

Interference Management Schemes for High Spectral Efficiency Satellite Communications

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ABSTRACT

This paper presents a short review on the main high spectral efficient systems for multibeam satellite communications. In this regard, we introduce the pros and cons of systems based on Multiuser Detection System (MUD) and Successive Interference Cancellation (SIC) applied to aggressive frequency reuse, frequency packing and Non Orthogonal Multiple Access (NOMA). Furthermore, we have also considered the presence of co-channel interference and spectrum limitations. The experimental validations have been conducted using DVB-S2 waveform. The results point out that the residual co-channel interference reduce the benefits of using frequency packing schemes. Furthermore, the best strategy to target a given FER when two streams are received with the same energy is to select a combination of low and high order modulation formats. Moreover, we investigate the effect of asynchronous reception of data streams in our previously proposed interference management scheme based on cooperative NOMA in multibeam satellite systems.

Categories and Subject Descriptors

G.3 [Mathematics of Computing]: Probability and Statistics—*Queueing Theory*

General Terms

Theory, Performance

Keywords

SIC, GEO, spectral efficiency, NOMA, multibeam satellites, CCI, MUD

1. INTRODUCTION

The contribution of this paper is to show the spectral efficiency and BER/FER of full frequency and FR4 systems with and without frequency packing, and cooperative NOMA. In this latter case, we also report the effect of asynchronous reception of data streams at the target user. The ever-growing demand for capacity in multibeam satellite communication (SatCom) systems has fueled the research towards spectrally efficient transmission techniques.

In this scenario, high spectral efficiency has been achieved by adopting aggressive frequency reuse schemes, such as the 2 color beam pattern, combined with decentralized multi-user detection (MUD) techniques [1]-[3]. Recent studies, e.g. [4],[5] have shown that a considerable capacity improvement can also be achieved in the four color beam pattern by relaxing the signal orthogonality either in frequency or time domains. This strategy, referred to as Time-Frequency Packing (TFP) (See [6]), has also been successfully applied to multiple-input multiple-output (MIMO) communications systems for Geostationary Earth Orbit (GEO) satellites in [7],[8]. Next, from the 3GPP arena, systems based on NOMA and superposition coding have shown they provide a larger spectral efficiency than the schemes based on orthogonal ones [9].

Non-orthogonal multiple access (NOMA) has recently been proposed as the means of sharing the limited available resources with more users [11]. In our previously proposed cooperative NOMA scheme, we have shown that by managing the interferences, we can use them as extra sources of data, as if there was no interference at all [12]. Our proposed cooperative NOMA is based on power-domain NOMA, where the transmitters at the gateway share the target users data and send it at the same time and frequency band. The cooperation is between the incumbent beam and one or two beams with the most dominant interferences; whereas, the signals received from all other beams are considered as noise. The target user recovers both data streams using successive interference cancellation (SIC), as proposed in NOMA.

Yet, our investigations as well as previous studies are based on synchronous reception of data streams at the target receiver which is not justifiable in practice. Indeed, it is necessary to recover the transmission parameters even in the existence of the most aggressive interferences. Data-aided and non-data aided channel estimation schemes have been extensively studied, both in forward and return multibeam satellite links [13]-[15].

In this paper, we adopt the pilot-aided technique presented by DVB-S2X standard, Annex E.4 [16] for channel estimation of cooperative NOMA in the forward link of multibeam satellite systems. This is based on the findings in [17] where the authors have investigated the Cramer-Rao lower bound (CRLB) for the parameter estimations using super-frame (SF) in interference-limited scenarios. It is shown that due to orthogonal Walsh-Hadamard (WH) codes used in super frame as preamble and pilot sequences, the signal timing

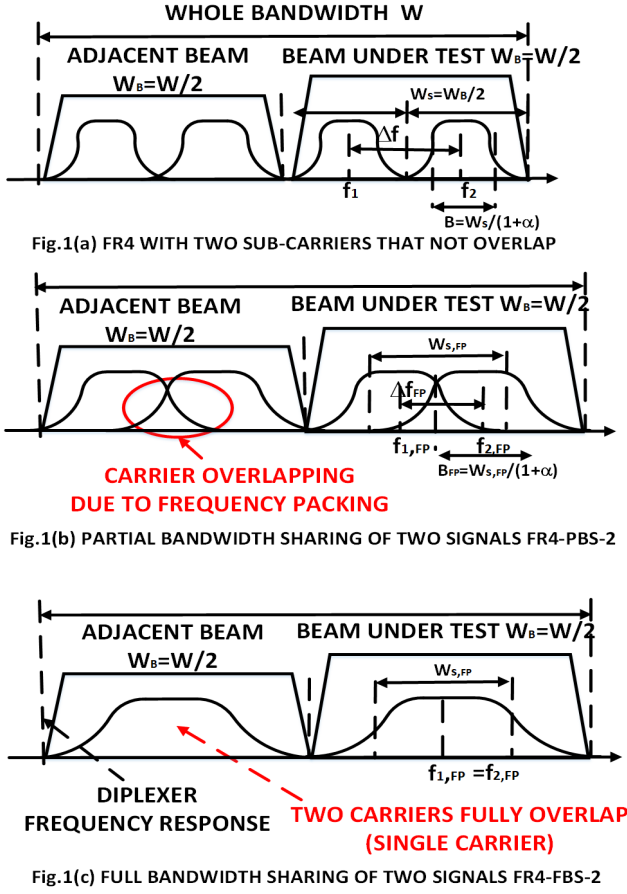


Figure 1: Bandwidth schemes of the investigated FR4 systems.

