EFFECTS OF CHANNEL PHASE IN MULTIBEAM MULTICAST SATELLITE PRECODING SYSTEMS

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Abstract

This paper revisits the impact of channel phase in multibeam multicast satellite precoding. First, we analyze the unicast case showing that the phase components relative to the different slant paths to each user do not affect the precoding performance. Then, we indicate that for the multicast transmission, the mentioned phase effect may have impact depending on the employed clustering technique. Finally, we propose an alternative clustering solution based on normalizing out the phase components relative to the different slant paths. According to our simulation results, this novel clustering technique provides robustness to these phase components and also behaves better than previously reported clustering schemes.

1 Introduction

Precoding techniques in multibeam satellite systems enable full frequency reuse resulting in a significant capacity increase with respect to standard four or seven colour schemes. Due to the large pathloss, these systems use long codewords including data addressed to multiple users; hence, precoding techniques must deal with the multicast nature of the transmission [1].

Multicast precoding and user clustering has been widely addressed in the literature [1]-[3]. Interestingly, all these works showed a significant impact of the phase of the channel coefficients on the performance of multicast precoding and, in particular, of the phase components corresponding to the different slant paths (i.e distance between satellite antenna and user) experienced by each user. In particular, the authors in [2] directly addressed this issue, concluding that the most critical parameter in multicast precoding was the outdated slant path phase estimation, which introduced errors in the prediction of channel phase components related to the slant paths, thus related with satellite movements in one-second time-frame. These results were obtained grouping the users based only on the magnitude of the channel matrix coefficients, which is equivalent to form groups of closely located users in the geographical sense [1]-[2].

The authors in [1] and [3] showed that the performance of multicast precoding can be increased by taking also into account the phase of the channel matrix components in the user grouping process, which is done by means of the Euclidean distance. Let us remark here that in all these works, the virtual channel coefficients relative to one group is obtained as the arithmetic mean of the channel coefficients corresponding to all users within the group.

In this work we investigate the impact of the different channel phase components in multicast multibeam satellite precoding. The initial motivation was the fact that each user presents the same spatial signature to the satellite feed-array since the slant path from a single user to any of the satellite feeds in the satellite is assumed to be the same, due to the large distance between satellite and Earth. Bearing this in mind, it was initially expected and here demonstrated that phase components due to slant path do not affect unicast precoding at all.

In view of this, we analyse the multicast case and illustrate that the reported impact on multicast transmissions is caused by how the group equivalent channel vector is obtained (i.e. averaging the different channel vectors of users belonging to the same cluster), which artificially change the channel matrix structure. As discussed in the paper, this technique introduces different spatial signatures for each user (i.e. the phase coefficient for a single user to all antenna feeds is different). In order to solve this problem, we propose an alternative clustering technique based on normalizing out the phase component due to the slant path, which not only provides robustness to outdated slant path phase estimation issues but also provides higher system performance.

The paper is organized as follows. Section II describes the system model; Section III analyses the sensitivity of unicast precoding to channel phase estimation errors and Section IV proposes and evaluates the alternative clustering solution. Finally, Section VI concludes the work.

2 System model

We focus in the forward link of a GEO satellite, in which a multibeam system with \( N \) beams serves \( K \) uniformly distributed users on the Earth surface. The \( K \times 1 \) received vector containing the stack of received signals at all user terminals writes as

\[
y = H_s W s + n, \tag{1}
\]

where \( H_s \) refers to the \( K \times N \) channel matrix; \( W \) is the \( N \times K \) precoding matrix; and \( s \) denotes the \( K \times 1 \) vector containing the stack of \( K \) information symbols intended for the \( K \) user.
2.1. Channel Model
The components of the channel matrix $H_o$ write as

$$[H_o]_{kn} = [\bar{H}_o]_{kn} e^{(j \varphi_{PLn})} e^{(j \varphi_{LNBk})},$$

where $\lambda$ is the wavelength; $r_k$ refers to the slant range to user $k$; $\varphi_{PLn}$ accounts for the phase deviation of the payload oscillator related to the $n$-th antenna feed, which is modelled as a Gaussian random variable with zero mean and $\sigma_{PL}=20^\circ$ [2]; $\varphi_{LNBk}$ accounts for the phase deviation of the oscillator of the low noise block (LNB) of user $k$, which is modelled as a Gaussian random variable with zero mean and $\sigma_{LNB}=0.24^\circ$ [2].

