Perspectives Of Adopting Inteference Mitigation Techniques In The Context Of Broadband Multimedia Satellite Systems

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This paper presents an overview of possible interference mitigation techniques applicable to broadband multimedia satellite systems. A multi-star network architecture based on a multi-beam transparent satellite is considered and application of interference mitigation to both Forward Link (FL) and Reverse Link (RL) is discussed. Proposed techniques are however quite general and also applicable to regenerative satellite systems.

Nomenclature

ACM	=	Adaptive Coding & Modulation
BC	=	Broadcast Channel
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
LMMSE	=	Linear MMSE
MIMO	=	Multiple In – Multiple Out
MMSE	=	Minimum Mean Square Error
MPA	=	Multi-Port Amplifier
RL	=	Return Link
UT	=	User Terminal

I. Introduction

This paper presents an exploratory analysis of possible techniques for improving the channel capacity in modern multi-beam satellite systems. A transparent bent-pipe satellite architecture is assumed in conjunction with a multi-star network topology.

Quantitative system analysis have been performed assuming a European region coverage with 88 beams.

For the FL, techniques based on GateWay (GW) centralized precoding were examined assuming a TDM transmission strategy. It is shown that even a simple linear precoding technique can allow a significant improvement of the achievable spectral efficiency (> 50%) by using as much as possible full frequency reuse Achievable performances for some study case will be quantitatively assessed.

The constraints imposed by the precoding approach on the system will be assessed. A first problem is the need for a quite linear on-board HPA section. Degradation which may be incurred due to on-board non-linearity, evaluated via physical layer simulations, will be shown. Another problem is the need for system calibration. The implication of that will be briefly discussed.

For the RL a possible approach for interference mitigation is the use of a LMMSE detector with spatial processing. A potentially more performing approach is the use of joint detection techniques with spatial processing. These algorithms are able to achieve spectral efficiency close to the orthogonal limit even with full frequency reuse. In this paper, however we will only consider linear techniques as LMMSE.

The hypothesis here is to exploit when possible a full frequency reuse and mitigate the resulting interference from adjacent beams through a GW centralized spatial processing. In each beam, a single User Terminal (UT) per frequency slot is assumed, hence no intra-beam co-channel interference is present. A discussion of the complexity of the various approaches, of the consequent system constraints and of their compatibility with current physical layer standards, e.g. DVB-S2 and DVB-RCS, is also performed.

Quite remarking is the fact that even using the simple LMMSE solution a spectral efficiency improvement greater than 80% (gain would further increases with increasing UT powers) can be achieved on the RL when compared with a system exploiting a conventional, e.g. three-colours, frequency reuse. This solution is even compatible with current DVB-RCS systems and only require ad-hoc processing at the GW.

II. System Assumptions

In order to get some feeling of the potential gain provided by the proposed techniques a reference scenario was designed using a DVB-S2 ACM physical layer standard for the Forward Link (FL) and an ACM enhanced DVB-RCS access for the RL.

Clearly, the advantage provided by the Interference Mitigation (IM) techniques may be more or less significant depending on how the reference system is designed. Ideally, one should compare the cost per transmitted bit of each possible alternative system. However assessing the system cost is not trivial. We will take a pragmatic approach here in which we design a reference system according to current practice and then cast on that system the (IM) schemes to assess the improvement resulting in spectral efficiency.

Figure 1 shows the antenna coverage of the reference system assumed for the analysis. In particular, the European region was assumed as target coverage areas. 88 spot beams whose 3 dB beamwidth was approximately 0.5° were required to achieve the desired coverage area. For the reference system we assumed that a conventional frequency reuse based on a three-colours scheme is used in both the FL and RL.

We compared then the spectral efficiency available with the conventional scheme with that achievable by using the same total bandwidth but with full frequency reuse.

In this last case some means to counter-act the interference is obviously required. At this regard in this paper we will consider the use of linear precoding on the FL to mitigate the interference. Section III will illustrate the technique and provide some results on the potentiality of the technique. Section IV will address the performance achievable on the RL by using the LMMSE spatial processing technique.

