On the Application of Multiuser Detection in Multibeam Satellite Systems

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Abstract—We study the achievable rates by a single user in multibeam satellite scenarios. We show alternatives to the conventional symbol-by-symbol detection applied at user terminals. Single user detection is known to suffer from strong degradation when the terminal is located near the edge of the coverage area, and when aggressive frequency reuse is adopted. For this reason, we consider multiuser detection, and take into account the strongest interfering signal. Moreover, we analyze a different transmission strategy, where the signals from two adjacent beams jointly serve two users in a time division multiplexing fashion. We describe an information-theoretic framework to compare different transmission/detection strategies by computing the information rate of the user in the reference beam.

I. INTRODUCTION

The recent years have witnessed the explosion of satellite services and applications, and the related growing demand for high data rates. Next-generation satellite systems need new technologies to improve their spectral efficiency, in order to sustain the information revolution of modern societies. The grand challenge is to satisfy this demand by living with the scarcity of the frequency spectrum. Resource sharing is probably the only option, and can be implemented by adopting a multibeam system architecture which allows to reuse the available bandwidth in many beams. The interference caused by resource sharing is typically considered undesirable, but a way to dramatically improve the spectral efficiency is to exploit this interference, by using interference management techniques at the receiver.

In this paper, we consider the forward link of a multibeam satellite system, where an aggressive frequency reuse is applied. Under these conditions, the conventional single user detector (SUD) suffers from a severe performance degradation when the terminal is located near the edge of the coverage area, due to the high co-channel interference. On the other hand, the application of a decentralized multiuser detector (MUD) at the terminal which is able to cope with the interference can guarantee the required performance.

The literature on multiuser detection is wide, and in the area of satellite communications essentially focuses on the adjacent channel interference mitigation for the return link [1]–[3], and includes centralized techniques to be applied at the gateway. Less effort has been devoted to the forward link.

Recently, we investigated in [4] the benefits that can be achieved, in terms of spectral efficiency, when high frequency reuse is applied in a DVB-S2 [5] system, and multiuser detection is adopted at the terminal to manage the presence of strong co-channel interference. The superiority of the MUD has been demonstrated through error rate simulations. In [6], the authors study the applicability of a low complexity MUD based on soft interference cancellation. The advantage of the proposed detector is shown in terms of frame error rate.

In this paper, we generalize the analysis of [4] by supplying an information-theoretic framework which allows us to evaluate the performance in terms of information rate (IR), without the need of lengthy error rate simulations and hence strongly simplifying the comparison of various scenarios. Furthermore, we consider also a different transmission strategy, where the two signals intended for the two beams cooperate to serve the two users (one in the first beam and the other in the second one) in a time division multiplexing fashion. In other words, instead of serving simultaneously the two users in the adjacent beams, the users are served consecutively in an exclusive fashion.

The conclusive picture is complex, since our results show that a transmission/detection strategy which is universally superior to the others does not exist, but the performance depends on several factors, such as the signal-to-noise ratio (SNR), the users’ power profile, and the rate of the strongest interferer. This fact outlines the importance of the proposed analysis framework, which can avoid to resort to computationally intensive simulations.

In the following, Section II presents the system model and describes the two considered scenarios and related detection strategies. The information-theoretic analysis is treated in Sections III and IV and gives us the necessary means for the computation of the information rate for the reference beam. Section V presents the results of our study, whereas conclusions are drawn in Section VI.

II. SYSTEM MODEL

We focus on the forward link of a satellite communication system. Figure 1 depicts a schematic view of the baseband model we are considering. Signals \( s_i(t) \), \( i = 1, \ldots, K \), are \( K \) signals transmitted by a multibeam satellite in the same frequency band. The satellite is thus composed of \( K \) transmitters (i.e., transponders) and serves \( K \) users on the ground. The nonlinear effects related to the high power amplifiers which compose the transponders are neglected since a multibeam satellite generally works in a multiple carriers per transponder modality, and hence the operational point of its amplifiers is far from saturation. We consider the case where the users experience a high level of co-channel interference, since we assume that they are located close to the edge of the coverage area.
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generality, we assume that “User 1” is the reference user and
the remaining signals are considered as additional thermal noise.

Scenario 1. Signal s1(t) is intended for user i, and we are
interested in the evaluation of the performance for “User 1”,
whose information is carried by the signal with i=1. For this
scenario, we evaluate the IR, or equivalently the achievable
spectral efficiency, when “User 1” employs different detectors.
In particular, we consider the case when “User 1” employs:

- A SUD. In this case, all interfering signals s_i(t), i = 2, . . . , K are considered as if they were additional thermal
noise.

