Transmission Systems

Beamforming for satellite communications in emergency situations

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SUMMARY

We consider a multi-beam Ka-band satellite communication system aimed at operating in emergency situations where terrestrial communications systems are no longer effective. In contrast to most systems which use one single beam to cover a large area, we study here the feasibility of a one beam per user concept, where a beamformer is calculated for each user. This should allow to guarantee the maximum antenna gain towards each user.

We assess the performance of the minimum variance distortionless response (MVDR) beamformer and of a beamformer using a training sequence in realistic scenarios including channel, steering vector and synchronisation errors. We show that both beamformers provide a sufficiently high output signal to noise ratio in a DVB–RCS system.

1. INTRODUCTION

In emergency situation or in the case of disasters (cyclone, flood, etc...), there is a vital need for communication services such as voice, video or useful data (logistical, medical data, support for stricken population...) in order to assist populations. In most cases, terrestrial communication networks have been destroyed, overflown or are no longer effective. This is why considerable interest has focused on satellite links as a mean to provide secure and high data rate communications in these situations [1, 2]. The system analysis proposes an emergency multi-service platform based on a dedicated payload, taken on board of a geostationary satellite as a piggyback [3, 4]. This small payload link low power transportable ground terminals located in disaster area to a central station in Europe or to other terminals in the disaster area. Transmissions must comply with European standards like DVB–S in downlink and DVB–RCS in uplink.

Typical coverage for such a mission should be of 1000 km (1.6° as seen from a geostationary satellite). Satellite antenna gain should be around 40–45 dB. Users terminals would have about 40 cm antenna diameters in order to be easily transportable.

In classical solution, coverage is provided with one single beam. Within the spot, users share resources either in time, frequency or code without reuse. Since a single spot is formed for a large area, the antenna is designed to have a maximum gain at the centre of the spot. Therefore, users on the edges of the spot are received with a smaller gain, usually 4 dB less than in the centre of the spot. This is an important drawback especially with low-power terminals.

It is anticipated that in forthcoming satellite communication systems the payload will include (when required by the mission) arrays antennas associated with on-board digital beamforming networks. These systems are able to generate a large number of high gain beams. For classical fixed multi-beam coverage, each beam covers a few 100 km wide region, which corresponds to a 1–2° beamwidth as seen from a geostationary satellite. However, the use of digital beamformer (DBF) makes it possible to form one beam
for each user, still improving performances. Maximum gain is guaranteed to each user and resource reuse can be envisaged.

In multi-beam satellite communication systems, existing antenna level trade off have shown that focal array fed reflector (FAFR) is usually the best solution for the reception antenna. The antenna reflector focuses the received signals on a reduced number of sensors. As antenna gain is determined by reflector size, this allows reducing the total number of elementary feeds as compared to a direct radiating array (DRA), and thus decreases antenna and beamforming network complexity, cost and burden.

In this paper, we study the feasibility of forming one spot per user (using a spatial division multiple access (SDMA) technique [5]) in order to provide the maximum gain on the whole coverage, and avoid gain differences between users located at the centre of the spot and users at the edges of the spot. Another interest is the possibility to reuse frequency or time resource. In Section 2, we describe our data model and discuss several beamforming techniques. Exploiting simulation results obtained in Section 3, a general strategy is proposed in Section 4 for the system access. Section 5 is devoted to conclusions.

2. DATA MODEL AND BEAMFORMER DESIGN

2.1. Data model

In this section we present the data model used in next section. The output of the $K$ element array can be modelled as

$$x(t) = a(\theta, \phi) s(t) + n(t) \tag{1}$$

where $a(\theta, \phi)$ is the steering vector for the user of interest. $\theta$ and $\phi$ are the elevation and azimuth of the source and $s(t)$ corresponds to the emitted waveform. In order to have a realistic setup, we assume that the signal waveform complies with DVB–RCS standard [6, 7]. $n(t)$ denotes the noise contribution including thermal noise and possibly other users interference signals. In satellite application, $a$ is usually not perfectly known. In fact, phenomena such as dispersion of reception chains, due to temperature variations, and satellite instabilities are unavoidable sources of errors. The former results in gain and phases uncertainties on the steering vector while the latter leads to pointing errors. The overall spatial signature can thus be modelled as

