Lessons Learnt from 10 years of Alphasat Q/V Band Satellite Communication Experiments

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Abstract

It was 2008 when the Italian Space Agency (ASI), on the basis of its well known pioneer position on the scientific analysis of Extremely High Frequency (EHF) satellite communication, successfully proposed to the European Space Agency (ESA) to host an experimental payload working in Q/V band on board the Alphasat GEO satellite. The latter has been launched on July 25, 2013; this large platform hosted the so-called TDP#5 (Technology Demonstration Payload), aimed at performing the first Q-V band telecommunication and propagation experimental campaign. The payload was then renamed in memory of Professor "Aldo Paraboni", pioneer of scientific research on EHF satellite propagation.

Since 2013 a large number of satellite communication scientific experiments have been conducted by University of Rome "Tor Vergata", Principal Investigator for ASI. Due to the excellent scientific results and the high reliability of the system, the experimental campaign is still on-going. The main objective of the telecommunication experiments is to demonstrate the feasibility of broadband satellite communications in Q/V band, optimizing and assessing, over-the-air, the performance of the indispensable adaptive transmission techniques. Moreover, the application of innovative paradigms related to system "softwarization", as SDN and NFV, has been analysed in the framework of satellite systems exploiting "beyond Ka-band" frequencies.

The goal that drives this experimental activity is to provide to the academic community, manufacturers and service providers useful tools to understand how to exploit Q/V band for future satellite communication systems.

In this paper the main results of the last ten years of experiments are presented, as well as the plans for future scientific activities.

1. Introduction

In order to overcome the "spectrum crunch" issue for next generation ICT infrastructures a breakthrough in terms of bandwidth availability is needed. In this framework, satellite communications can play a fundamental role with the exploitation of Extremely High Frequency (EHF) band (30-300 GHz) [1], [2], [3]. EHF band offer a large uncrowded spectrum for satellite communications that could be used to deliver higher and higher capacity ("terabit connectivity") with a quality comparable to FTTH and at the current consumer price. On the other hand, there are well known challenges when going to such high frequency bands as: channel propagation impairments (in particular rain and clouds attenuation), need for Propagation Impairments Mitigation Techniques (PIMT), technological challenges such as power generation (in particular broadband high power amplifiers), antennas with increased C/I, phase noise [4] [5] [6].

In this framework the ASI proposed to ESA to host an experimental payload working in Q/V band on board the Alphasat GEO satellite, launched on July 25, 2013 from the European Spaceport in Kourou via the Ariane 5 rocket. The experimental payload called TDP#5 (Technology Demonstration Payload), aimed at performing the first Q-V band telecommunication and propagation experimental campaigns. The payload was then renamed in memory of late Professor “Aldo Paraboni”, pioneer of scientific research on extremely high frequency satellite propagation [7].

The main objective of the Italian Space Agency telecommunication experiments campaign, performed through the TDP5 “Aldo Paraboni Payload”, is to demonstrate the feasibility of broadband satellite communications in Q/V band (40-50 GHz), optimizing and assessing, over-the-air, the performance of the indispensable adaptive access techniques.vThe main objective of the propagation experiments campaign is to investigate the so-called second order channel statistics, that are essential for the optimization of adaptive communication systems.

This paper reports the main scientific outcomes of the last ten years of Q/V band communication experiments performed through the Aldo Paraboni P/L. Section 2 is devoted to the description of system architecture, Section 3 reports the main experimental activities related to channel estimation, prediction and modeling; in Section 4 the experimental activities related to PIMT, as adaptive transmission, channel equalization and spatial diversity, are summarized, while Section 5 reports some scientific tests on the opportunistic use of EHF satellite links. Conclusions are drawn in Section 6.

2. System Architecture of the Q/V-band Communication Experiment

The system architecture of the communication experiments is reported in Fig.1. The space segment is composed by two transparent transponders operating in Q/V band. Two 10 MHz channels have been used, having central uplink frequencies at 47.9 GHz and 48.1 GHz and downlink central frequencies at 37.9 GHz and 38.1 GHz. The ground segment used to collect the experimental data is composed by two stations, located in Tito Scalo (Southern Italy) and in Spino d'Adda (Northern Italy). [7], [8]. An additional Tx-Rx station is located in Graz (Austria). Air interface is based on DVB-S2 standard [9], [10], the operative SNR dynamic range is about 20 dB.