Both on the FL and RL centralized Interference Mitigation techniques were employed. These techniques are thus implemented at the GW and no additional complexity is required at the UT side. With the proposed techniques the GW is able to only mitigate the interference generated by beams managed by them. Hence a given cluster of beams

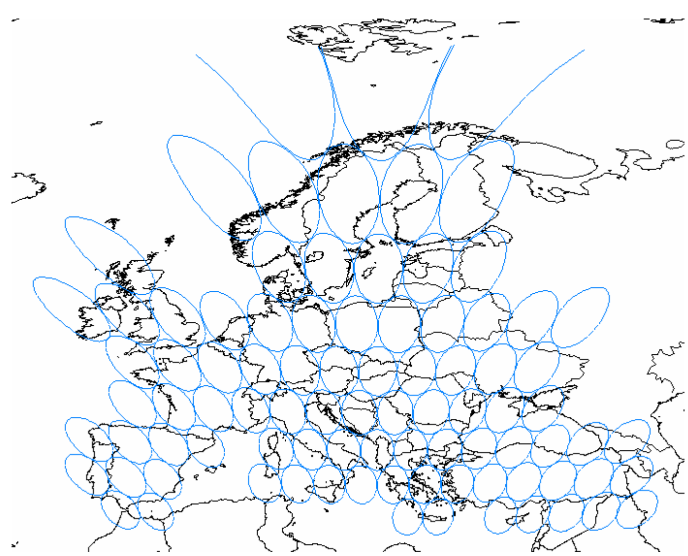

Figure 1. Assumed user link antenna coverage

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. Hence, in some of the evaluation below, and in particular in the RL, the available total bandwidth has been divided into two slots. Beams which are at the periphery of one cluster are allocated only one frequency slot to minimize the intercluster interference.

III. Forward Link

A. Algorithms

The idea of precoding has been explored to investigate the feasibility of improving FL spectral efficiency. 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) [1] 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 only consider linear precoding technique. To introduce such a technique let us show the signal model on the FL. 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 beam (and hence of users) equal to K. We also neglect the contribution of the up-link, which is here assumed ideal.

We can then write the signal received at any single instant at each receiver as a column vector of size K, $\mathbf{y}=\{y_1, y_2, \ldots, y_K\}^T$. We can then write:

$$\mathbf{y}=\mathbf{ABGx} + \sigma\mathbf{I} = \mathbf{\Lambda Hx} + \mathbf{I}$$

where **B** represents the beamforming matrix, i.e. the element b_{ij} of **B** represents the spacecraft antenna gain of beam i towards user j. **G** is a diagonal matrix representing the complex gain of the GW and on-board repeater chains. **A** is a diagonal matrix representing the complex fading on the down link toward each user. σ is the noise variance at each on ground receiver (assumed equal for all receivers*) and I is the identity matrix. The matrix $\mathbf{\Lambda}$ is the same as **A** but normalized with respect to σ. In the following we will also call the matrix **H** as the beam forming gain matrix although it also takes into account the effects of the repeater chains.