$$a(\theta, \phi) = \pi(\theta + \tilde{\theta}, \phi + \tilde{\phi}) \otimes g \tag{2}$$

where $g$ is the vector of complex random gains, $\tilde{\theta}$ and $\tilde{\phi}$ stand for random pointing errors and $\pi(\theta, \phi)$ denotes the nominal steering vector of the perfectly calibrated array. In Equation (2), $\otimes$ stands for the Hadamard (i.e. element wise) product.

The simplified model of reception chain, we use, is presented in Figure 1.

Note that operations of frequency transposition are not detailed here although we work with baseband signals. The antenna noise temperature is quoted $T_A$. The reception filter $h(t)$ allows the reduction of equivalent noise bandwidth and increases correlation of external noise between reception chains. A low noise amplifier (LNA) with gain $g$ and noise figure (NF), an analog to digital converter (ADC) with an equivalent noise temperature $T_{\text{ADC}}$ due to quantisation and at last a beamforming network (BFN) complete the simulated front end.

The equivalent temperature noise at the beamformer input can be written [8]:

$$T_{\text{input}, i} = T_A + (\text{NF} - 1) T_0 + \frac{T_{\text{ADC}}}{g} \tag{3}$$

$T_0$ being normalised standard temperature ($T_0 = 290$ K).

2.2. Beamformer design

Our goal is to retrieve the signal waveform $s(t)$ in Equation (1), given the knowledge of $\pi(\theta, \phi)$. In order to derive a beamformer, we first observe that the conventional beamformer [9, 10] is likely not to perform well in presence
of interferences (e.g. other users of the covered area) as its main lobe is too wide to achieve interference rejection. Note that conventional beamformer consists in applying the steering vector in the direction of interest as a weighting vector:

$$w_{\text{adv}} = \mathbf{a}(\theta_u, \phi_u)$$  \hspace{1cm} (4)

We use $\mathbf{a}(\theta_u, \phi_u)$ instead of $\mathbf{a}(\theta_u, \phi_u)$ as the latter is not known. The subscript $u$ stands for the user of interest.

Furthermore, using conventional beamforming requires the knowledge of the actual steering vector which, as said above, is not exactly known. Therefore, we consider only adaptive beamformers. More precisely, we have chosen to study one adaptive beamformer relying on an approximate knowledge of signal direction of arrival (DOA), and another relying on the detection of a reference sequence. This will allow to assess which of these two types of method is the most efficient in the type of context we deal with.

We first consider the MVDR beamformer [10] which is given by

$$w_{\text{adv}} = \frac{\mathbf{C}^{-1}(\theta_u, \phi_u)}{\mathbf{a}^H(\theta_u, \phi_u) \mathbf{C}^{-1}(\theta_u, \phi_u) \mathbf{a}(\theta_u, \phi_u)}$$  \hspace{1cm} (5)

where $\mathbf{C}$ is the interference plus noise covariance matrix. In Equation (5) the subscript $u$ stands for the user of interest. Observe that we use $\mathbf{a}(\theta_u, \phi_u)$ instead of $\mathbf{a}(\theta_u, \phi_u)$ as the latter is not known. In order to implement the MVDR beamformer [9], we need to know the user’s position as well as $\mathbf{C}$. Despite the fact that we do not know the exact location of the user of interest, the DVB–RCS standard allows for a coarse pre-localisation of the users and therefore the direction of arrival $(\theta_u, \phi_u)$ can be known within a small error. However, as each beam is pointed towards one particular user, a small pointing error may not introduce big losses on gain. The interference plus noise covariance matrix can be estimated only on a time slot where signal of the user of interest is absent, which is a major constraint. This algorithm will then be taken as a reference.

