Interference Mitigation Techniques for Broadband Satellite Systems

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This paper presents an overview of possible interference mitigation techniques aiming at increasing the system capacity of broadband multimedia satellite systems. A multi-star network topology using a bent-pipe transparent satellite is assumed. After a general overview, the paper concentrates on the assessment of Linear Precoding techniques for increasing the potential system capacity on the Forward Link. Potential performance improvements achievable in real systems are investigated as well as resulting system constraints.

Nomenclature

ACM	=	Adaptive coding and Modulation
AFR	=	Array Focused Reflector
BC	=	Broadcast Channel
DC	=	Direct Current
DPC	=	Dirty Paper Coding
DVB	=	Digital Video Broadcasting
DVB-RCS	=	DVB- Return Channel via Satellite
DVB-S2	=	DVB-Satellite version 2
FL	=	Forward Link
GW	=	GateWay
HPA	=	High Power Amplifier
IM	=	Interference Mitigation
LMMSE	=	Linear MMSE
MIMO	=	Multiple In – Multiple Out
MMSE	=	Minimum Mean Square Error
MPA	=	Multi-Port Amplifier
MUD	=	Multi-User Detector
RF	=	Radio Frequency
RL	=	Return Link

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SFPB	=	Single Feed Per Beam
TDMA	=	Time Division Multiple access
TDM	=	Time Division Multiplex
UT	=	User Terminal
UW	=	Unique Word

I. Introduction

Growing interest in multimedia fixed applications calls for the development of point-to-point satellite systems capable of providing high-speed links at a competitive price. In order to meet this goal, next generation broadband satellite systems need to significantly increase their overall throughput. From a system point of view, this leads to the utilization of high frequency bands (e.g. the K_a-band) and to the deployment of a large number of beams per satellite to increase to overall system bandwidth.

Systems performances are, as a consequence more, and more affected by intra-system interference, as the same frequency band is reused by multiple beams. From a physical layer perspective, highly efficient coding schemes are already used in the Reverse Link (RL) of current DVB-RCS [1] satellite systems and will be soon deployed in the Forward Link (FL) thanks to the new DVB-S2 [2] transmission standard. Furthermore, fading mitigation techniques, as Adaptive Coding and Modulation (ACM), are also emerging with the aim of providing a higher flexibility and improve the overall system efficiency [3-4].

Exploitation of very efficient coded modulations operating at low signal-to-noise ratios renders more challenging the introduction of interference mitigation techniques in wireless systems. Multi User Detection (MUD) techniques appear, in this context, as a promising solution to further increase system capacity in an interference-limited and heavily loaded system.

In the last decade, an impressive amount of theoretical investigations in the field of MUD algorithms have been carried out. In particular, the efforts have been focused on CDMA systems, while considering TDMA systems to a lesser extent. A host of advanced signal processing concepts for interference mitigation have been conceived but often analyzed in quite idealized scenarios. Only limited effort has been devoted to making the theoretical background effectively applicable to practical systems. As a consequence, only few techniques really suitable for practical implementation have been appearing in the literature or are being considered for wireless standards. It is felt that only pragmatic solutions featuring affordable-complexity, remarkable performance improvement and a limited impact on the cost of current User Terminals (UT) and Gateways (GW), are likely to be considered by industry.

This paper summarizes some of the results of an investigation of possible techniques for improving the channel throughput in modern multi-beam satellite systems. A transparent bent-pipe satellite architecture is assumed in conjunction with a multi-star network topology.

For the FL, techniques based on GW centralized Precoding were examined assuming a TDM transmission strategy. Precoding techniques are based on the joint encoding of all (co-frequency) signals transmitted by a GW to its served beams. The joint encoding is done to minimize the mutual interference that each user will experience as a result of the transmission from the other co-channel beams. This joint encoding is practically possible if the same GW manage the set of interfering beams as otherwise the GW would have no knowledge of the other beam signals in order to do its joint encoding. In practice, as multiple GWs are typically present in a system, only interference coming from beams served by the same GW can be mitigated. This is however still enough to achieve some quite significant improvement in system throughput. In particular, it is shown in section 2 that even a simple Linear Precoding technique can allow an improvement of the achievable spectral efficiency of about 25 ÷ 50% or even more depending on the specific system assumptions.

Unfortunately, Precoding introduces some new problems and constraints in the system design. A first problem is the need for a quite linear on-board HPA section. Degradation which may be incurred due to the on-board non-linearity may greatly reduce the potential advantage of Precoding as it was shown by physical layer simulations [12]. Another problem is the need for accurate channel estimation. The implication of these problems will be discussed and the impact on performance derived.

It shall be observed that our proposed Precoding scheme actually exploits spatial processing which is made possible by the assumed multi-beam satellite coverage. For the RL, taking into account the assumed multi-beam coverage, spatial processing also appears the preferred approach for interference mitigation. At this regard, the achievable performance of a spatial LMMSE (Linear Minimum Mean Square Error) detector has also been investigated as well as a combination of spatial LMMSE with Successive Interference Cancellation (SIC). These techniques were shown to give an even larger boost to the system throughput than that typically achievable in the FL[†].