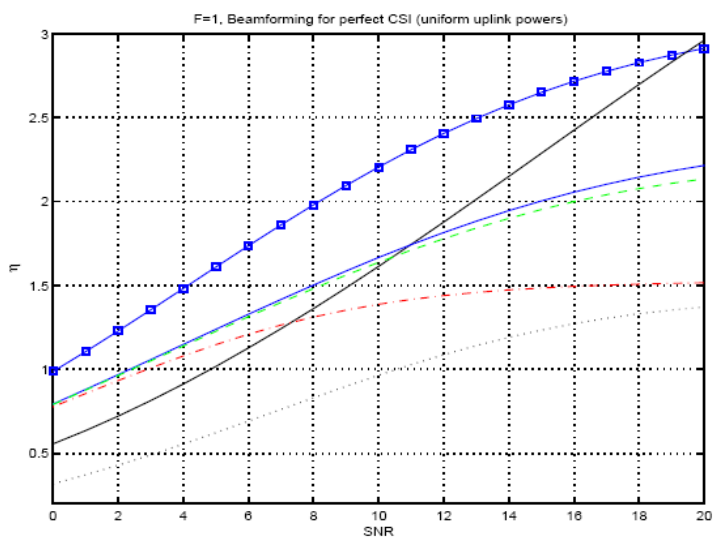

Figure 2 MMSE beamforming with dual uplink uniform power allocation. Solid, dashed and dash-dotted curves refer to Gaussian codes, ACM and QPSK. The upper solid line refers to the optimal DPC strategy with clustering and F = 2, the solid line with square marks refers to the optimal DPC strategy with full frequency reuse and the dotted line is ACM with three colour frequency reuse, for comparison.

In linear precoding schemes, the vector to be transmitted **x** is computed starting from the actual signal vector **s** through a linear transformation **x**=**F s**, where **F**, referred as the precoding matrix, is selected according to some optimality criterion.

It is apparent from the above equation that the SNIR ratio at the k receiver is:

$$SNIR_k = \frac{\left|\Lambda_k \mathbf{H}_k \mathbf{F}^k\right|^2}{1+\sum_{i\neq k}\left|\Lambda_k \mathbf{H}_k \mathbf{F}^i\right|^2}$$

where with $\mathbf{H}_k$ we indicate the k-th row of matrix **H** and with $\mathbf{F}^i$ we indicate the i-th column of matrix **F**. Also the assumption that $E\{\|s_k\|^2\}=1$ and that the s_k are uncorrelated with noise and between them is taken.

For the zero forcing (decorrelating) precoding, the matrix **F** is:

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

* Even with perfectly identical receivers the thermal noise level may differ due to the antenna temperature which depends on the atmospheric fading level. This is however inessential because we can adjust the diagonal matrix **A** to reflect the correct S/N ratio in all the receivers.

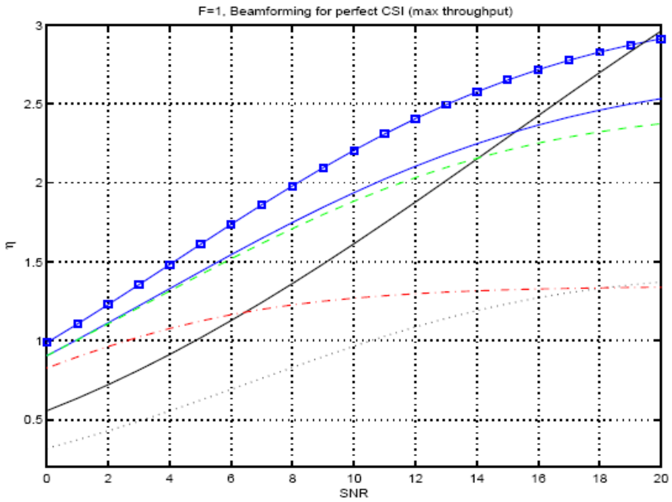

Figure 3 MMSE beamforming with max throughput power allocation. Solid, dashed and dash-dotted curves refer to Gaussian codes, ACM and QPSK. The upper solid line refers to the optimal DPC strategy with clustering and F = 2, the solid line with square marks refers to the optimal DPC strategy with clustering and F = 1 and the dotted line is ACM with F = 3, for comparison.

where $\mathbf{H}^+$ is the Moore Penrose pseudo inverse of the matrix **H** and **P** is a diagonal matrix $diag[p_1, p_2, \ldots p_N]$ introduced to possibly weight, according to some criteria, each component of the original signal **s**. For example, **P** could be selected to maximize the achievable throughput.

Another practical choice might be (regularized inversion):

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

where **H** is the channel matrix suitably normalized to the noise floor density and **P** is a diagonal scaling matrix having the same role as above.