Note that the MPDR beamformer [10], given by Equation (6), is in theory equivalent to the MVDR one as long as the covariance matrices and $(\theta_u, \phi_u)$ are known. However, in practice, we deal with a finite number of snapshots and the signal direction of arrival $(\theta_u, \phi_u)$ is not perfectly known. The MVDR beamformer is then much more performant [10] than the MPDR as it converges faster and it is less sensitive to steering vector errors. For this reason, the MVDR beamformer has been preferred to the MPDR one.

$$w_{\text{adv}} = \frac{\mathbf{R}^{-1}(\theta_u, \phi_u)}{\mathbf{a}^H(\theta_u, \phi_u) \mathbf{R}^{-1}(\theta_u, \phi_u) \mathbf{a}(\theta_u, \phi_u)}$$  \hspace{1cm} (6)

$\mathbf{R}$ stands for the covariance matrix of the received signal $x(t)$.

In order to relax the need of data without main user’s signal and to be more robust to steering vector perturbations, we propose to use a training sequence $s_d(t)$ [10] which is feasible within the DVB–RCS standard as it allows to insert pilots in the data stream. The beamformer is then designed so as to minimise the mean square error between the beamformer’s output and $s_d(t)$. This beamformer corresponds to the minimum mean square error (MMSE) solution beamformer, i.e.

$$w_s = w_{\text{MMSE}} = \arg \min_{\mathbf{w}} E[|\mathbf{w}^H x(t) - s_d(t)|^2]$$

$$= \arg \min_{\mathbf{w}} E[\mathbf{w}^H \mathbf{R} \mathbf{w} - \mathbf{w}^H \mathbf{r} + \mathbf{r}^H \mathbf{w} + P_s]$$

$$= \mathbf{R}^{-1} \mathbf{r}$$  \hspace{1cm} (7)

where

$$\mathbf{r} = E[\mathbf{x}(t) \mathbf{x}^H(t)]$$  \hspace{1cm} (8)

$$P_s = E[\mathbf{s}_d(t) \mathbf{s}_d^H(t)]$$  \hspace{1cm} (9)

$P_s$ being the power of the user’s signal.

The main interest of using $w_s$ is that it does not require knowledge of either $\mathbf{a}(\theta_u, \phi_u)$ or the direction of arrival. Moreover, even if the array is not perfectly calibrated, this is more or less compensated by $\mathbf{r}$ which bears information about the actual steering vectors. However, a major drawback of this method is that it requires a perfect synchronisation. In other words, there must be a perfect time alignment in Equation (9); otherwise, the beamformer tries to approximate a time-delayed version of $s_d(t)$ and then becomes ineffective. In order to make up for this problem we propose a new scheme. Assuming that a coarse pre-synchronisation is available, which is possible in DVB–RCS, a fixed beamformer is first applied to the data stream. The output of the fixed beamformer is then fed to a matched (with respect to $s_d(t)$) filter and it achieves a fine synchronization as presented more precisely in next paragraph. $w_s$ can then be computed using Equation (7). The fixed beamformer is preferred to the MVDR because it is more simple to implement.
3. SIMULATION RESULTS

3.1. Description of the antenna

The Ka-band antenna is constituted of two reflectors and a hexagonal array of 19 elementary feeds. The main reflector has 1 m diameter and 515 mm focal length. Maximal gain of this antenna is 47 dB at 30 GHz. Figure 2 shows the isolevel representation of elementary antenna patterns of a FAFR antenna in the plane \((\theta \cos(\phi), \theta \sin(\phi))\).

For each of the 19 radiating elements of the antenna, we plot the contour (little circles) corresponding to a 45 dB antenna gain. As can be observed, only seven antenna feeds are required to cover the area of interest (big dotted circle).

3.2. Hypothesis on signal levels

In the numerical examples, we consider that the main user is located on the edge of spot coverage and there is an interfering user with the same transmission power within the spot. The operational power flux density \([11]\) is fixed to \(-132 \text{ dBW/m}^2\) in accordance to effective isotropic radiated power (EIRP) of users’ terminals (better than 30 dBW).