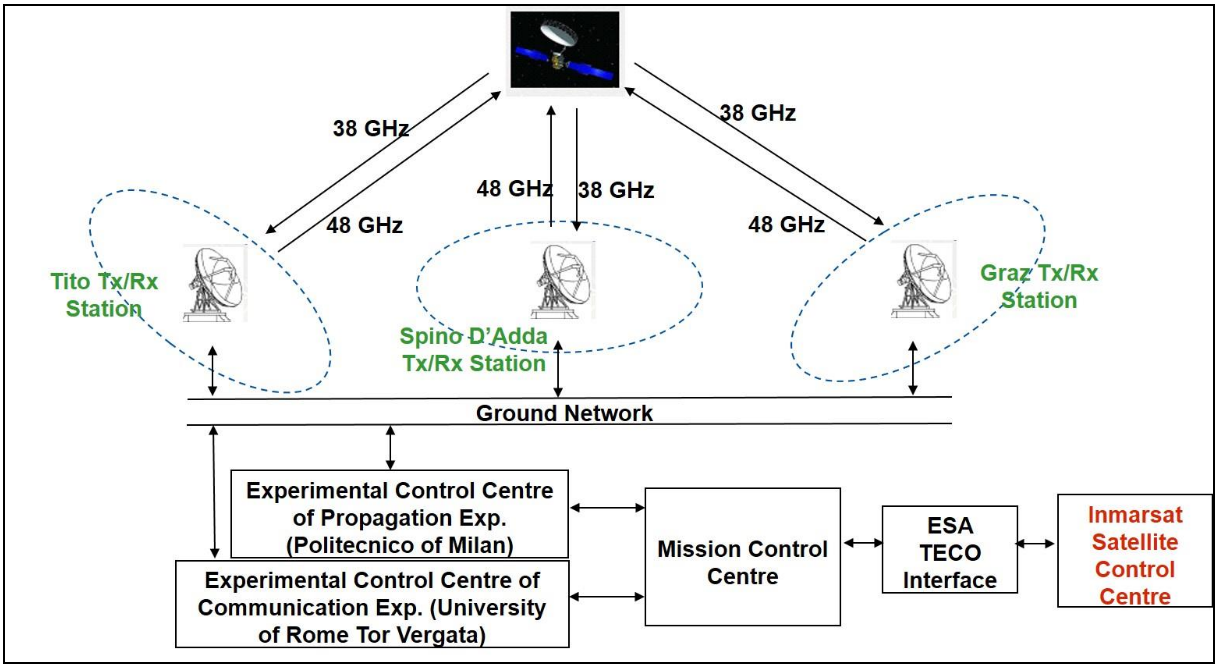

Figure 1: System Architecture.

For the experiments performed by the ASI, there are two control centres, one for the propagation expeirments (ECC-P), located at Politecnico of Milan, and one for communication experiments (ECC-C), located at the University of Rome Tor Vergata. These control centres are managed by a mission contro centre (MCC) located a Airbus Italy premises. MCC exchanges commands and telemetries with the Inmarsat control centre through and interface (TECO) managed by the ESA.

The main activities related to communication experiments can be divided into:

- activities related to the analysis the channel; in particular estimation, modeling and prediction;
- test and optimization of PIMT such as: adaptive coding and modulation (ACM), smart gateway diveristy (SGD), up-link power control, channel equalization;
- application of new paradigms related to "softwarization" such as: software degfined netowrk (SDN), network function virtualization (NFV), software defined radio (SDR);
- analysis of the opportunistic use of EHF satellite links in the framework of space sustainability.

In the following Sections the main scientific results of the communication experimental campaign are reported.

3. Channel Estimation, Prediction and Modeling

3.1 Channel estimation

A PIMT control algorithm is responsible of the decision making process regarding the transmission parameters that should be adapted in real-time on the basis of channel conditions with the goal to maximize the perceived quality of service and to minimize the use of system resources. In this framework, an optimal control algorithm should take into account the propagation channel characteristics in terms of time-scale and dynamic range of variations as well as the performance of the channel estimator in terms of variance and slope. In this context, one of the first experimental activity that has been performed was related on channel estimation. In particular a Data Aided (DA) SNR estimation algorithm has been analysed, being possible to insert pilot symbols within the frame structure of a DVB-S2 trasmission. The SNR estimation algorithm is based on DA ML (Maximum Likelihood) Signal to NOise plus interference Ratio Estimator (SNORE), as suggested by the DVB-S2 standard [9] [10]. The metric used to evaluate channel estimator performance is the standard deviation of the estimation with respect to the average SNR value.