This paper concentrates on the FL performance assessment when Linear Precoding is used. For the detailed performance achievable on the RL with either LMMSE spatial processing or LMMSE-SIC see [9].

II. System Assumptions

The advantage provided by the Interference Mitigation (IM) techniques may be more or less significant depending on the considered system configuration. Ideally, one should compare the cost per transmitted bit of each possible alternative system. However, assessing the system cost is not trivial. We took here a pragmatic approach .In particular, we designed a reference satellite system according to current best practice and then cast on that system the selected Interference Mitigation (IM) scheme in order to assess the improvement resulting in the overall system throughput (or equivalently, spectral efficiency).

Figure 1 shows the antenna coverage of the reference system assumed for the analysis. In particular, a European coverage implemented by means of 88 spot beams was assumed. Each spot beam had a beamwidth of approximately 0.5° (corresponding to an antenna gain of about 47 dBi at beam edge).

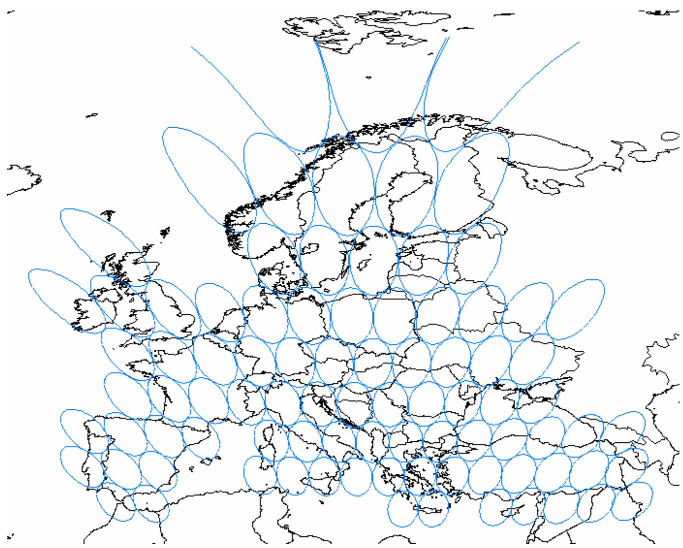

Figure 1 Assumed user link antenna coverage

For the reference system we assumed that a conventional frequency reuse based on a three-color scheme is adopted.

We compared then the spectral efficiency achievable in such reference system with that achievable with the selected IM technique allowing full (or near full) frequency reuse of the available bandwidth.

As already mentioned, the selected IM technique for the FL was Linear Precoding. This technique is based on centralized processing at the GW side thus minimizing the cost of the user segment.

With the proposed techniques the GW is able to only mitigate the interference generated by the beams it manages[‡]. Hence a given cluster of beams managed by a single GW can fully reuse the same frequency band.

Viceversa, the interference coming from beams belonging to different clusters cannot be mitigated very effectively as the GW processor does not have much knowledge of the characteristics of such interference.

Quantitative simulation results reported in later sections assumed a ground segment composed by GWs and UTs whose RF characteristics are shown in Table 1 below. Characteristics of the on-board transponders are given in Table 2 below. The satellite is assumed using an Array Fed Reflector Tx Antenna configuration with HPA allocated to feeds and thus operated in multi-carrier mode (see also discussion in section III-C).

Adaptive Coding and Modulation has been assumed. The operating modes and required Es/No for the FL are shown in Table 3. The assumed performances correspond to those achievable at the optimum OBO when a linearized TWTA is used in multi-carrier mode in absence of any Precoding. The required Es/No also includes an additional

[†] Reason of this is that the FL is typically more power limited than the RL as the on-board power is very costly and system designers tends to design the FL for minimum usage of on-board power.

[‡] This is a practical constraint: in fact, if proper information is exchanged between GWs, this constraint can be removed. However, such an approach would not be practical particularly in the FL where a GW has to know the data to be transmitted by the other GWs in addition to all user positions (and SNIR, depending on the selected Precoding algorithm). On the RL, the number of information to be exchanged by GWs is more limited as it could be limited to the other GWs user scheduling (and position) information. Moreover, even this limited information is not strictly required and, with a proper system design and over sizing of the LMMSE processor, the interference of beams from other nearby GW clusters can also be mitigated by a given GW.

0.5 dB margin for ACM operation (apart for the lowest mode). When evaluating the performance with Precoding, a further penalization of 0.5 dB has been considered with respect to the required Es/No quoted in Table 3. Such a penalization was introduced on the basis of the results obtained in physical layer simulations (see Section III-C). The assumed signal format was DVB-S2 for the conventional system or a slight variant when Precoding is used (the modifications with respect to DVB-S2 were introduced to best adapt to the use of Precoding as detailed in section III-B).