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 the precoding algorithm as the MaxMin algorithm. The performance of the MaxMin algorithm are not optimum as it provide maximum fairness (as all user are given the same SNIR and hence the same rate) but at the expense of the overall maximum throughput achievable. A linear precoding algorithm which is optimum as far as the maximization of the user sum rate (given the constraint on the sum power) has also been devised [2] and will be referred here as the MaxThroughput algorithm.

Performance of these algorithms with the considered antenna pattern assuming full frequency reuse are shown in figure 2 and 3. It shall be recalled that the 88 beams are divided in 11 clusters of 8 beams with each cluster managed by a different GW. Precoding is performed by a GW on its 8 beams to mitigate intra-cluster interference. However, interference between clusters cannot be mitigated. From the figures it s apparent how the MaxThroughput algorithm has better throughput performance than the MaxMin one. Comparing figure 4 and figure 5 showing the cumulative distribution of rate per user and time slot, it is apparent that some of the user are not allocated any power by the GW when the MaxThroughput algorithm is used. This implies that the GW completely switch-off certain beams, in given time slots, if it detects that it can improve the total throughput by doing so. Clearly we have assumed that the on-board transmit section can flexibly allocate the power to the beams according to the needs (e.g. the use of a Multi-Port Amplifier or an active antenna is assumed).

B. Issues

Precoding strategies requires good knowledge of the channel matrix **H** for the set of served UTs. This is all which 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 and MaxThroughput also requires knowledge of the S/N ratios, i.e. of the diagonal matrix **A** (normalized to σ).

The channel matrix **H**, assuming a perfectly stable spacecraft, can be readily retrieved once the user position is known (as we can assume here, at least for fixed applications). In practice aging, thermal effects and satellite attitude variations may cause slow changes which has to be compensated by calibration procedures. If methods requiring knowledge of the S/N ratio are adopted also matrix **A** shall be estimated (only amplitude as phase is irrelevant).

To this purpose, channel measurements could be done at the UTs and fed back to the GW for tracking channel variations. This approach can be effective if channel variations are sufficiently slow with time in order that they can be tracked notwithstanding the loop delay. This is certainly the case of the beam pointing error variations and of the on-board repeater complex gain drift due to aging and thermal effects. However this might not be the case if independent oscillators are used on-board to perform signal frequency conversion. Generating all frequency starting from a common reference is a requirement for these techniques.

The matrix **H** can be measured via a network of calibration earth stations. Each calibration earth station shall be able to simultaneously (or anyway in close succession) measure the signals coming from all the relevant co-channel satellite beams, as the relationship (relative amplitude and phase) between the different beam signals are what are relevant here.
To minimize the number of such stations, only stations located in proximity of beam edges can be considered. Locating stations at the cross-over point between three beams makes the number of required measurement stations less than the number of beams.
As measurement signals, ad-hoc, spread signals can be considered[†]. Such signals can share the same band of the communication signal (e.g. DVB-S2) if their power is minimized in order to not disturb the main signal.
To avoid using ad-hoc measurement stations, selected UTs can be utilized to host the measurement processor which would operate independently from the traffic demodulator. Measurements will be then fed-back via any communication means which can be available, including terrestrial lines or as data messages on, e.g. a DVB-RCS connection.
Placing the measurement earth station at the cross-over between three beams minimize their number (which becomes less than the number of beams) whilst maximizing their ability in measuring relative amplitude and phase difference between multiple beams.

The measurement of the **A** matrix, when needed, requires that each UT measures its SNR. This could be done using the same SNIR measurement strategy as required by ,e.g., DVB-S2. However, due to precoding, the useful signal arriving at a UT may be degraded, if precoding was not optimized for such UT. Use of the same calibration spread spectrum signal would then be preferable for SNIR estimation.