- A MUD for the useful signal and one interferer. In this
case, the receiver is designed to detect the useful signal
and the most powerful interfering signal (that with i=2 in
our model) whereas all the remaining signals are consid-
ered as if they were additional thermal noise. Data related
to the interfering user are discarded after detection.
This case will be called MUD×2 in the following.

Our analysis can be easily extended to the case of a MUD
designed for more than two users. On the other hand, given
the actual users’ power profile, it has been shown in [4] that
the MUD×2 offers the best tradeoff between complexity and
performance.

Scenario 2. A different strategy is adopted in this case. With-
out loss of generality, we will consider detection of signals
s1(t) and s2(t) and users 1 and 2 only. As in scenario 1, the
remaining signals are considered as additional thermal noise.
Instead of simultaneously transmitting signal s1(t) to “User 1”
and signal s2(t) to “User 2”, as in the previous scenario, we
here serve “User 1” first by employing both signals s1(t) and
s2(t) for a fraction α (0 ≤ α ≤ 1) of the total time, and then
“User 2” by employing both signals s1(t) and s2(t) for the
remaining fraction 1 − α of the total time. The fraction α can
be chosen in order to maximize the sum-rate or simply by
taking into account the different data rate needs of the users.

Signals s1(t) and s2(t) are independent (although carrying
information for the same user) and one of them is properly
phase-shifted with respect to the other one in order to maxi-
mize the IR. The value of this phase shift can be found by
computing the IR for a fixed value of the phase shift and then
looking for the value providing the maximum value of the IR.
A proper discretization of the phase must be used. The
receiver must jointly detect both signals and its complexity
is comparable to that of the MUD×2 described for the first
scenario.

III. INFORMATION-THEORETIC ANALYSIS FOR
SCENARIO 1

We first consider multiuser detection and describe how to
compute the IR related to “User 1” assuming the MUD×2
receiver. The same technique can be used to compute the IR
related to “User 2” and straightforwardly extends to the case
of MUD for more than two users. The channel model assumed
by the receiver is

\[ y = x_1 + \gamma x_2 + w, \]

where \( x_i \) is the \( M^{(i)} \)-ary complex-valued symbol sent over
the ith beam and \( w \) collects the thermal noise, with power \( N \),
and the remaining interferers that the receiver is not able to
cope with. Symbols \( x_1 \) and \( x_2 \) are mutually independent and
distributed according to their probability mass function \( P(x_i) \).
They are also properly normalized such that \( E[|x_i|^2] = P \),
where \( P \) is the transmitted power per user. Parameter \( \gamma \) is
complex-valued and models the power unbalance and the
phase shift between the two signals. Random variable \( w \) is
assumed complex and Gaussian. We point out that this is an
approximation exploited only by the receiver, while in the
actual channel the interference is clearly generated as in (1).
The MUD×2 detector has a computational complexity which
is proportional to the product \( M^{(1)} M^{(2)} \) [7].

We are interested here in the computation of the maximum
achievable rate \( R_1 \) for “User 1” when “User 2” adopts a fixed
rate \( R_2 \), and the MUD×2 is employed. Rates are defined as
\( R_i = r^{(i)} \log_2(M^{(i)}) \), where \( r^{(i)} \) is the rate of the adopted
binary code. The rates of the other \( K-2 \) interferers do not
condition our results since at the receiver they are treated just
as noise. This problem is quite different with respect to the
case of the Multiple Access Channel (MAC) discussed in [8]
where both rates \( R_1, R_2 \) are jointly selected, while here the
rate \( R_2 \) is fixed and data of “User 2” can be discarded after
detection.

The IR for “User 1” in the considered scenario is given by
Theorem [1], whose proof is based on the following two
lemmas.

\[ \text{Figure 1. Block diagram of the considered system.} \]
Lemma 1. For a fixed rate $R_2$, the rate

\[ I_A = \begin{cases} I(x_1; y | x_2) & \text{if } R_2 < I(x_2; y) \\ I(x_1, x_2; y) - R_2 & \text{if } I(x_2; y) \leq R_2 < I(x_2; y | x_1) \\ 0 & \text{if } R_2 \geq I(x_2; y | x_1) \end{cases} \]

is achievable by “User 1” and is not a continuous function of $P/N$. Namely, a cut-off $\text{SNR}_c$ exists such that $I_A = 0$ for $P/N \leq \text{SNR}_c$ and $I_A > 0$ for $P/N > \text{SNR}_c$ with a discontinuity.