	Gateways	**User terminals**
Saturated EIRP	44.5 dBW	81.7 dBW
Antenna Gain (Tx / Rx)	45.1 dBi / 41.4 dBi	61.0 dBi / 57.5 dBi
HPA Saturated Power	1 W	120 W (for 4 carriers)
Post-HPA Loss	1 dB	2. dB
Minimum Operational OBO	2 dB	2.5 dB
Pre-LNA Losses	0.5 dB	0.5 dB
Receiver Noise Figure	2.5 dB	2. dB
Clear Sky G/T	17. dB/k	33.9 dB/k

Table 1 UT stations RF parameters

Total DC Power	7742 W
Nominal OBO	3 dB
TWTA Eff. @ OBO	46%
Antenna Gain (EOC)	47.3 dBi
Post-HPA Loss	3.5 dB
Receiver Noise Figure	2.5 dB
Pre-LNA Loss	1.5 dB

Table 2 FL Satellite Repeater characteristics – AFR Configuration

Modulation	Code Rate	Req. Es/No (dB)
QPSK	1/4	-1.31
QPSK	1/3	0.3
QPSK	2/5	1.24
QPSK	1/2	2.54
QPSK	3/5	3.77
QPSK	2/3	4.64
QPSK	3/4	5.57
QPSK	5/6	6.72
8PSK	3/5	7.92
8PSK	2/3	9.04
8PSK	3/4	10.33
8PSK	5/6	11.77
16APSK	3/4	13.01
16APSK	5/6	14.41

Table 3 FL ACM modes and corresponding required Es/No for the non-precoded mode. For the precoded case the above figures have to be degraded by 0.5 dB.

III. Forward Link Interference Mitigation

A. Algorithms

The FL channel can be modeled as a Multiple Input – Multiple Output (MIMO) Broadcast Channel (BC) in the parlance of Information Theory. An important result of the theoretical research on such type of channel has shown that the so called Dirty Paper Coding (DPC) [7] scheme can achieve the capacity region of such channel.

Unfortunately DPC is a non-linear technique whose feasibility has not yet been practically demonstrated and is still under research.

In this paper we will limit ourselves to Linear Precoding techniques only. These techniques are sub-optimal but their simplicity makes them ideal for our scopes.

To introduce such techniques let us define the signal model. The transmission scheme is TDM based. Without loss of generality we assume a single carrier per beam which, at each given time slot, is addressed to a single user (one per beam). We will assume a number of beams (and hence of users) equal to K. We also neglect, for notation simplicity, the contribution of the up-link (feeder-link), which is here assumed ideal. Please note that simulation results in section IIID also include the effects of the feeder-link.

We can then write the signals received at any single instant by each of the receiver as a column vector of size K, $\mathbf{y} = \{y_1, y_2, \ldots, y_K\}^T$ where y_j is the signal received by receiver j. In particular, indicating with $\mathbf{x} = \{x_1, x_2, \ldots, x_K\}^T$ the vector of the transmitted GW signals (the element x_j of $\mathbf{x}$ representing the signal to be transmitted to the satellite beam j), we can write:

$$\mathbf{y}=\mathbf{ABGx} + \mathbf{n} \qquad (1)$$

where **B** represents the antenna beamforming matrix, i.e. the element b_{ij} of **B** represents the spacecraft antenna gain of beam j towards user i. **G** is a diagonal matrix representing the complex gain corresponding to the GW transmitter, up-link and on-board repeater chains. **A** is a diagonal matrix whose element a_{jj} represents the complex fading on the down link toward user j. **n** is a noise vector whose elements represents the sum of the thermal noise plus external cluster interference at the input of the on-ground receiver of user j. In the following we will indicate with **H** the product of **ABG**. The matrix **H** is also referred in this paper as the channel matrix.

By scaling each row of the systems of equation (1) by the corresponding standard deviation of the noise plus external cluster interference, equation (1) can be rewritten as:

$$\mathbf{z}=\mathbf{\Lambda H}\,\mathbf{x} + \mathbf{w}$$

where $\mathbf{\Lambda}$ is a diagonal matrix expressing the applied scaling factor and **w** is the noise (plus external cluster interference) vector whose components have now unitary variance. In Linear Precoding schemes, if **s** is the signal vector which is desired to be transferred to the users, then the GW, instead of directly transmitting **s**, will transmit a vector signal **x** to the satellite which is derived from **s** through a linear transformation:

$$\mathbf{x}=\mathbf{F}\,\mathbf{P}\,\mathbf{s}$$

where the linear transformation matrix **F** is known as the precoding matrix and **P** is a diagonal matrix $diag[p_1, p_2,\ldots p_K]$ introduced to possibly weight, according to some optimality criteria, each component of the original signal **s**.

It is apparent from the above equations that the SNIR ratio at the j-th receiver is:

$$SNIR_j = \frac{\left|\Lambda_j \mathbf{H}_j \mathbf{F}^j p_j\right|^2}{1+\sum_{n\neq j}\left|\Lambda_n \mathbf{H}_n \mathbf{F}^n p_n\right|^2}$$

where we have indicated with $\mathbf{H}_n$ the n-th row of matrix **H** and with $\mathbf{F}^n$ the n-th column of matrix **F**. Also the assumption that $E\{||s_k||^2\}=1$ and that the s_k components are uncorrelated with noise and between them was considered.

In the following, for notational simplicity, we will ignore the scaling factor **Λ** or, equivalently, we will assume that it is absorbed in the channel matrix **H**.