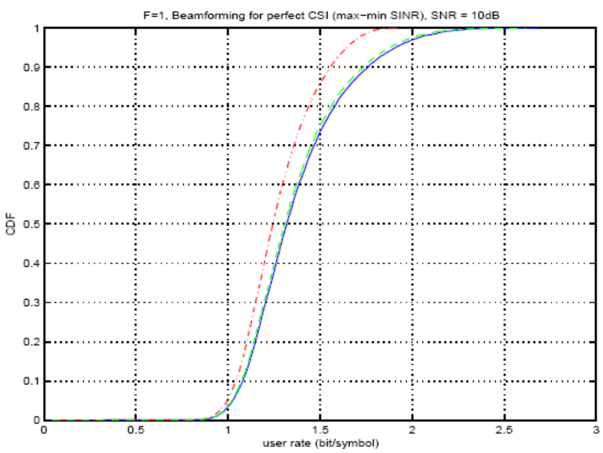

Figure 4 MMSE beamforming with max-min per user SINR power allocation. Solid, dashed and dash-dotted curves refer to Gaussian codes, ACM and QPSK.

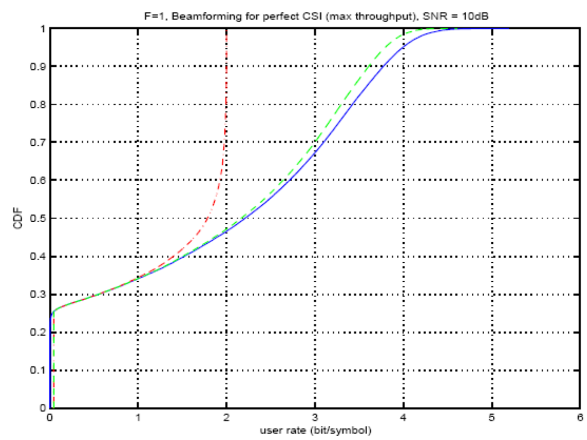

Figure 5: MMSE beamforming with max throughput algorithm. Solid, dashed and dash-dotted curves refer to Gaussian codes, ACM and QPSK.

C. Performance in non-linear Channel

Some simulation in–non-linear channel were done to assess the impact of non-linearity on precoding. Both a Multi-Port Amplifier (MPA) structure and a configuration with conventional multicarrier HPA were considered. In particular a cluster of 8 beams has been simulated and an 8x8 MPA or a single HPA with 8 carriers have been considered.
The investigation has confirmed that MPAs are not well matched to precoding characteristics, due to the signal correlation introduced by the precoding process. Due to such correlation the load of MPA is not equalized and this would bring each amplifier in the MPA group to work at a different back-off point.
Distributed amplification, not based on MPA principle, are thus better suited for use in conjunction with precoding. At this regard we tested the use of a single multicarrier HPA. In particular, most of simulations concentrated on the use of a linearized TWTA fed with 8 carriers. Total degradation can be limited to 4 dB, at least for the highest data rate carriers (8PSK with code rate 2/3 was used for such carriers).

[†] Using the same DVB-S2 signal for calibration purpose is probably not possible, because each station shall track the signals from multiple (at least 2) beams. This may not be possible (although different scrambling per beam can be used for DVB-S2).

Such a degradation appears quite reasonable when compared to analogous multicarrier configurations without precoding. It shall be also considered, in fact, that without precoding, the same spectral efficiency would require to operate with higher modulation levels (e.g. 16APSK instead of 8PSK) due to the need for bandwidth repartition between adjacent spots.

Figure 6 shows a snapshot of user location during a communication session. Some of the users are located at the beam edge and would suffer excessive interference in a conventional system (we are using here full frequency reuse between the beams).