In a DVB–RCS system [7], a turbo code with coding rate 1/2 requires a level in \(E_b/N_0\) of 5.7 dB to guarantee the transmission. A degradation of about 2 dB due to practical implementation and other imperfections is considered. In order to assess the performance of the beamformers, we require that they provide an \(E_b/N_0\) above this level while providing a main user gain superior to 40 dB.

The training sequence consists in a constant amplitude and zero autocorrelation (CAZAC) sequence used in the global system for mobile (GSM) communications system for the estimation of the mobile radio channel impulse response. The sequence length is 240 QPSK symbols obtained by the repetition of a 16 symbols CAZAC sequences. To compute the MVDR beamformer, 480 samples (equivalent to 240 coded symbols) of data without main user signal are used to estimate the covariance matrix \(C\). The direction of arrival \((\theta_u, \phi_u)\) is supposed to be known within a small error (which is about 0.1° in \(\theta\) direction).

Processing a one beam per user concept, this localisation error should not degrade much main user gain as the latter is on the centre of the beam. However, the gain loss \(x\) for a pointing error \(\theta_{\text{e}}/2\) is approximately given by
Equation (10):

\[
\frac{\theta_{3dB}}{\sqrt{3}} \approx \frac{\theta_{x dB}}{\sqrt{3}}
\]

\(\theta_{3dB}\) stands for the antenna 3 dB beamwidth and \(\theta_{x dB}\) for the \(x\) dB beamwidth. If we suppose a localisation error of 0.1°, for example, and a 3 dB beamwidth of about 0.8° (Figure 3), gain loss \(x\) would be around 0.2 dB. This is still much better than the gain loss encountered in the single fixed beam solution for the edge of coverage user.

Only the seven sensors that receive most of the emitted power are used to determine the beamformer weighting. Figure 3 shows antenna pattern cuts obtained in an ideal case (absence of perturbations and good synchronisation).

The useful user is located in the direction \((\theta_u \approx -0.28^\circ, \phi_u = 0^\circ)\) and an interfering user is in the direction \((\theta_i \approx 0.21^\circ, \phi_i = 0^\circ)\). The pattern corresponding to the fixed beam directed towards the spot centre is also plotted. This fixed beam is obtained with an antenna of the same size as the FAFR.

Here, MVDR and training sequence beamformers have equivalent performances. Main user’s gain is about 46.5 dB for the training sequence beamformer and 46.1 dB for the MVDR one, whereas for the fixed beam we had 43.2 dB in main user’s direction. We observe here about 3 dB gain thanks to beamforming towards main user.

The corresponding obtained \(E_b/N_0\) is 6.7 dB for the two adaptive beamformers and \(-1.3\) dB for the fixed beam.

In the next paragraph, we assess the robustness of the two possible beamformers in the presence of channel errors, perturbations on steering vectors, and in the case where we have synchronisation errors.

3.3. Algorithms sensitivity

3.3.1. Channel perturbations

Going through the transmission channel, the emitted signal \(\tilde{s}(t)\) is affected by phase and frequency errors \((\Delta f' \text{ and } \Delta \psi')\), respectively. The corresponding received signal \(s(t)\) is thus written as:

\[ s(t) = \tilde{s}(t) \exp(j2\pi\Delta ft + j\Delta \psi) \]

In next simulation, the phase error is fixed to 45°. We study the influence of frequency errors on \(E_b/N_0\) obtained at the
output of the beamformers, through the value of $\Delta f/R_s$, $R_s$ being the symbol rate. $R_s$ is fixed to $7 \times 10^7$ symbols per seconds for our system.