The matrix **F** can be computed according to different criteria. For the Zero Forcing (decorrelating) Precoding, the matrix **F** is:

$$\mathbf{F}=\mathbf{H}^+$$

where $\mathbf{H}^+$ is the Moore-Penrose pseudo inverse of the matrix **H** (or **ΛH** if the factor **Λ** has not been absorbed in **H**). The diagonal power weighting matrix **P** could be selected to maximize the achievable throughput [8].

Another practical choice might be (regularized inversion):

$$\mathbf{F} = (\mathbf{I} + \mathbf{H}^H \mathbf{H})^{-1}\mathbf{H}^H$$

where **H** is the channel matrix suitably normalized to the noise floor density and the ^{H} superscript implies Hermitian transpose.

In this case the matrix **P** can be chosen according to different criteria: for example, it can be chosen to maximize the minimum SNIR per user (*MaxMin* criteria) under a constraint on the total sum power $\Sigma_k p_k^2$. In such a case we will refer to that Precoding algorithm as the *MaxMin* algorithm. The performances of the *MaxMin* algorithm are not optimum from the point of view of the provided system throughput. However, it provides maximum fairness (as all users are given the same SNIR and hence the same rate) by renouncing to maximize the throughput as much as possible. A Linear Precoding algorithm which is, instead, optimum as far as the maximization of the user sum rate (given the constraint on the sum power) has also been devised [8] and will be referred here as the *MaxThroughput* algorithm.

Performances of these algorithms where computed assuming the satellite coverage of Figure 1 and a repartition of beams between GW such as each GW manages 8 beams. Obtained results are summarized in [8] and [10]. A problem with the *MaxThroughput* algorithm was the lack of fairness as users in bad propagation conditions (or in heavily interfered areas) are often not served at all. Hence a different power allocation scheme was considered here which is intermediate between the *MaxMin* and *MaxThroughput* algorithms as far as fairness and throughput are concerned. As such, we consider such an algorithm a good compromise between the desire to maximize the system throughput and the one to provide a good fairness to users independently of their location and propagation conditions. This algorithm is here referred as the *UpConst* algorithm. The reason of such a name is due to the fact that the algorithm is actually derived applying the duality principle between up-link and down-link [11] to the LMMSE solution of the equivalent up-link problem where a fixed, constant power (hence the *UpConst* label) is assumed transmitted by all UTs.

The diagonal matrix **P**, according to the *UpConst* algorithm results to be [8] equal to:

$$\mathbf{P}=[\mathbf{I}-\mathrm{diag}(\mathbf{SNIR})\,\mathbf{\Phi}^T]^{-1}\,\mathbf{SNIR}$$

where **SNIR** is the vector of the achievable SNIR per user (which can be computed by solving the dual u-link problem) and **Φ** is a matrix containing the squared modulus of the elements of the matrix product between **H** and **F**, (i.e. **Φ =H F**).

The achievable **SNIR** vector can be computed from the matrix $\mathbf{M} = \mathbf{H}\,(\mathbf{I} + \mathbf{H}^H\,\mathbf{H})^{-1}\,\mathbf{H}^H$. In particular, the i-th element of the **SNIR** vector, snr_i, is:

$$snr_i = m_{ii}/(1- m_{ii})$$

where m_{ii} is the i-th diagonal element of matrix **M**.

B. Channel Estimation

Precoding strategies requires good knowledge of the channel matrix **H** for the set of served UTs. This is all that is needed in case simple channel inversion is considered (i.e. a strategy which we may consider the equivalent of the decorrelator in CDMA multiuser detection). Algorithms like *MaxMin*, *MaxThroughput* and *UpConst* also require knowledge of the noise (plus external cluster interference) variance (or equivalently the of the normalization factor **Λ** in the channel matrix **H**).

The estimation of the matrix **H** can be done either by using an external calibration network which measures the beam patterns on ground through suitable calibration signals (e.g. low power spread spectrum signal, one for each beam) or using directly the communication stations (i.e. the UTs) for the measurements.

The second alternative was considered here as it may potentially reduce the total system cost as the additional complexity imposed on the UTs is actually quite limited. In such alternative a FL signal format as in Figure 2 has been considered.