and phase could be recovered with jitter variance very close to Modified CRLB (MCRLB). In other words, due to orthogonality of the preamble codes in super frame, the clock and phase recovery is possible separately for the two-user multiple access channel. This is also confirmed in [18], where frame synchronization and interferer frame synchronization performance is shown in forward link, using super frame.

This paper is organized as follows. In Section II, system model for different scenarios are provided. Section III pursues the discussed concepts presenting the information theoretic evaluations. In Section IV, simulation results are provided. Analytical results are confirmed by simulation which is concluded in Section V.

2. SYSTEM MODEL DESCRIPTION

The increasing need for anytime and anywhere content implies that communication systems have to increase the capacity to keep the pace with the users demands. In the two colour frequency reuse (FR2) scheme, the capacity can be increased by exploiting co-channel interference. Towards this end, the content is shared between two beams and it is assumed that the receiver can benefit from multi-user detection (MUD) techniques. On the contrary, four colour frequency reuse (FR4) schemes cannot exploit co-channel interference to boost the capacity, because the interfering

signals are too weak. In our proposed cooperative NOMA, we consider full frequency reuse in the multibeam satellite systems. This results in huge co-channel interference (CCI) imposed on the users. The system model is provided in this section.

2.1 FR4 systems based on frequency packing

The solution to increase the data rate in FR4 is based on applying frequency packing in multicarrier systems. It is worth highlighting that in FR4 (See Fig. 1a) we have distinguished between two scenarios. In Scenario 1, subcarrier signals are not orthogonal in the frequency domain, so that they are partially overlapped (See Fig. 1b). Therefore, it is deemed necessary to remove the interference before applying MUD. In Scenario 2, all signals have the same carrier frequency and span the total beams bandwidth (See Fig. 1c). This case is especially interesting, because inter-symbol interference can be avoided by using pulses that satisfy the Nyquist constraint.

2.1.1 Scenario 1: FR4 with Partial Bandwidth Sharing of K signals (FR4-PBS- K) (Multi-carrier).

In Scenario 1, we have considered that the subcarriers partially overlap. The transmitted pulses follow the Nyquist criterion. However, at the receiver side the orthogonality between the pulses is destroyed. Therefore, it will be necessary to equalize the data before being processed by the MUD. Otherwise, the interference level may degrade the MUDs performance in a serious way. Here the received signal is modelled as:

$$d[k] = Ae^{j\varphi} \sum_{m=0}^{K-1} x_m[k] + \eta[k], \quad (1)$$

where the transmitted signal x_m expressed in terms of the information data and the pulse-shape one is:

$$x_m[k] = \sum_n s_m[n] \cdot p_m[k - n \cdot M], \quad (2)$$

being M the oversampling factor. This means that the sampling frequency is $f_s = \frac{M}{T_{S,FP}}$, where $T_{S,FP}$ is the symbol period. The pulse that shapes the m -th subcarrier can be expressed in terms of the low-pass band filter $p[k]$ as:

$$p_m[k] = p[k]e^{j2\pi \cdot f_m \cdot k}. \quad (3)$$

Hence, $p_m[k]$ is obtained by frequency-shifting the prototype pulse. At the output of the filters, the signal is down-sampled by a factor M . The rate conversion is performed to get an estimate of the transmitted symbols. By stacking column-wise the signal filtered on each subcarrier, we get

$$r_q[n] = (d[k] \star p_q^*[-k])_{k=nM}, \quad 0 \leq q \leq K-1, \quad (4)$$

where the operator \star stands for the linear convolution, $\mathbf{s}[n] = [s_0[n], \dots, s_{K-1}[n]]^T$ and $\boldsymbol{\omega}[n] = [\omega_0[n], \dots, \omega_{K-1}[n]]^T$. The filtered noise on the q -th subcarrier is formulated as $\omega_q[n] = (\eta[k] \star p_q^*[-k])_{k=nM}$. The channel matrix $\mathbf{H}[n] \in \mathbb{C}^{K \times K}$ is defined as

$$\mathbf{H}[n] = \begin{bmatrix} h_{0,0}[n] & \cdots & h_{0,K-1}[n] \\ \vdots & \ddots & \vdots \\ h_{K-1,0}[n] & \cdots & h_{K-1,K-1}[n] \end{bmatrix}. \quad (5)$$

