall 1189 gateway handovers are estimated during a one-year simulation. The 70% increase in handover events introduced by the predictor is ascribable to the decision rule: if at least one sample within the 30-sample decision window exceeds the margin, the gateway is considered in outage and a switching process starts. Hence, a single false alarm in the decision window triggers a switching process.

Finally, Table 3 summarizes the 9+1 system performance in terms of system outage. The error in rain propagation channel prediction turns into a decrease of 9+1 system availability from 99.79% to 99.66% (assuming the system is not operational during the latency time).

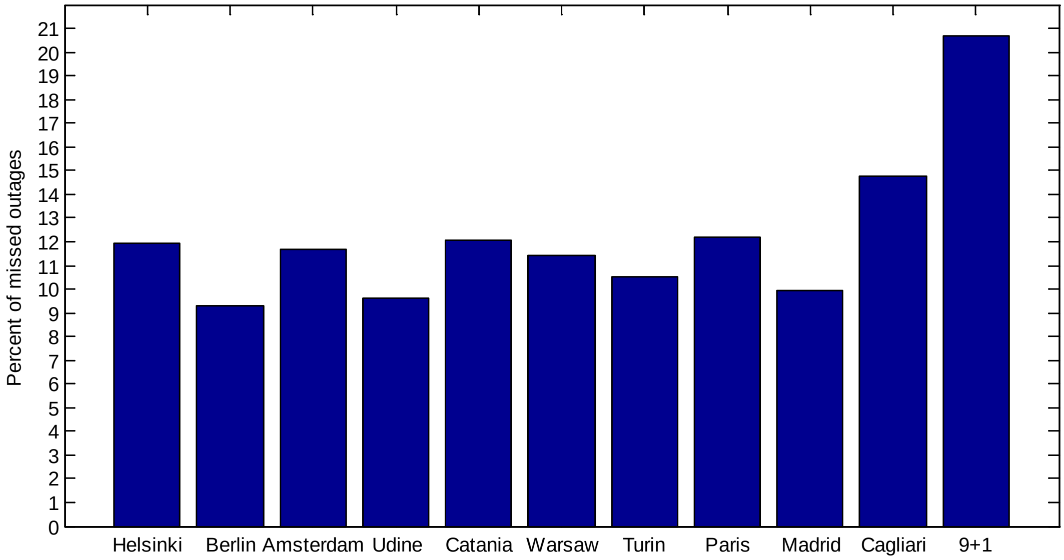

Fig. 7 Percentage of outages missed by every station and by the 9+1 SGD system (last bin) when channel attenuation is estimated by a LPF.

Table 3 System status with and without the SGD 9+1 system (FO=fully operational system, NFO=not fully operational system)

System type	Status			
	FO		NFO	
9+1, no latency	99.856%		0.144%	
9+0 (i.e. no diversity)	96.419%		3.581%	
	Deterministic channel		LPF	
	FO	NFO	FO	NFO
9+1, FO during latency	99.854%	0.146%	99.814%	0.186%
9+1, NFO during latency	99.793%	0.207%	99.663%	0.337%

8. Conclusions

The performance of rain fade mitigation based on SGD has been evaluated through simulations over the V-band feeder link of a HTS system for broadband TLC services. A cluster of ten European gateways and a $9+1$ SGD scheme have been assumed. As $N+P$ diversity schemes require a gateway handover process, which introduces a latency time, a linear predictor of channel attenuation and a switching decision algorithm have been designed. One-year long time series of rain attenuation have been generated for each link as well by a multi-site time series synthesizer.

Assuming a deterministic channel as benchmark (i.e., the sequence of future rain attenuation values is known in advance), the linear predictor produces two different degradations in the performance of the feeder link: a) $9+1$ system availability decreases from 99.79% to 99.66% of yearly time, assuming the system is not operational during the 30-s latency time required to complete gateway handover and b) the yearly number of handover events increases by about 70% (from 673 to 1189). The above results have been obtained assuming ten identical gateways, hence there is not priority order in deciding the set of nine active gateways when all are operational.

The simulation parameters have been chosen to minimize the missed outages. Future work will focus on the optimization of the above parameters in order to find an optimum trade-off between the number of handovers and the number of missed outages.

9. ACKNOWLEDGEMENTS

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