2.2. Precoding strategy

With respect to the precoding matrix $W$, we follow the heuristic approach of [2], in which the so called Minimum Mean Square Error (MMSE) precoder is normalized in order to fulfil per beam power constraints, i.e. the maximum power available at each beam is $P_{max}$. In this way, the unnormalized precoder writes as

$$U = (H^H H P_{max} + I_k)^{-1} H^H.$$  

In order to fulfill the per beam power constraints, we first normalize the columns of $U$ so that the total power transmitted to each user is 1. Expressing $U$ as a collection of column vectors $u_k^T$

$$U = [u_k^T, ..., u_k^T],$$

the columns of the precoder $C$ after column normalization can be written as

$$\forall k \quad C_k^T = \frac{u_k^T}{||u_k^T||}.$$  

Then we normalize the rows of the matrix resulting of (6) so that the total power transmitted by each beam is $P_{max}$. Expressing $C$ as a collection of row vectors $C_n^T$

$$C = [c_n^T, ..., c_n^T]^T,$$

the rows of the normalized precoder $W$ can be written as

$$\forall n \quad W_n^T = \frac{c_n^T}{||c_n^T||}.$$  

And so the normalized precoder can be collected as

$$W = [w_1^T, ..., w_N^T]^T.$$  

It is worth mentioning here that this solution forces each beam to transmit at its maximum available power, though the interference mitigation properties of the unnormalized precoder are not fully preserved. Still, for the Signal-to-Noise Ratio regimes evaluated in this work, it was found to perform better than other power normalization solutions.

2.3. Multibeam system and performance metrics
The multibeam satellite system considered here consists of 245 beams over Europe, which footprints at -4.3 dB are shown in Fig. 1 and which gains were provided in [4]. Other system parameters are defined in Table 1.

| Parameter          | Value          |
|--------------------|----------------|
| Frequency          | 20 GHz         |
| Bandwidth (BW)     | 500 MHz        |
| $P_{max}$          | 17.4 W (12.4 dBW) |
| User G/T           | 17.94 dB/K     |

Table 1 System parameters

![Image](Fig. 1 4.3 dB contour of the 245 beams over Europe)

The system will be evaluated through its average sum rate across the whole coverage, which in the unicase, can be expressed as
\[ R_s = BW \sum_k \log_2 (1 + SINR_k). \]  
(10)

where \( SINR_k \) to the Signal-to-Interference-plus-Noise Ratio of user \( k \). In the multicast case, the expression becomes

\[ R^M_s = BW \sum_c \log_2 (1 + \min(SINR_{k \in c_k})). \]  
(11)

where \( c \) refers to the cluster index.

3 Unicast

In the unicast case, we assume that a single user is randomly selected and served within each beam. In order to analyse the sensitivity of the precoding to the estimation of the different phase components in \( H_o \) (i.e. the real channel matrix) we consider that the channel matrix for precoding calculation in (4) is not directly \( H_o \) but

\[ \tilde{H}_o = \Phi_{err} H_o \Phi_{err} \]  
(12)

where \( \tilde{H}_o \) denotes the estimated matrix during the channel acquisition process, which is affected by phase estimation errors. In particular, \( \Phi_{err} \) is a \( K \times K \) diagonal matrix whose entries present modulus one and their phase is modelled as a random Gaussian random variable with zero mean and standard deviation \( \sigma_{us} \). It accounts for estimation errors related to the relative position user-satellite or to the phase deviations in the LNBs, thus related with the second and third phase terms in (2). Note that these phase errors are constant across rows of \( \tilde{H}_o \), keeping the channel matrix structure unaltered. Similarly, \( \Phi_{err} \) is an \( N \times N \) diagonal matrix whose entries present modulus one and their phase is modelled as a random Gaussian random variable with zero mean and standard deviation \( \sigma_{pl} \). It accounts for estimation errors related to the deviations in the payload oscillators, thus related with the first phase terms in (2). Let us also remark that these phase errors are constant across columns of \( \tilde{H}_o \).

Fig. 2 analyses the sensitivity of precoding to both types of phase errors in an independent manner, thus keeping the other phase error contribution equal to 0.