Figure 4 shows that MVDR beamformer is not affected by these errors whereas training sequence beamformer shows a degradation of the output $E_b/N_0$ for $\Delta f/R_s$ above $10^{-3}$ (loss of nearly 7 dB for a level of $5 \times 10^{-3}$ in $\Delta f/R_s$). Performances in main users gain are equivalent. This is due to the fact that frequency error causes a phase increment for each sample. Consequently, the more important the error, the less the received signal matches the training sequence. This error affects the performances mainly because of the training sequence length (240 QPSK symbols). The normalised frequency accuracy, $\Delta f/F_0$, is about $10^{-8}$ in the DVB–RCS standard. With a carrier frequency of 30 GHz, we can estimate our worst $\Delta f/R_s$ to $5 \times 10^{-4}$. In this case, training sequence is not affected by frequency errors.

### 3.3.2. Steering vectors perturbations

We study here the influence of steering vector errors on the beamformer performances. The vector of complex random gains in Equation (2), $g$, is assumed to be a random vector of $K$ elements (for a $K$ sensors antenna array). To model it, we consider two random errors vectors drawn from centered Gaussian distribution $A_{dB}$ and $\phi$ corresponding respectively to amplitude (in dB) and phase errors.

$$g = 10^{A_{dB}/20} \odot \exp(j\phi) \quad (12)$$

$\odot$ stands for the Hadamard (i.e. element wise) product. For simulation, $A_{dB}$ has a standard deviation of 0.5 dB and $\phi$ one of $5^\circ$. We also consider a pointing error, $\tilde{\theta} = 0.12^\circ$.

After 1000 Monte Carlo runs of perturbations, we determine mean gain towards main user, mean output $E_b/N_0$ and minimum performances guaranteed at 99% (Table 1).

Using a training sequence, an average gain of 46.4 dB is obtained in main user direction (with a standard deviation of 0.29 dB) while the MVDR provides a 45.6 dB gain (with a standard deviation of 0.32 dB). On average, the main user gain is the same as in the ideal case when using a training sequence beamformer whereas, for the MVDR beamformer, we observe a decrease of 0.5 dB in main user gain. In the same way, in terms of $E_b/N_0$, if we observe for the MVDR a decrease of 0.4 dB of the average value (6.3 dB with a standard deviation of 0.32 dB) in comparison with a training sequence beamformer.
Table 1. Performances obtained in case of steering vector perturbations.

<table>
<thead>
<tr>
<th></th>
<th>Mean Gain Gain minimum guaranteed</th>
<th>Mean $E_b/N_0$ $E_b/N_0$ Standard deviation</th>
<th>$E_b/N_0$ Minimum guaranteed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training Sequence</td>
<td>46.4 0.29 46.1</td>
<td>6.6 0.30</td>
<td>5.8</td>
</tr>
<tr>
<td>MVDR</td>
<td>45.6 0.32 44.5</td>
<td>6.3 0.32</td>
<td>5.6</td>
</tr>
</tbody>
</table>

To the ideal case, for the training sequence, decrease does not exceed 0.1 dB (mean value of 6.6 dB with a standard deviation of 0.30 dB). Figure 5 plots the antenna patterns obtained for the minimum guaranteed $E_b/N_0$ at 99% by each algorithm (5.8 dB for training sequence and 5.6 dB for MVDR) which represents the worst case.

Thus, as predicted, inaccuracy in user steering vector degrades MVDR performances but does not affect the training sequence based beamformer. In fact, steering vector errors result in a shift of the MVDR diagram and thus a degradation of main user’s gain.

3.3.3. Synchronisation errors

Another kind of perturbation that may affect the beamformer performances are errors due to a non-perfect synchronisation of the received signal. In fact, emitted signal undergoes a propagation delay uncertainty that leads principally to a poor estimation of the training sequence. We assume here that time error recovery (which corresponds to reception clock precision) has been performed prior to any processing. To recover synchronisation (which corresponds here to training sequence detection), we propose to first apply a fixed beamformer and then detect the training sequence thanks to a matched filter (with respect to the training sequence) [12]. Weighting of this fixed beamformer is calculated by evaluating the mean of received signal on each antenna sensor. This detection method is referred to as passive correlation.