Experimental data have been at first edited to identify time periods with “stable channel conditions”, i.e. when the atmospheric attenuation fluctuations are very low, using radiometric estimation of attenuation. DVB-S2 modulations used in the experiments are QPSK, 8PSK, and 16APSK. Morover, channel adaptation shall be controlled by a very stable SNR estimation, hence an average windowing has been used to increase SNR estimation stability, thus reducing the variance and the fast switching between similar channel estimated conditions (increasing PIMT efficiency).

Results are summarized in Fig. 2, where channel estimator variance is reported as a fuction of SNR for various average windowing length [11].

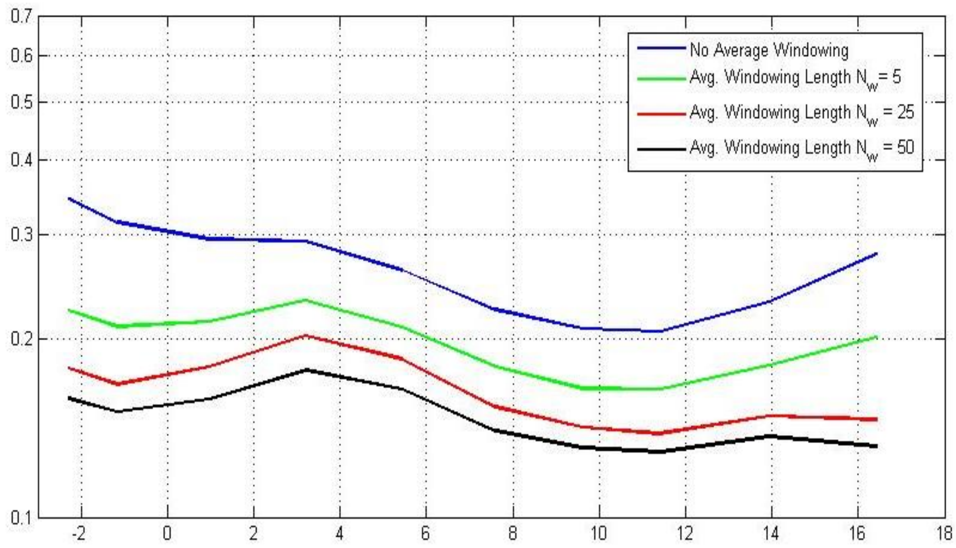

Figure 2: Channel estimatior variance as a function of SNR for different windowding legth [11].

Experimental results show that, as expected, the windowing reduces the SNR estimator variance. If no windowing is performed the estimator variance is higher than 0.2 dB for the whole DVB-S2 SNR operational range; for SNR values lower than 1 dB the variance is even larger than 0.3 dB. For a windowing length of 5 samples, the SNR estimation variance is lower than 0.2 dB, when the SNR is higher than 6 dB. A windowing length higher than 25 samples guarantees a SNR estimation variance lower than 0.2 dB for the whole SNR operational range.
PIMT control loop parameters should be selected on the basis of the channel estimator performance and link delay in order to be robust to fast channel variations and to effectively follow slow channel variations; hence further analysis on SNR estimator has been performed considering the second-order statistics as slope. SNR estimator slope is strictly connected to the rate of change of atmospheric propagation channel (caused by rain or other meteorological events).
The SNR estimator slope depends on atmospheric attenuation level, on sampling time and on climatic parameters. The experimental results show that using a windowing length of 5, the SNR slope absolute value can reach values higher than 0.1 dB with an high probability (more than 10% in case of SNR lower than 2 dB and left derivative calculation), while, using a windowing length of 25, the SNR slope is under 0.05 even for a low level of SNR. Detailed results on this analysis are reported in [11].