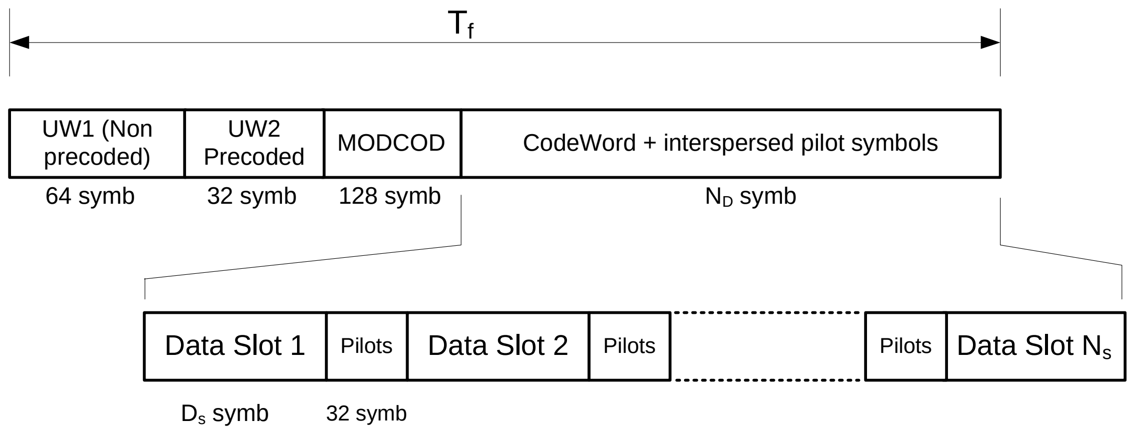

Figure 2. Forward Link TDM carrier frame format

As already mentioned, the assumption of having one TDM carrier per beam was considered. The TDM carrier is organized in constant length frames (frame duration, T_f). Each frame starts with two Unique Words (UW1 and UW2). The first UW (UW1) is not precoded and is used to estimate the channel matrix and the noise (plus external cluster interference) variance.

UW1 is also usable by UTs for frame synchronization and (coarse) frequency synchronization. At this regard, the assumed constancy of the frame length would easy such process.

The sequence of UW1 used by the GW for each of the served beams of the cluster can be written in the form a matrix, **C**, having K rows (the number of served beams) and L column (the length of the UW1 sequence).

Hence we can write the following matrix equation:

$$\mathbf{Y}=\mathbf{H}\,\mathbf{C}+\mathbf{N}$$

where now **Y** is a matrix whose *i*-row represents the sequence of sample received by the UT#i during the UW1 section of the frame.

Similarly row-i of matrix **N** represents the sequence of noise samples at UT#i in the same period. Each receiver obviously has only knowledge of one row of matrix **Y**, i.e.:

$$\mathbf{y}_i=\mathbf{h}_i\mathbf{C}+\mathbf{n}_i$$

where $\mathbf{h}_i$ represent row *i* of matrix **H** and $\mathbf{n}_i$ represent row *i* of matrix **N**.

Each station can thus estimate a row of the **H** matrix (the one which is relevant for that station itself) by postmultiplying the row vector $\mathbf{y}_i$ by the matrix $\mathbf{C}^+$ (the pseudo inverse of **C**):

$$\mathbf{y}_i\,\mathbf{C}^+=\mathbf{h}_i\,\mathbf{C}\,\mathbf{C}^+ + \mathbf{n}_i\,\mathbf{C}^+ = \mathbf{h}_i+\mathbf{n}_i\,\mathbf{C}^+$$

Hence each UT can estimate a row of the matrix **H** by postmultiplying the sequence of samples received during the UW1 period by the matrix $\mathbf{C}^+$ of the pseudo inverse of the UW1 sequences, i.e.:

$$\tilde{\mathbf{h}}_i = \mathbf{y}_i \, \mathbf{C}^+$$

These measures can be fed-back to the GW which can then construct the whole **H** matrix to be used for precoding computation.

The covariance, $\mathbf{\Sigma}_i^2$, of the estimation error affecting each element of the row $\tilde{\mathbf{h}}_i$ is:

$$\mathbf{\Sigma}_i^2 = [\mathbf{C}^H (\mathbf{C}\mathbf{C}^H)^{-1}]^H E\{ \mathbf{n}_i^H \mathbf{n}_i \} \mathbf{C}^H (\mathbf{C}\mathbf{C}^H)^{-1} = (\mathbf{C}\mathbf{C}^H)^{-H} \sigma^2 \mathbf{I}$$

where the relation $\mathbf{C}^+=\mathbf{C}^H(\mathbf{C}\mathbf{C}^H)^{-1}$ has been used for the pseudo inverse together with the assumption that the noise (plus external cluster interference) has constant power σ^2 during the UW1 preamble. Further, independence of the noise samples from symbol to symbol has also been assumed.

If orthogonal preambles are used in each beam then $\mathbf{C}\,\mathbf{C}^H = \mathbf{I}$ and $\mathbf{\Sigma}_i^2 = \sigma^2 \mathbf{I}$. With random preamble sequences the estimation errors affecting each element of the estimated channel matrix are slightly correlated as $\mathbf{C}\,\mathbf{C}^H$ is not any more equal to the identity matrix.

For computation of the precoding matrix with MMSE-based methods, an estimate of the variance of vector **n** is also required.

As already mentioned several times, vector **n** shall include, in addition to thermal noise also interference from external clusters (but not intra-cluster interference).

The total SNIR (including the intra-cluster interference) can readily be computed on the UW1 sequence with classical SNIR estimator algorithms, e.g. with the DA-SNORE algorithm [13].

According to this algorithm the signal and noise (plus external and internal cluster interference) power at user *i* with respect to signals from beam *j* would be estimated as:

$$P_s^{ij} = (1/L)\mathbf{y}_i \mathbf{C}_j^H$$

where $\mathbf{C}_j$ is row *j* of the matrix **C** of the UW1 sequences.