Proof: In [8], it is shown that the achievable region for the MAC is given by the region of points $(R_1, R_2)$ such that

\[ R_1 < I(x_1; y | x_2), I(x_1, x_2; y) - R_2 \]

when $R_2 < I(x_2; y | x_1)$. The first term is lower when

\[ R_2 < I(x_1, x_2; y) - I(x_1; y | x_2) = I(x_2; y). \]

Thus, $I_A$ is an achievable rate for “User 1”.

We now prove that $I_A$ has a cut-off rate. Since, $I(x_2; y | x_1)$ is a non-decreasing function of $P/N$ [9], there exists $\text{SNR}_c$ such that $I(x_2; y | x_1) = R_2$, and hence

\[ I_A(\text{SNR}_c) = 0. \]

On the other hand for a small $\varepsilon > 0$, it holds $R_2 = I(x_2; y | x_1) - \delta$ where $\delta > 0$. It follows that $I(x_1; y | x_2) > I(x_1, x_2; y) - R_2$. Thus

\[ I_A(\text{SNR}_c + \varepsilon) = I(x_1, x_2; y) - R_2 > I(x_1; y) > 0 \]

for $\varepsilon \to 0^+$.  

Discussion: The proof of the lemma can be done graphically by considering the intersection of the achievable region with a horizontal line at height $R_2$.

When $R_2 > I(x_2; y | x_1)$ clearly the rate of “User 2” cannot be achieved. However, we also have to account for this case and therefore we consider also the achievable rate $I(x_1; y)$, which is the relevant rate when “User 2” is just considered as interference. In this case, the receiver exploits the statistical knowledge of the signal $s_2(t)$ but does not attempt to recover the relevant information.

Lemma 2. The rate $I_S(P/N) = I(x_1; y)$ as a function of $P/N$ is always greater than 0 and satisfies

\[ I_S(\text{SNR}_c) = \lim_{\varepsilon \to 0^+} I_A(\text{SNR}_c + \varepsilon) \]

\[ I_S(\text{SNR}_c + \delta) < I_A(\text{SNR}_c + \delta) \]

for any $\delta > 0$.

Proof: The proof is straightforward. It can be done by observing that $I(x_1; y) \leq I(x_1; y | x_2)$ and that $I(x_1; y) \leq I(x_1, x_2; y)$.

Theorem 1. The achievable information rate for a single user on the two users multiple access channel, for a fixed rate $R_2$, is given by

\[ R_1 < \max\{I_S, I_A\}, \]

and is a continuous function of $P/N$.

Proof: Proof made by means of the Lemmas. In fact, $I_A$ and $I_S$ are the maximum rates achievable by “User 1” when “User 2” can be perfectly decoded, or not. An alternative graphical proof can be derived from Figure 3 which plots the rate achievable by “User 1” as a function of $R_2$, for a generic fixed value of $P/N$. We clearly see that inequality (6) holds.

Example 1. For Gaussian symbols and $K = 2$, we obtain that

\[ R_1 < \begin{cases} C \left( \frac{P}{N} \right) & \text{if } R_2 < C \left( \frac{P^2 \gamma^2}{N + P \gamma^2} \right) \\ C \left( \frac{P(1+\gamma^2)}{N + P \gamma^2} \right) - R_2 & \text{if } C \left( \frac{P^2 \gamma^2}{N + P \gamma^2} \right) \leq R_2 < C \left( \frac{P^2}{N} \right) \\ C \left( \frac{P}{N} \right) & \text{if } R_2 \geq C \left( \frac{P^2}{N} \right) \end{cases} \]
where $C(x) = \log_2(1 + x)$. All curves are shown in Figure 4 for the case of $|\gamma| = 0.79$, $R_2 = 1/2$, and the overall bound is given by the red curve. We can see from the figure that this bound is clearly continuous.

The computation of the IRs $I(x_1; y|x_2)$, $I(x_2; y|x_1)$, $I(x_1, x_2; y)$, $I(x_1; y)$ can be performed by using the achievable lower bound based on mismatched detection [10].

When a SUD is employed at the terminal, the theoretic analysis can be based on the following discrete-time model

$$y = x_1 + w,$$

where $w$ includes the thermal noise and the interferers that the receiver ignores. As known, the complexity of the SUD is much lower than that of the multiuser receiver, and is proportional to $M^{(1)}$. The computation of the IR $I(x_1; y)$ is again based on mismatched detection [10] and allows us to select the maximum rate for “User 1” when the co-channel interference is not accounted for.