3.2 CHANNEL PREDICTION

Physical layer adaptation is in general based on instantaneous estimated channel quality to select the optimal physical layer configuration (e.g.:modulation and coding); in satellite networks this approach is not very effective due to the long delays between the time when the channel quality is estimated at the receiver and the time when the channel quality feedback is received at the transmitter. In this framework, predictive channel estimation techniques can be used to extract the future channel quality metric from time series. Hence, the basic problem is to estimate a channel parameter at time index $i+T$, using the information available up to time index *i*.; where T is the delay between the time when the channel prediction is performed and the time when the signal with new parameters adapted to the predicted channel condition is received. The number of samples used for the estimation (length of the estimation window) is W.

Different linear regression techniques have been analysed implementing Linear Prediction Filters (LPF) such as: moving average filter (MAF), linear ramp coefficients low-pass filter and least squares (LS) filter, which calculated the coefficients of the predictor through the minimization of the prediction error in the least squares sense [12]. The performance of each channel prediction method has been evaluated in terms of MSE as a function of the estimation window size, W.

The achieved results in terms of MSE as a function of the window size can be summarized as follows: for each channel prediction method, as expected, the MSE is a convex function of the window size W, i.e. it has a minimum for a specific value of W and this minimum is unique. This result is a consequence of the trade-off that exists between smoothing of the SNR sequence (tha increases with window dimension, W) and correlation of the considered SNR values in a window and the future SNR value to be estimated (that decreases with W).

The best channel prediction method is the linear prediction filter with linear ramp coefficients. On the other hand, it has to be outlined that the performance is very close to the one of moving average filter.
The optimal value of the window size is has a time duration of about 1,5 seconds.
There are many open research activities on channel prediction problem; as a matter of fact the use of non-linear predictors as neural netowrks or machine learning-based techniques could be used to improve estimation performance. These topics are part of the current and future research activity.

3.3 CHANNEL MODELING

Effective use of EHF satellite channels requires an accurate modeling; in general, memoryless AWGN channel model is inaccurate even in linear channels hence it is important to analyse channel memory.
In this context, an experimental activity to idenfy possible channel memory effects at small time scales has been performed with the goal to improve design coding schemes, packet length, interleaving depth and also simulate the system performance.

To conduct channel modeling experimental activity, a fixed QPSK modulation without channel coding has been used, disabling Interleaving and scrambling at the transmitter side; hard decision decoding is performed on the receiver side. The system works with long frames structure, containing 28720 useful QPSK symbols. Known data is transmitted so that to identify erroneous QPSK symbols and erroneous bis (within each symbol). Measurements have been collected during precipitation events, using a SNR that ranges between 0 dB and 16 dB. Some of the main results on the analisis off errors burst are reported in Fig. 3. In particular, the maximum run-length of erroneous symbols is reported in Fig. 3 (a), both for symbols with one or two erroneous bits. In Fig. 3 (b) the average run-length of correct symbols is depicted.

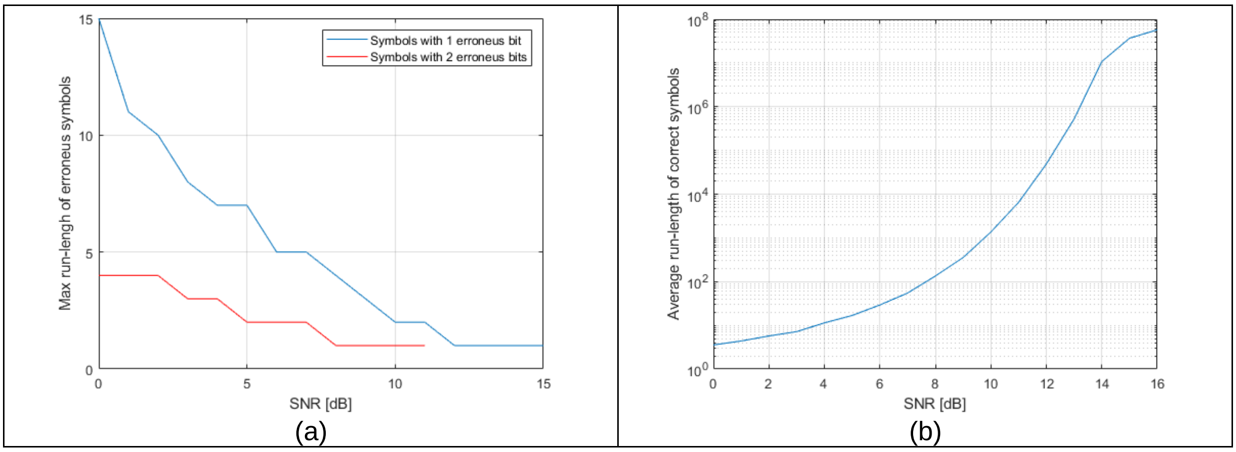

Figure 3: Channel errors bursts analysis: (a) maximum run-length of erroneous symbos, (b) average run-length of correct symbols [13].