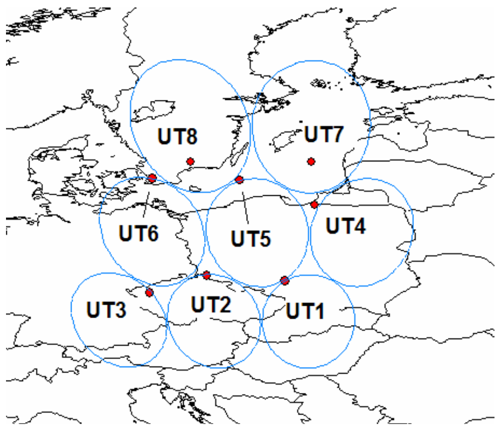

Figure 6 UT locations assumed in simulations

Using a linear precoding Up-Const algorithm (whose characteristics are intermediate between that of the MaxMin and MaxThroughput ones), under linear channel conditions, the scattering diagram of figure 7 and the SNIR quoted in table 1 would be achieved.

Example performance in a linearized TWTA (the AM/AM & AM/PM recommended in the DVB-S2 guidelines has been used) are shown for the best and worst UT (respectively UT#3 and UT#8) in figure 8 and 9.

For IBO equal 7 dB a total degradation of about 4 dB would result for UT#3. We can thus expect to limit the total degradation to about 4 dB at least for the best (and more important from the point of view of rate maximization) UTs of the group.

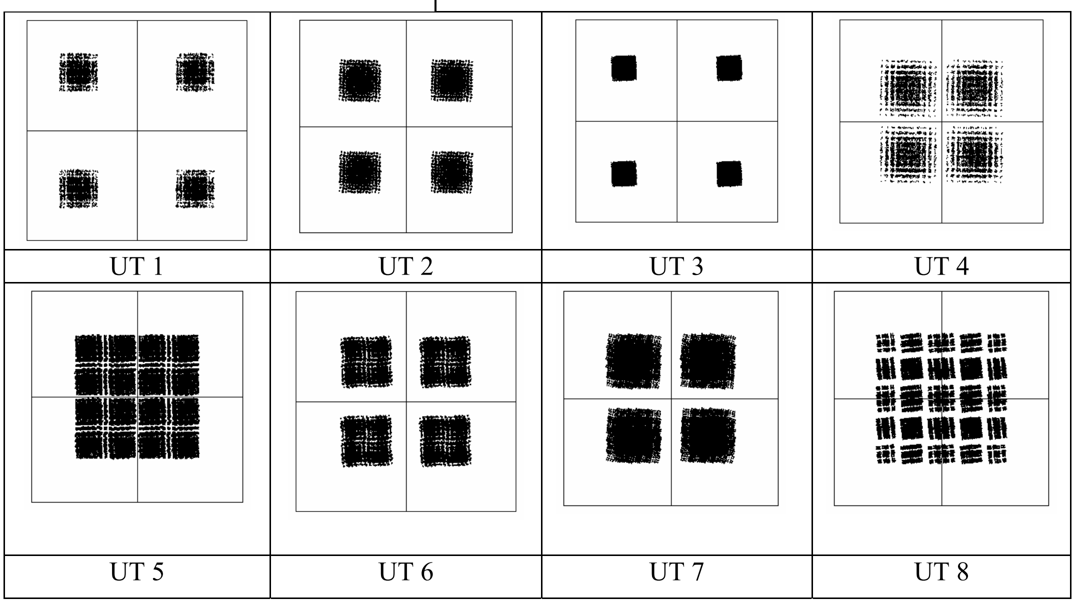

Figure 7 Scattering diagram in linear channelwith LMMSE UpConst algorithm in Figure 6 user location. Precoding computed assuming a noise floor at -13 dB with respect to average signal power.

	UT Achievable SNIRs (dB)							
Noise Floor	UT 1	UT 2	UT 3	UT 4	UT 5	UT 6	UT 7	UT 8
-21 dB	16.23	14.48	17.72	10.79	7.73	10.32	11.46	6.04
-16 dB	12.02	10.34	13.17	6.75	4.25	6.80	7.12	2.77
-13 dB	9.73	7.98	10.61	4.61	2.52	4.92	4.90	1.36
-10 dB	7.63	5.71	8.24	2.73	0.99	3.10	3.05	0.26

Table 1 Achievable SNIRs with LMMSE Up-Const algorithm in Figure 6 user location

For UT#8 the degradation appears somewhat larger than for UT#3. However, please note that results for UT#8 where obtained with QPSK rate 1/2. Probably a lower rate would have decreased the degradation. At this regard please note that, in the same channel conditions, the MaxThroughput algorithm would have been allocated a zero rate for UT#8.