It can be observed that the resulting sum rate across the whole coverage is only affected by \( \Phi_{err} \), corresponding to the estimation of the phase deviations in the payload (i.e. phase components constant across the columns of \( \tilde{H}_o \)), but not by any phase component constant across the rows of \( \tilde{H}_o \) corresponding to \( \Phi_{err} \), hence related to the users’ position or characteristics. Bearing in mind this result, it is interesting to reconsider the effects of the later phase components in the case of multicast transmission, since they were found to be the most critical aspect in multicast precoding [2]. It is worth remarking here the precoder is fully able to deal with the phase deviations in the payload if they are properly estimated [2].

4 Multicast

In the multicast case, several users are grouped together and served within the same codeword (i.e. frame) at each beam. The user grouping/clustering process usually consists of three main steps[1]-[3]: (i) select the initial user that will form the cluster; (ii) select the set of users more similar to the initial one; (iii) collapse the rows of the channel matrix of all users in a cluster to a single row representing the whole cluster. This results in a \( N \times N \) matrix (denoted here as \( H_c \)), since one cluster is formed for each beam. Then the precoding expressions (4)-(9) can be calculated using \( H_c \).

For step (i), we will just randomly select a user within each beam. In [3], it is shown that this approach is not complete fair, and provides an upper bound of the performance of more realistic approaches. However, it is used here for simplicity since it does not affect any of the performance comparison that are performed next.

For step (ii) we consider two widely used alternatives. On the one side, calculating the user similarity based on the n-dimensional Euclidian norm of the difference of the complex channel vectors under investigation. Expressing \( \tilde{H}_o \) as a collection of row vectors \( \tilde{h}_{ik}^T \)

\[ \tilde{H}_o = [\tilde{h}_{i1}^T, ..., \tilde{h}_{iK}^T]^T \]  
(13)

this similarity operation becomes \( ||\tilde{h}_{ik}^T - \tilde{h}_{ij}^T|| \).

On the other hand, calculating it based on the n-dimensional Euclidian norm of the difference of the magnitude of the channel rows, i.e. \( ||\tilde{h}_{ik}^T|| - ||\tilde{h}_{ij}^T|| \), which corresponds to a geographic user clustering as described in [2].

For step (iii) the works in [1]-[3] propose to perform an arithmetic mean across the complex channel rows corresponding to the users in a cluster. Therefore

\[ H_c = \left[ \frac{1}{K_c} \sum_j \tilde{h}_{oj}^T, \cdots, \frac{1}{K_c} \sum_j \tilde{h}_{oj}^T \right]^T \]  
(14)

where \( K_c \) denotes the number of users per cluster and \( c_o \) refers to the cluster index.
As a consequence of this operation, it can be easily checked that the phase structure of $H_c$ differs to the original $H_o$. In particular, $H_c$ is not formed by a phase component constant across their columns (i.e. first phase term in (2)) and a phase component constant across their rows (i.e. last two phase terms in (2)). Indeed, each cluster presents a different phase signature to each of the satellite beams. Therefore, after applying the precoder, we are pointing to virtual users which have no physical meaning, and which do not keep the phase characteristics of the cluster there are representing. This becomes the main difference with respect to unicast case and explains the already reported [1-3] sensitivity of multicast precoding to channel phase coefficients, as will be shown by numerical results.

In order to solve this issue, we propose to eliminate the phase components constant across the columns of $H_o$ before calculating the arithmetic mean of the channel rows. This can be done by using an auxiliary matrix $H_{aux}$ in which the phase coefficients at each column are normalized by the phase coefficients of the first column. Expressing $H_o$ as a collection of column vectors $\mathbf{h}_{c,n}$ the columns of $H_{aux}$ can be written as

$$\forall n \ h_{aux,n}^c = |\mathbf{h}_{c,n}^c| e^{j \mathbf{h}_{c,1}^c}.$$  \hspace{1cm} (15)

Then the user selection in step (ii) is done according to the Euclidian norm of the difference of the magnitude of the channel rows, i.e. according to a geographic user clustering.

4.1. Comparison of clustering techniques

In this section we evaluate the performance of the proposed method against that achieved by the traditional arithmetic mean in combination with user grouping based either on the Euclidian norm of the difference of the complex coefficients (denoted hereafter norm-based clustering) or of the coefficients magnitude (denoted hereafter as geographic clustering). In all cases we consider perfect CSI, so $H_o=H_c$.

Fig. 3 compares the three solutions as the number of users per beam (i.e. per cluster) grows from 1 to 10. The total number of available users per beam is set to 10.

The proposed method outperforms the others providing sum rate improvements at 4 users per beam of 30% and 47% with respect to geographic and norm-based user clustering, respectively. It can be also observed that, in contrast to previous works [1], [3], in this scenario the geographic clustering performs slightly better than the norm-based. Note however that precoder normalization and the SNR regimes used here are note the same as in those works.