On the basis of errors analysis a model for a channel with memory has been developed with the goal to provide an effective tool to test communication schemes at different protocol layers [13] [14]. The errors are modeled at symbol level (for a QPSK symbol) using a three state first-order discrete-time Markov chain where the states are related to: the absence of errors and the presence of one or two errors over the symbol. The state transition probabilities are the model parameters. The model has been extended to cope with long term analysis, developing a two level hierarchical Markov chain that takes into account the SNR range. The model architecture is reported in Fig. 4, In particular the outer layer models the SNR level, while the inner layer models the symbol errors.

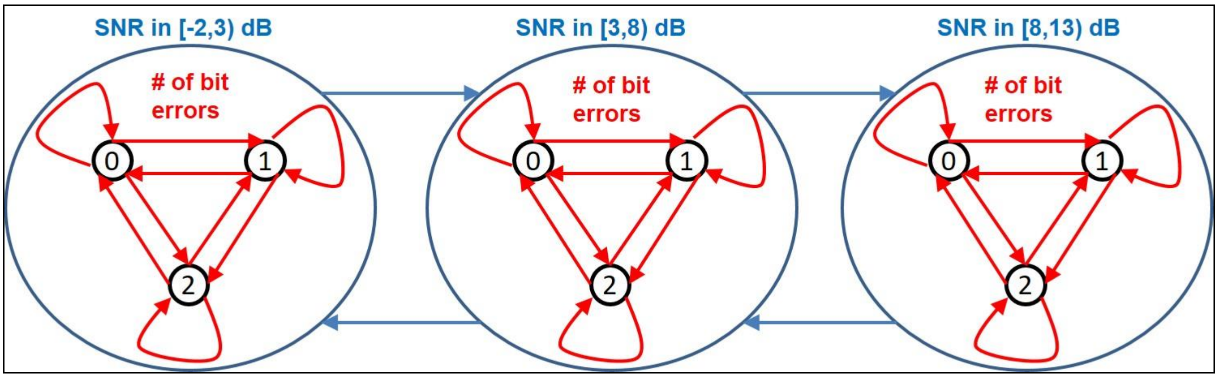

Figure 4: Channel errors model: hyerarchical Markov chain.

The analysis on channel memory outlined the existence of channel memory effects at symbol level. Future research activities are pointed towards the analysis of these effects to identify the main causes, thus improving the knowledge of this channel.

4. PROPAGATION IMPAIRMENTS MITIGATION TEHCNIQUES

4.1 ADAPTIVE TRANSMISSION OPTIMIZATION

The exploitation of EHF satellite links requires the dynamic adaptation of the coding and modulation scheme to the channel conditions, privileging more spectrally efficient Modulation and Coding schemes (MODCODs) in clear sky and more robust schemes if propagation impairments are present. In this framework is very important to optimize the selector of the transmission schemes indetifying also the threshold levels, in terms of SNR, and the logic for the switching between available modulation and coding schemes. An experimental activity has been performed to fully characterize each DVB-S2 MODCOD (using QPSK, 8PSK and 16APSK modulations) in a real satellite channel, in terms of frame error rate (FER) as a function of SNR [15]. The main results are reported in Figure 5, it can be noticed that the curves are different from the ones reported in DVB-S2 standard; this is due to the fact that the standard report an analysis over an ideal AWGN channel, while FER curves depends also on linear and non-linear channel effects which can be a consequence of non-ideal behaviour of electronic circuits and other factors, as: nonlinear effects of the power amplifiers, scintillations, phase noise, I/Q imbalance etc.