IV. INFORMATION-THEORETIC ANALYSIS FOR SCENARIO 2

Let us consider the fraction $\alpha$ of time when both signals are used to send information to “User 1”. Hence, during this time slot both signals $s_1(t)$ and $s_2(t)$ are intended to “User 1”. Since $s_1(t)$ and $s_2(t)$ are independent, we are exactly in the case of the MAC. By properly selecting the rate of the two signals any point of the capacity region can be achieved [8]. Clearly, we are interested in selecting the two rates in such a way that the sum-rate $I(x_1, x_2; y)$ is maximized.

V. NUMERICAL RESULTS

In this section, we compare the two scenarios described in Section IV and the corresponding detection strategies by considering the performance of “User 1”, evaluated in terms of IR.

We assume as reference system the DVB-S2 standard [5] and hence consider adaptive coding and modulation. We choose a frequency reuse with factor two, to generate a high co-channel interference, and consider the users which are located close to the edge of the coverage area of the reference beam. In this case, it has been shown [4] that it is sufficient to consider the five strongest interfering beams. Therefore, we simulate $K = 6$ users, employing different modulation formats. Particularly, users with $i = 1, 2$ adopt a QPSK modulation, users with $i = 3, 4$ and 6 adopt a 8PSK modulation, and the user with $i = 5$ adopts a 16APSK modulation.

To identify the users’ power profile, we define the signal-to-interference power ratio as

$$\lambda_i = |\gamma_i|^2 / |\gamma_i|^2,$$

and consider three realistic cases which have a different power profile, and are listed in Table 1. These distributions are typical of the forward link of a multibeam broadband satellite system with 2 colors frequency reuse.

Figures 5–7 show the IR related to “User 1” as a function of $P/N$ for the three considered interference patterns. In the case of scenario 1, we evaluate both the IR achievable by a SUD and that achievable by the MUD×2 algorithm. In case of MUD×2, the performance is heavily affected by the rate of “User 2”, and hence we have to analyze performance for a fixed rate of the binary code employed by the signal $s_2(t)$. We thus have three IR curves for the MUD in scenario 1, to consider the case where “User 2” adopts a low code rate (3/5), an average code rate (5/6) and a high rate (8/9), chosen among the ones foreseen by the standard. In the case of scenario 2, it is assumed that $\alpha = 0.5$ and this has been taken into account in the computation of the IR. We recall that for this scenario the relative phase shift of signals $s_1(t)$ and $s_2(t)$ has been optimized by simulation.

Our results show that we cannot identify the strategy which universally achieves the best performance. In particular, the figures show that “User 1” has the best IR in scenario 2 for low-to-medium SNR values in the first case, where the interference of the second signal is very strong, while in the other cases the advantage of scenario 2 is reduced.

As expected, in scenario 1 the adoption of the MUD gives the best results with respect to the SUD, and this is at the price of an increased complexity. Moreover, the performance of the MUD heavily depends on the rate of the strongest interfering user. In case 3, the SUD gives very good IRs and hence it is the best choice to compromise between complexity and performance for a large SNR range.

| Table I | POWER PROFILES FOR THE CONSIDERED SIMULATIONS, CORRESPONDING TO A TWO COLORS FREQUENCY REUSE. |
|---------|-------------------------------------------------------------------------------------------------|
| Case    | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $\lambda_5$ | $\lambda_6$ |
| 1       | 0 dB        | 25 dB        | 27 dB        | 27 dB        | 30 dB        |
| 2       | 2 dB        | 26 dB        | 27 dB        | 27 dB        | 30 dB        |
| 3       | 4 dB        | 27 dB        | 27 dB        | 27 dB        | 30 dB        |

Figure 4. Maximum rate achievable by “User 1”, for $K = 2$, Gaussian symbols, and $R_2 = 1/2$. 
VI. CONCLUSIONS

In this paper we have addressed the problem of multiuser detection in the forward link of a multibeam satellite system, in the presence of strong co-channel interference. We considered alternative techniques to the single user detection, that take into account the strongest interfering signal. We have shown that this technique can considerably increase the achievable rate at the cost of a higher computational complexity.

Furthermore, we considered a transmission strategy where the signals from two beams serve two users in a time division multiplexing way, and we show that this approach is effective at low signal-to-noise ratio, when the co-channel interference is very strong. However, our results reveals that there is no clear winner. In fact, the best strategy depends on the power profile of the interfering signals, the rates of the signals, and the signal-to-noise power ratio.

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