![Antenna patterns obtained in case of steering vector perturbations.](image-url)
Note that the fixed beamformer described here is not optimum. This fixed beamformer has been preferred to the MVDR one because it does not require a high level of computational load in contrast to the MVDR.

We study the influence of different synchronisation delays on beamformers’ performances. Figure 8 shows output $E_b/N_0$ obtained for training sequence beamformer (synchronised thanks to passive correlation or not synchronised) and MVDR beamformer. Delays from 0 to 6 symbol periods ($T_s$) are applied.

If a shift of at least one symbol occurs, a crash in not synchronised training sequence performances is observed. The main user’s gain is of 17.2 dB and $E_b/N_0$ of $-12.1$ dB which is clearly insufficient performance. On the contrary, MVDR performances are not affected.

Concerning the synchronised training sequence beamformer, it appears that the sequence detection helps avoiding this drawback, performances similar to MVDR are then obtained. Performances of this synchronised beamformer clearly rely on the quality of the clock recovery algorithm and also on the gain performances of the fixed beamformer applied. Therefore, passive correlation proves to be an efficient solution to cope with synchronisation errors. It allows to recover the performances obtained without any error, given that fixed beamformer applied provides a sufficiently high gain towards the user of interest.

To conclude this section, Table 2 sums up gain obtained in the main user direction by the beamformers. In most cases, we obtain gains which are 3 dB above the gain...
obtained with the traditional fixed beamformer (which was about 43.2 dB).

4. PROPOSED SYSTEM

The overall proposed system is described in Figure 9. Disaster area is covered by $P$ fixed beams, each obtained by a combination of $m$ sensors through the $K$ available sensors of the antenna array. Communication is established through two main stages:

- In the first one, a user tries to get access to the network. A signalling channel allows him to transmit his position. Note that there is one access channel by fixed beam and thus, two users of the same beam cannot connect at the same time. Once we get the position of all users, a time/frequency slot resource is allocated according to the frequency reuse constraint and to the minimum angular distance required by the antenna to separate two users while guaranteeing performances in $E_b/N_0$. The value of the frequency reuse factor will depend on the antenna capacity to reject nearby interferences.
- In the second stage, for a given frequency resource and for each user concerned, we select the fixed beam associated to the user of interest (definition of the $m$ principal sensors to be used for adaptive beamformer’s weighting). Training sequence is then detected in the

<table>
<thead>
<tr>
<th>Ideal case</th>
<th>Channel perturbations ($\Delta f = 5 \times 10^{-4}$)</th>
<th>Steering vector perturbations (mean gain)</th>
<th>Synchronisation errors ($\Delta \tau = T_1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training sequence Gain (dB)</td>
<td>46.5</td>
<td>46.5</td>
<td>46.4</td>
</tr>
<tr>
<td>MVDR gain (dB)</td>
<td>46.1</td>
<td>46.1</td>
<td>45.6</td>
</tr>
</tbody>
</table>
signal received through the reserved fixed beam. Adaptive beamformer using the training sequence is then computed to ensure a maximum gain to main user while reducing gain towards interfering users. Demodulation and other treatments follow.

5. CONCLUSIONS

In this paper, we studied the feasibility of a one beam per user concept for a multi-beam satellite communications that would operate in emergency situations over a limited disaster area. Two beamformers are studied: the minimum variance distortionless response (MVDR) and a beamformer using a training sequence. Their performances are compared in scenarios where channel, steering vector and synchronisation errors occur. Training sequence beamformer is robust to steering vector perturbations in contrast to MVDR, but is particularly sensitive to synchronisation errors and channel perturbations. However, using a filter matched to the training sequence (at the output of a fixed beamformer) helps recovering synchronisation and thus computing the correct beamformer. It appears that despite the possible degradations that may happen, the achieved $E_b/N_0$ is compatible with DVB-RCS system.

Further work will be done on the characteristics of the satellite reception chains and evaluation of different noise contributions to assess effective final performances of the two algorithms. Study of time delay estimation, evaluation of frequency reuse factor and minimal angular distance allowed by the antenna are also being studied.
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