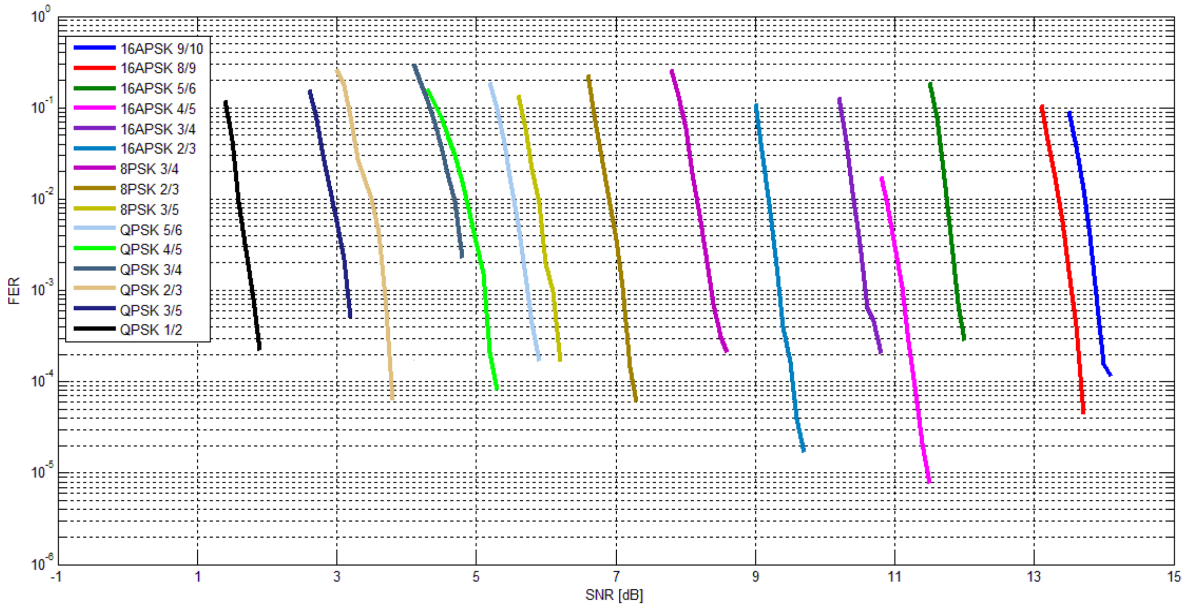

Figure 5: FER vs SNR for Q/V-band satellite channel and DVB-S2 MODCODs [15].

After the characterization of each MOCODs a simulation analysis to test different ACM control logics has been performed considering:

- Static shifted thresholds (ST): fixed margin for MODCODs switching, function of channel estimator standard deviation;
- Dynamic hysteresis-based thresholds (HBT): two different thresholds vectors are introduced with the goal to minimize the “slot payload loss event” (i.e. the probability that the received frames will not be correctly decoded) and to reduce the amount of reverse link signaling.

The performance of the control logic have been evaluated in terms of:

- “average spectral efficiency”, which consists in the evaluating the arithmetic average of the communication efficiencies associated to each data window
- “packet loss event percentage”, which basically counts the number of times in which the frames are successfully transferred
- “efficiency loss events percentage”, which are the frames transmitted using a lower efficiency MODCOD w.r.t. the one that could have been used on the basis of the actual SNR
- “number of switching” between MODCOD, in order to minimise the need for reverse link signaling when estimated SNR is jittering around one of the MODCOD threshold.

As a result HBT control logic has been evaluated as the optimal solution for the optimization of MODCODs switching.
Future research activities on ACM techniques will be focused on the analysis of the application of machine learning techniques to improve MODCODs selector and overall performance metrics.