The noise (including external cluster interference) can be thus estimated as:

$$P_n = \mathbf{y}_i \mathbf{y}_i^H - \sum_{j=0}^{K} P_s^{ij}$$

It shall be finally observed that, in order that the above channel estimation strategy be effective, the measurement reporting period between UTs and the GW shall be sufficiently frequent with respect to the channel dynamic to avoid significant channel variations between two successive measurements (at least for active UTs). At this regard the requirements are the same as for the SNIR estimator with an ACM transmission scheme like DVB-S2. A problem with Precoding is however that the different feeder link chains (represented by the diagonal **G** matrix in eq. 1) shall also not change appreciably between measurements. At this regard, relative amplitude variations in the elements of matrix **G** are typically very slow as they are produced by aging and / or thermal effects. Vice versa, minimization of the relative phase variation between different feeder link chains requires the use of a common frequency reference for all frequency conversion on-board.

C. Channel non-Linearity Effects

Channel non-linearity represents the other important issue to assess for evaluating Linear Precoding feasibility on the FL of a star-network satellite system. Linear Precoding, in fact, results in significant envelope fluctuation affecting the signal to be transmitted from each beam even when constant envelope modulations are used. The signal coming out from each beam transmitter is in fact, the linear combination of multiple signals (i.e. all those belonging to that beam cluster). This implies that it is not possible to operate the on-board HPA close to the saturation as it is normally done in conventional systems when a single TDM carrier per beam is used. The HPA back-off required by Linear Precoding is thus a draw-back which may potentially reduce the attractiveness of such technique. The increased HPA back-off requirement, in fact, reduces the efficiency with which DC power is converted in RF power. Hence, for the same DC power, less RF power is available with a negative impact on the achievable system throughput.

Current evolution of high capacity, multibeam satellite systems is however going towards the adoption of active Tx antennas where each on-board HPA is not any more associated to a single beam but instead to a single antenna feed which is in turn used for implementing multiple beams, e.g. through the use of a phased array antenna or a so-called AFR (Array Fed Reflector) antenna. These more advanced antenna solutions have the advantage of allowing a higher flexibility as the available on-board power can be easily reallocated where traffic demand arises.

This is a particular important problem for multi-beam satellites where it is difficult to foresee the traffic requirements of each beam. This problem is so important that Multi-Port Amplifiers (MPAs) have been developed to allow flexibility in power reallocation even when a simple antenna configuration, i.e. one envisaging a Single Feed Per Beam (SFPB), is used. MPAs are, anyway, also used in conjunction with AFR antennas to further improve the power reallocation capability of the system.

In satellite systems employing either MPAs or active antennas (or both), the HPAs are always operated in multi-carrier mode. So there should be no further penalization due to the use of Linear Precoding in such scenarios.

The performance with Linear Precoding in a scenario where an 8x8 MPAs configuration is used has been simulated through a transmission simulator program [10, 12]. In addition, also the performance of a conventional system where HPAs are used in multi-carrier mode (4 or 8 carriers per beam) has been simulated. This last configuration was justified by the fact that it may not be possible in high capacity systems (with large number of beams) to operate with a single carrier per beam as the carrier baud rate may become excessive with respect to the available receiver processing capability.

From the waveform simulations in non-linear channel it was verified that in the worst case the non-linearity degradation with Precoding is less than 1 dB (with respect to performance in a linear channel) assuming to operate the HPA at an OBO of 3 dB. For the sake of performing a conservative comparison between system performance with and without Precoding we have thus assumed that Precoding incur in an additional 0.5 dB degradation with respect to the non-precoded case.

D. System Performance

System throughput and availability with and without the use of Linear Precoding have been evaluated in the system scenario summarized in Section II. A three-color frequency reuse pattern was used for the conventional processing system. Different frequency reuse patterns as well as cluster organizations were investigated for the Linear Precoding option.

Most of the simulation results here shown have been obtained partitioning the 88 beams in 11 clusters of 8 beams each. If not otherwise stated, the cluster organization of Figure 3 has been used in the simulations. The reason why clusters of 8 beams have been used is related to the bandwidth requirement of the feeder link. If a larger cluster size would have been employed, then a single GW per cluster would have not been possible given the bandwidth constraint on the Feeder Link. However, a larger cluster could be actually possible if either a smaller total user link bandwidth is considered or multiple GWs per cluster, each managing a smaller segment of the total User Link bandwidth, are deployed. In this last case, obviously, the GWs shall be accommodated in different feeder link beams which are sufficiently spaced to allow the reuse of the same feeder link bandwidth.

Results shown here are based on the simulation of a large number of UTs dispersed in the coverage area of the satellite. Each terminal is subject to a random tropospheric fading computed according to the ITU rain fading model of Rec. P.618 [14]. At each simulation step one UT station per beam is randomly selected for transmission. Each GW will then compute the precoding matrix for the scheduled UTs according to the resulting Beamforming matrix (which is user location dependent) and the time-varying channel conditions of those randomly selected users. Obtained performances are then actually the average over all possible patterns of UT combinations and propagation conditions.

Using Linear Precoding in conjunction with full frequency reuse we got a throughput of 22.3 Gbit/s (against 18.55 Gbit/s for the reference system using conventional processing and a three-color frequency reuse pattern). The average availability result was however only 84.63% averaged over time and space. Table 4 reports such results and the reference results obtained for the conventional processing case with the three-color frequency reuse pattern.