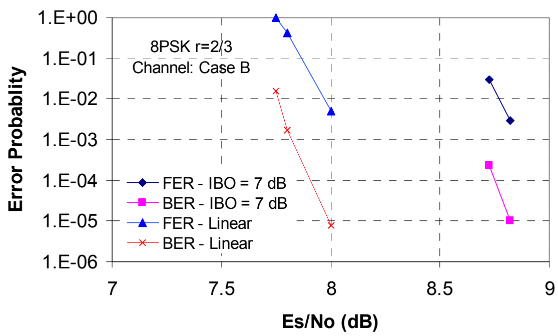

Figure 8 FER and BER performance in non-linear channel of UT#3 with UpConst precoder algorithm in figure 6 user location. 8PSK modulation and code rate 2/3 has been used. Linearized TWTA with 7 dB IBO has been used.

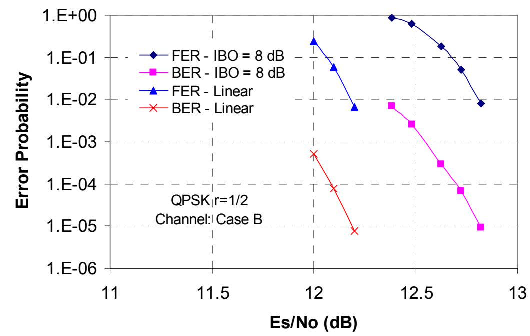

Figure 9 FER and BER **performance in non-linear channel of UT#8 with UpConst precoder algorithm in figure 6 user location. QPSK modulation, LDPC code rate 1/2, linearized TWTA with 8 dB IBO have been used.**

Clearly, with a different and more benign user location, much lower degradation could be obtained and a net gain from precoding available.

IV. Reverse Link

D. LMMSE Background and Performance

As mentioned a candidate solution for improving reverse link spectral efficiency is the use of a spatial processor LMMSE algorithm.

According to this algorithm each GW will receive, for each frequency slot, multiple signals, each one coming from a different beam. As usual we assume also here that a GW is in charge of managing 8 beams. We can write the signals more compactly in vector notation. Hence the signals received from each beam chain can be represented as a column vector, **y**, as the signals transmitted by the user terminals, one per beam, in each time slot which can be represented as column vector **x**..

We can then write the following equation relating the vector of received signals, **y**, to the vector of transmitted signals, **x**:

$$\mathbf{y} = \mathbf{GBAx} + \sigma\mathbf{I}$$

where:

- σ represent the noise power floor at each of beam chain receiver at the GW (assumed equal for all chain);
- **A** is a diagonal matrix expressing the up-link complex channel gain (it does take also into account possible up-link fading)
- **B** is the beamforming gain matrix. The element b_{kj}, of such matrix expresses the complex gain of beam k towards user j.
- **G** is a diagonal matrix whose diagonal element g_k. expresses the complex gain of the link from the on-board beam k receiver input to the GW. Such matrix takes into account the differential amplification and phase shifts of such different paths from each beam input to the GW processor.

The product **GBA** will be in the following indicated with **H** which will be also referred as the beamforming gain matrix.

To improve the performance, the GW can transform the received signal vector, **y**, through a matrix **F** to minimize the MSE between the obtained vector and the original transmitted vector **x**. Such matrix, **F**, representing the LMSSE solution to this detection problem, can be computed as:

$$\mathbf{F} = \left[\sigma^2 I + \mathbf{H}^H \mathbf{H}\right]^{-1} \mathbf{H}^H$$

It appears that the LMMSE filter does not depend on the signal phases but only require knowledge of the beamforming matrix **H** and the S/N ratios of each signal.