4.2 Channel Equalization

When very high frequencies are used it is also important to design the system in order to save precious resources; ib this context efficient channel equalization techniques have been analyzed in order to improve link performance. Goal of equalization is to mitigate electronic circuits impairments, such as group delay and amplitude distortion, caused by filters in the gateway, satellite, and terminals.
A very efficient and robust algorithm for receiver side equalization has been testd, the so-called Constant Modulus Algorithm (CMA) that exploits the property of symbols constant modulus (blind equalization). This algorithm has also a low implementation cost (low computational complexity) and can be efficiently introduced in a user receiver.
Experimental test have been performed with and without CMA equalization and link performance has been evaluated in terms of packet error rate (PER) for different DVB-S2 ModCods [16]. The data have been collected during clear sky conditions, adjusting the transmitted power so that to collect data at different values of SNR at the receiver side. Figure 6 reports an example of experimental results, showing packet error rate (PER) vs SNR curves for a particular DVB-S2 MODCOD (16APSK 2/3) in case of ideal AWGN channel and real channel with and without equalization. It can benoticed that equalization is able to provide a performance improvement, in general ranging between 0.1 and 0.3 dB. It has to be outlined that even the small improvement provided by equalization contributes to the full optimization of resources, making it possible to decrease the ACM switching threshold between DVB-S2 ModCods, thus increasing overall spectral efficiency.

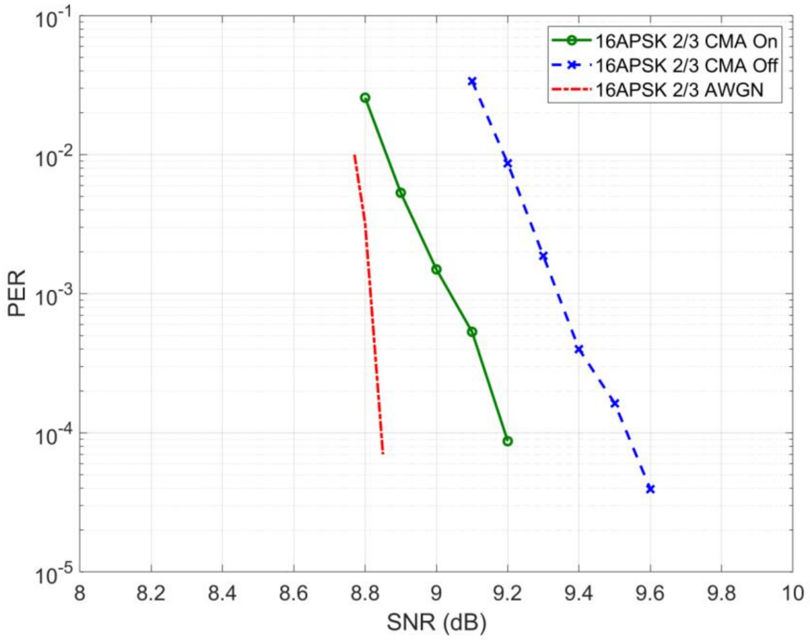

Figure 6: Example of equalizer performance in terms of PER vs SNR [16].

4.3 Smart Gateway Diversity

Severe rain attenuation at EHF bands in the feeder link raises the problem of link availability. In many world regions, it is not possible to reach a commercially acceptable system availability (i.e., 99.5%–99.9%) having unique feeder links and maintaining a reasonable link dimensioning (i.e., reasonable antenna size, power amplifiers). This leads to the exploitation of site diversity solutions; one of the most interesting is the so-called Smart Gateway (SG) diversity [17] [18].

SG is a site diversity scheme for the feeder link based on the use of a pool of synchronized gateways (GWs), connected with a terrestrial fiber network; this brings the possibility to route and distribute feeder-link traffic so as to counteract deep fades on one (or more) GWs.

SG configuration has to be tailored on the particular HTS system, together with the related traffic handover/switching control procedure and diversity management logic. SG diversity has to be optimized on the basis of concurrent targets: availability, infrastructure/operations cost, aggregated throughput, service perfromance, etc.
Experimental data has been used to conduct an analysis of the use of SDN to support a SGD management logic and handover control procedure taking into account a ''graceful degradation'' of the link [19]. Reallocation of traffic between GWs is triggered by different SNR thresholds: only a portion of the groups of user beams served by the impaired GW is reallocated to the other GWs. An example of the analysed architecture is reported in Figure 7 [19].