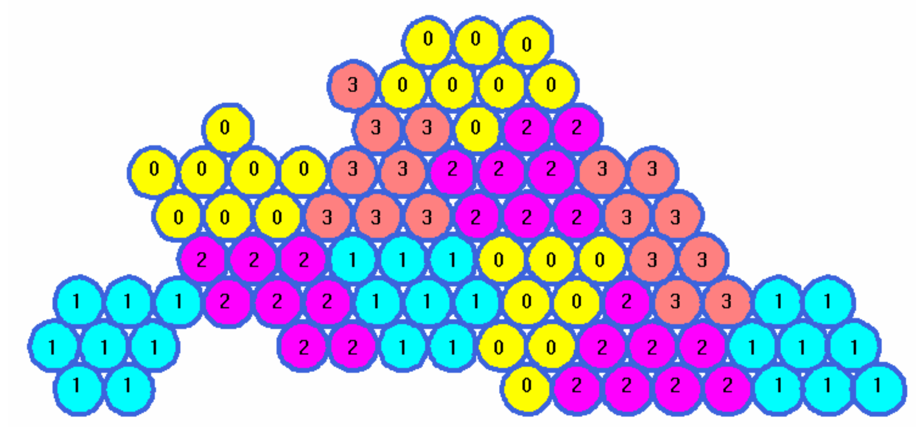

Figure 3. Cluster definition.

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	Precoding		
	11 Clusters of 8 Beams	Single Cluster	Conventional
Availability	84.63%	98.53%	99.887%
Throughput	22.3 Gbit/s	28.8 Gbit/s	18.55 Gbit/s

Table 4 Performance Results with Uniform Traffic. The conventional system uses 3 color frequency reuse whilst full frequency reuse is adopted with precoding

It shall be observed that the precoding advantage in terms of provided system throughput, although limited in these simulations, can be increased with further increase of the on-board power. In fact, with precoding, three times more bandwidth is available if full frequency reuse is adopted. However, given the fact that simulations were done for equal total on-board power, the power per carrier is reduced by a factor three in the precoding case with respect to the conventional case. This also explains part of the decrease in the availability as, with precoding, there is less margin between the clear sky operating mode and the most protected operating mode (QPSK with rate ¼ in our simulations). Clearly availability also decreases for the effect of uncompensated interference especially at cluster borders as it is clearly shown in the availability map of figure 4. From that availability map it is readily apparent how low availability zones are those at the cluster borders due to the fact that precoding cannot mitigate inter-cluster interference.

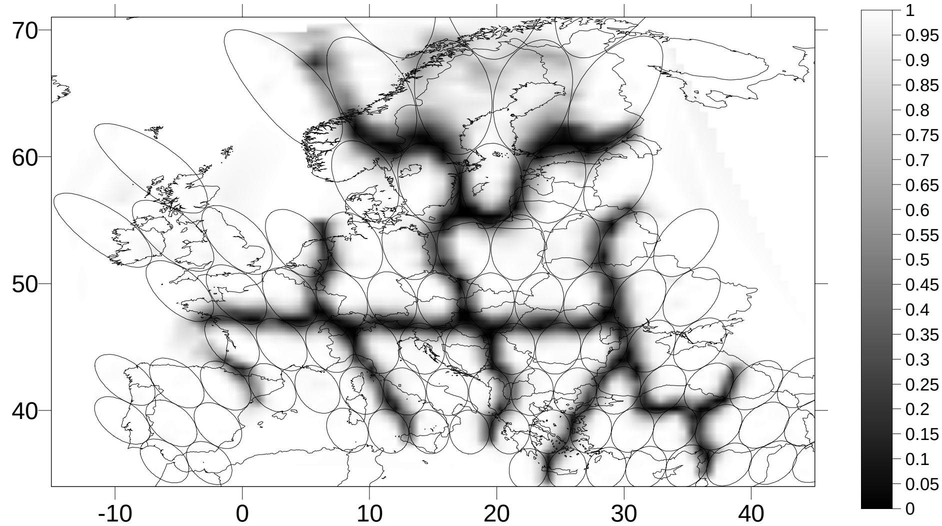

Figure 4 Availability Map

If a single cluster of 88 beams would have been used, instead, a remarkable performance improvement, both in throughput and availability, would have been achieved (see Table 4 and availability map of Figure 5). In particular, the throughput improvement allowed by precoding (with respect to the throughput of the reference system with three-color frequency reuse) would be higher than 55%.