It shall be observed that no frame synchronization is in principle required by linear MMSE algorithms as they inherently operates symbol-by-symbol. Obviously, hardware complexity would be reduced by some form of frame

synchronization as computation of the MMSE filters need to be carried out only when a new burst start in any of the beams in the GW beam cluster.
Figure 10 shows an analysis of the achievable performances in a coverage like the one in figure 1. It appears that the performance of LMMSE are not very far from the performance which would be achievable in absence of interference or with an optimal non linear processing (optimal joint decoding) and are significantly better (80% or even higher at high S/N ratios) with the performance which would be achievable in a conventional system with three-colour frequency reuse (No MUD curve). The worst curve (SUMF) correspond to the so-called Single User Matched Filter receiver where matrix $\mathbf{F}=\mathbf{H}^H$ is used as detector. Its performance are worst then not doing nothing as the interference is not spatially white.

E. Issues

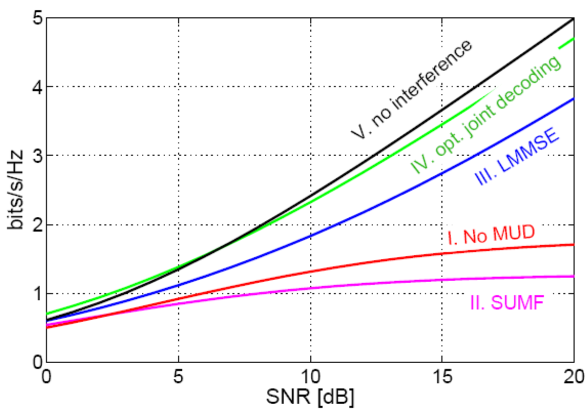

Figure 10 Spectral efficiency for several methods of receiver processing.

As already mentioned no frame synchronization between signals in different beams (managed by the same GW) is in principle required by linear MMSE algorithms as they inherently operates symbol-by-symbol. Obviously, hardware complexity would be reduced by some form of frame synchronization as computation of the MMSE filters need to be carried out only when a new burst start in any of the beams in the GW beam cluster.
Linear MMSE can be applied to every modulation format and even spread signals can be considered. As with all spatial processing algorithm there is the need of channel estimation. Channels has to be known for the algorithms to be effective.
The situation is quite specular to that on the Forward Link with the only differences that:
- relative phase variations between different signals can be faster due to the phase noise of UTs.
- signal fading may be different for the different signals.

As in FL case, also in this case a calibration measurement system has to be envisaged. The same stations used for measurement on the FL can be used on the RL to transmit a low-power spread spectrum signal (either superimposed on the useful signal bandwidth, or, given the relatively narrow bandwidth of typical RL access schemes like DVB-RCS, in a reserved frequency slot).

V. Conclusion

The potentiality of advanced linear processing techniques for improving the capacity of satellite communication systems has been investigated. Improvements larger than 80% are potentially available both on the FL and RL. To achieve such a potential gain accurate calibration is required. On the FL a further practical issue which may decrease the attractiveness of the proposed precoding technique is the effect of non-linearity. This problem will make the precoding approach likely attractive only in conjunction with a payload with an active Tx antenna where beam power amplification is distributed over all active feeds.

References

[1] G. Caire and S. Shamai, “Writing on dirty tape with LDPC codes,” in proc. DIMACS Workshop on Sig. Proc. for Wireless Transmission, Rutgers University, NJ, USA, October 2002.
[2] G. Caire, L. Cottatelluci, M Debbah, G. Lechner and R. Muller “Interference Mitigation Techniques for Satellite Systems,” TR1 / TR2 Report of ESTEC Contract No. 18070/04/NL/US “Novel Intra-System Interference Mitigation Techniques &Technologies for Next Generations Broadband Satellite Systems”, April 2005