Fig. 4 investigates the sensitivity of multicast performance to the available power per beam. In particular, it plots the average sum rates as the available power per beam (i.e. $P_{max}$) increases, fixing the number of users per cluster to 4 and the number of available users per beam to 10. It follows that the proposed method outperforms the methods based on arithmetic mean clustering for a large range $P_{max}$. The power sweep is limited below 15 dBW since, beyond this point, the power normalization in (5)-(9) is no longer providing the best results.

Finally, in Fig 5 we evaluate the sensitivity of the multicast performance to the available number of users per beam, keeping fixed the number of users served per beam/cluster to 4. As expected, the performance provided by the three methods increase with the increase in the number of available users since it permits clustering users with higher similarity. Still, the proposed method outperform the other two while the difference between geographic and norm-based increase as the number of available users increase.
4.2. Sensitivity to phase estimation errors

In this section we evaluate the robustness of the different methods to errors in the estimation of phase components corresponding to the slant path of each user, which were concluded to be the ones having a larger impact on the multicast performance [2]. Errors in the estimation of the phase components related to payload features are not considered here since they are constant across the columns of the estimated channel matrix, thus they are transparent to the method used for collapsing the different channel rows in a single one. Basically, the effects of these errors are similar in multicast and unicast cases. Therefore, we consider here that the estimated matrix $\tilde{H}_u$ expresses as (11) but fixing $\sigma_{\mu}=0$.

Fig. 6 compares the performances of the three methods as the standard deviation of the phase error increases. Interestingly, as shown by the solid lines, none of the methods results affected by the phase errors, though the proposed method keeps outperforming the other two. The reasons for the robustness to these phase errors are different for the three methods. Our proposed method is not affected at all by any phase component that remains constant across the rows of the estimated channel matrix, since they are normalized out. In contrast, the performance of the methods based on arithmetic mean is affected by the phase components related to the different slant paths even if they are perfectly estimated.

Indeed, as shown in Fig. 7, the channel phases due to the different slant paths (i.e. the second phase term in (2)) are already uniformly distributed between -180º and 180º, thus adding Gaussian phase errors does not impact the overall performance. In order to better exemplify this issue, in Fig. 6 we plot also the curves obtained when the second and third terms of (2) are neglected (see dashed lines), thus the phase components constant across the rows of $\tilde{H}_u$ directly follow the Gaussian distribution of $\Phi_{\mu}^{\mathbf{w}}$. The resulting curves for the methods based on arithmetic mean resemble those obtained in [2], with a decreasing performance with the increase of phase errors. Note that the uniform phase distribution due to the real slant paths represents, in fact, a worst case. In contrast, our proposed method keeps unaltered with the increase of phase errors.

![Fig. 6 Sum rate sensitivity to estimation errors in the phase components depending on users' position or features; solid lines: phase errors added to channel expression in (2); dashed lines: phase errors added to a channel expression neglecting the two last phase terms in (2)]

![Fig. 7 Histogram of the phases across one column of $\mathbf{H}_u$, which are related to the last two phase terms in (2), thus only depending on users' relative position or characteristics]

5 Conclusions and discussion

In this paper we revisited the impact of the phase of the channel coefficients to unicast and multicast satellite precoding. We first showed that unicast transmission remains unaltered by channel phase components that remain constant across the rows of the channel matrix, such as those related to the different slant paths of each user. Then, we illustrated that such phase components degrade the performance of multicast precoding when the channel rows of all users within a cluster are collapsed using the arithmetic mean. Finally we proposed a user clustering method, which outperforms those based on arithmetic mean since it is robust to these phase components. Indeed it is based on normalizing them out before collapsing the channel rows of each user cluster.

It is worth remarking here that the validity of these results are constrained to systems that could be modelled with the channel matrix expressed in [2]. Indeed, this model represents very well high frequency satellite transmissions to fixed earth stations. However, two concerns can be raised. On the one hand, in the case of a satellite system based on multiple reflectors, as considered in [5], the slant paths already create different phase signatures for each user to the beams on different reflectors, which cannot be normalized out as proposed here. On the other hand, beams created by reflector antennas are not only characterized by a beam pattern but also by a phase diagram pattern, which may end up introducing again different phase signatures for different users. Both aspects require a further study that will be object of future research.
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7 References

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