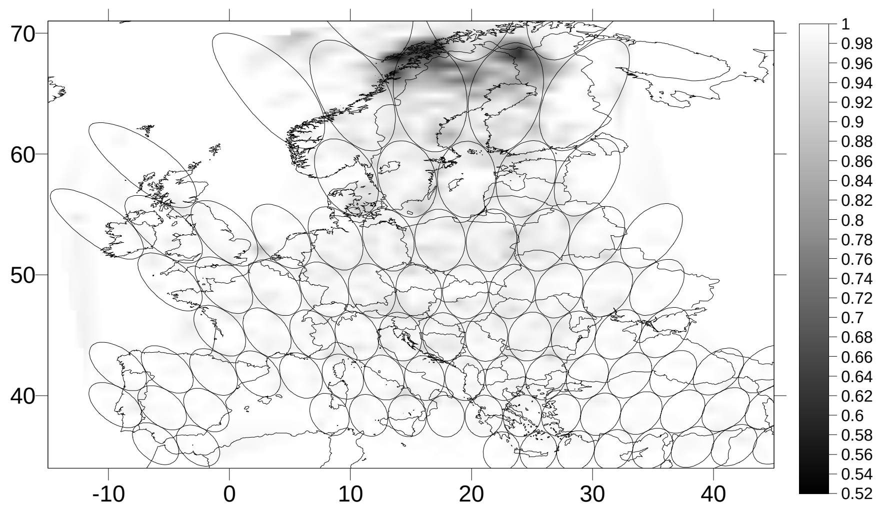

Figure 5. Availability map for the case of a single Cluster with 88 beams

To avoid the performance degradation at the cluster border, an ad-hoc frequency plan was also simulated. In such a case we maintained the repartition of the beams in 11 clusters of 8 beams. However we avoid reusing the same frequency slot in adjacent beams belonging to different clusters. The baseline on-board power was adopted (see Table 2).

The obtained performances for such ad-hoc frequency plan are shown in Table 5 (see column labeled "Perfectly Known Channel Matrix"). A throughput increase of about 30%, with respect to the conventional system with 3-colours frequency reuse, has resulted using the baseline on-board power hypothesis. Figure 6 reports on the resulting ACM mode usage statistics for the case where Precoding was adopted.

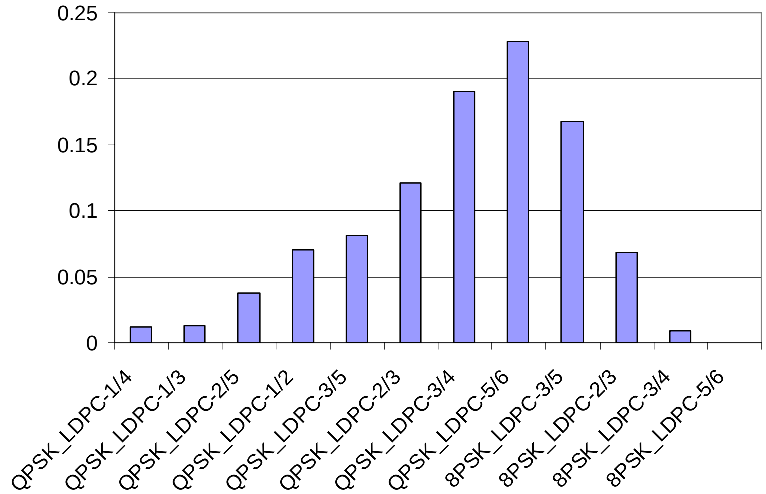

Figure 6. ACM Mode Usage with the ad-hoc frequency plan. Baseline on-board power option.

The effects of imperfect channel matrix estimation have also been evaluated, assuming that orthogonal training sequences are used for that scope. To understand the effect of such errors we repeated the simulation of the AFR payload configuration with the ad-hoc frequency plan. The performance loss is documented in. About 2.5% decrease in capacity results for case of preamble length equal to 64.

	Perfectly Known Channel Matrix	With Channel Estimation Errors	
		64 symb.	128 symb.
Availability	99.71%	99.60%	99.66 %
Throughput	23.85 Gbit/s	23.24 Gbit/s	23.54 Gbit/s

Table 5 Comparison of performance between ideal channel estimation and channel estimation based on known preamble sequences. An ad-hoc frequency plan, avoiding the use the same frequency in adjacent beams belonging to different clusters, has been used.

Finally, to assess the sensitivity of precoding performance to on-board power we have repeated the simulations for both the conventional system (using three-color frequency reuse) and for the Precoded case (with 11 clusters of 8 beams) assuming 4.77 dB more on-board power. Table 6 shows that the throughput advantage of precoding versus the conventional system is significantly increased in such conditions. For the case of full frequency reuse the availability with precoding is still limited by the intercluster interference. Availability with precoding is however on par with that of the conventional system with three-color frequency reuse when the ad- hoc frequency plan is used. The throughput advantage of precoding with respect to the conventional system increases to 36% in such a case.

	Linear Precoding		Conventional
	Full Freq. Reuse	Ad Hoc Frequency Plan	
Availability	86.3%	99.87%	99.917%
Throughput	27.7 Gbit/s	29.57 Gbit/s	21.8 Gbit/s

Table 6 Performance with 4.77 dB more on board power.

IV. Conclusions

The potentiality of advanced linear processing techniques for improving the capacity of satellite communication systems has been investigated. Throughput improvements greater than 50% are potentially available on the FL. Critical issues like channel estimation and on-board non-linearity have been shown to be manageable although non-linearity makes the precoding approach best suitable for payloads using an active transmit antenna, i.e. payloads in which beam power amplification is distributed over multiple feeds.

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