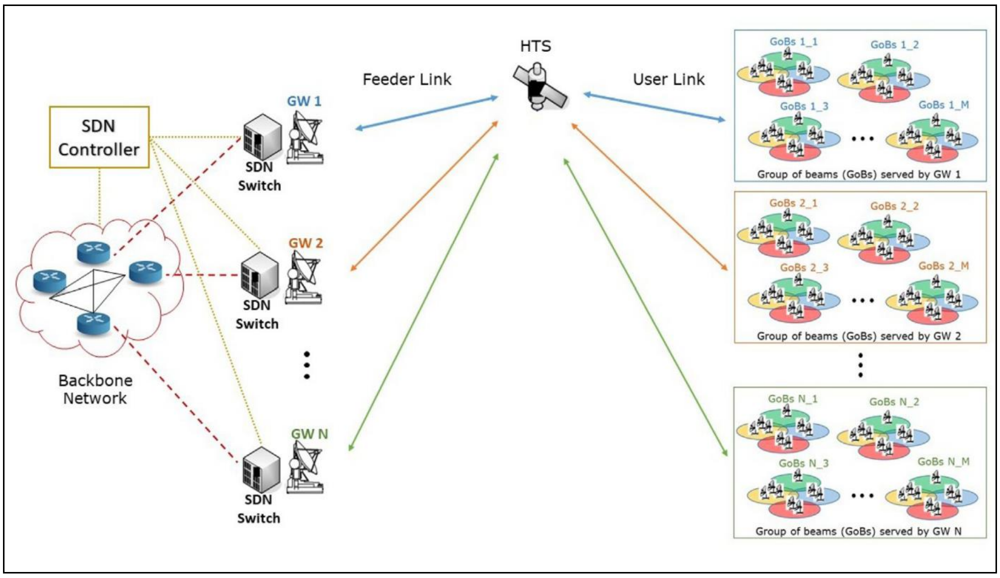

Figure 7: Example of SDN-based Architecture HTS Systems [19].

The developed algorithm is able to build flow tables for user beams allocation with the objective to minimize the number of groups of user beams that are reallocated, based on the specific feeder link degradation leading to a better use of the overall system capacity.
In the framework of SGD optimization many future research activities are planned, with the goal to improve switching performance and optimization of overall system resources exploitation.

5. OPPORTUNISTIC USE OF EHF LINKS

Rainfall monitoring is a very important task in many fields related to people security and everyday living. The possibility to have rain maps with high spatial-time accuracy and low delay is very important to predict extreme meteorological events. Rain maps are created using measurements from: rain gauges, weather radars and satellite observation systems.
The possibility to use signals of opportunity coming from telecommunication systems (using a wide number of geographically distributed receivers) to estimate rain rate is under analysis by the scientific community. Both terrestrial and satellite microwave communication systems can be used for this purpose. Rain rate estimation is basically performed through the analysis of signal-to-noise ratio (SNR) reduction during precipitation events; is has to be outlined that SNR variation is representative of the weather conditions along the propagation slant path. This a key point, being the rain rate estimation performed by the UT not only related to the zenithal precipitation.

Q/V-band SNR time series collected during experimental activities and Rainfall rate time series collected by a rain gauge (co-located at receiver GW) have been used to develop and test regression models [20]. In particular a novel regression model has been proposed that includes:

- Extraction of predictors from SNR time-series PSD analysis – sample mean of very-low frequency components (mainly due to rain), sample variance of low-frequency components (due to rain and scintillations),
- Linear regression function with model parameters identified through the method of Iteratively Reweighted Least Squares (IRLS) using 50% of the available time series.

Main results of this experimental activities can befound in [20]; the proposed model is able to reach a very good rainfall rate estimation statistical performance when compared to other methodologies (e.g. the one suggested by ITU-R) but despite the good results regression techniques are not able to model the low correlation between attenuation and rainfall rate when the rain event that affects the link is not centered over the receiving terminal. Future activities are pointed towards the analysis of machine learning techniques that could improve the estimation performance.

6. CONCLUSIONS

This paper reported the main results of Q/V-band satellite communications experiments that have been performed through TDP#5 "Aldo Paraboni" P/L, together with future research activities. In particular, the main outcomes in terms of channel estimation, prediction and modeling have been discussed as well as the optimization of adaptive transmission techniques, including ACM and SGD. Moreover, additional research analysis on the opportunistic use of EHF satellite links for rainfall rate estimation has been shown in the framework of space sustainability paradigm. As a conclusion it can be stated that the knowledge of EHF channel, in particular Q/V-band one, is improving day by day and the technology is mature. This is confirmed by the fact that main satellite operators are working on the development of broadband access systems exploiting architectures that include Q/V-band links.

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