The impulse response between the q -th and the m -th sub-carrier is given by $h_{q,m}[n] = h_c(p_m[k] \star p_q^*[-k])_{\downarrow k=nM}$. In order to estimate the transmitted symbols, the received data is MMSE equalized with the following matrix (See [19]):

$$\mathbf{A}_{eq} = \left(\mathbf{H}_{eq} \mathbf{H}_{eq}^H + \frac{\mathbf{R}_\omega}{E_s} \right)^{-1} \mathbf{H}_{eq,0}, \quad (6)$$

where $\mathbb{E} \{ \omega_{eq}[n] \omega_{eq}^H[n] \} = \mathbf{R}_\omega$ is the correlation matrix of the noise plus residual co-channel interference term and E_s is the mean energy symbol. To get (6) it has been assumed that symbols are statistically independent, i.e. $\mathbb{E} \{ s_q[n] s_m^*[l] \} = E_s \delta_{q,m} \delta_{n,l}$. Concerning the notation, \mathbf{H}_{eq} is a convolution matrix defined as

$$\mathbf{H}_{eq} = \begin{bmatrix} \mathbf{H}[-L_c] & \cdots & \mathbf{H}[L_c] & 0 & \cdots & 0 \\ 0 & \mathbf{H}[-L_c] & \cdots & \mathbf{H}[L_c] & & \vdots \\ \vdots & 0 & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & \mathbf{H}[-L_c] & \cdots & \mathbf{H}[L_c] \end{bmatrix}, \quad (7)$$

being L_c the memory of the MMSE equalizer.

2.1.2 Scenario 2: FR4 with Full Bandwidth Sharing of K signals (FR4-FBS-K) (Single Carrier).

Regarding the Scenario 2, Full Bandwidth Sharing (FR4-FBS-K) can be considered as a particular case of Partial Bandwidth Sharing. If the overlapping between subcarriers increases, then the initial frequency distribution in the absence of frequency overlapping turns into a single carrier scheme, where all subcarriers occupy the whole bandwidth. In other words, there are K overlapped carriers in one beam conveying different information for the same user. This means that the communication channel is the same for all signals, since they are totally overlapped. Thus, the C/I is 0 dB. In the most general case, if necessary, we can introduce a phase offset between different signals and use different mapping schemes. In this case, we can control through the variable $\rho_m[n]$ the channel that undergoes the symbol $s_n[n]$. Then, the m -th transmitted signal becomes:

$$x_m[k] = \sum_n \rho_m[n] \cdot s_m[n] \cdot p_s[k - n \cdot M]. \quad (8)$$

Thus the received signal is:

$$d[k] = A e^{j\varphi} \sum_m^{K-1} x_m[k] + w[k]. \quad (9)$$

At the receive side, the signal is fed into a filter that is matched to $p[k]$, which it is the same for all signals. Hence, a single branch suffices to demodulate the signals. The output of the matched filter is given by

$$r[n] = (d[k] \star p^*[-k]). \quad (10)$$

2.2 Cooperative NOMA in multibeam satellite systems

We consider a multibeam satellite downlink transmission with full frequency reuse, consisting of B beams. The channel is considered to be AWGN. Due to the frequency reuse, each user receives the signals from all other beams as well. Uniform distribution of users in all beams in addition to equal number of users per beam (M) is assumed. So, in beam b , ($b=1, \dots, B$), the set of users is provided as $S=[u(b,1), u(b,2), \dots, u(b,M)]$. The term $u(b,k)$ stands for the k -th

($k=1, \dots, M$) user located at beam b . At the gateway, each $u(b,k)$ -th user data stream is channel coded and modulated independently. Considering $S_{u(b,k),b}$ as the coded-modulated symbol of user $u(b,k)$ from beam b , with average power equal to one ($E[|S_{u(b,k),b}|^2] = 1$), and the transmitted power for that user from beam b , as $P_{u(b,k),b}$, the transmission signal vector is:

$$x(t) = \sum_{b=1}^B \sum_{k=1}^M \sqrt{P_{u(b,k),b}} \cdot S_{u(b,k),b} \cdot p(t - kT). \quad (11)$$

The received signal vector at user $u(b,k)$ can be written as:

$$y_{u(b,k)} = H_{u(b,k)} \cdot x + w_{u(b,k)} \quad (12)$$

Where $H_{u(b,k)}$ is the $1 \times B$ -dimensional channel vector between multibeam satellite and user $u(b,k)$ indicating the relative interference caused by other beams, and $w_{u(b,k)}$ is the complex Gaussian noise $\mathcal{N}(0, n_{u(b,k)})$ received by the user $u(b,k)$. We define channel parameter as:

$$g_{u(b,k)} = \sqrt{|H_{u(b,k)}|^2} \quad (13)$$

So (14) could be written as:

$$y_{u(b,k)} = g_{u(b,k)} \cdot \sum_{b'=1}^B \sqrt{P_{u(b,k),b'}} \cdot S_{u(b,k),b'} + n_{u(b,k)} \quad (14)$$

After explaining describing the system model we introduce their mathematical performance evaluation expressions in terms of capacity.

3. CAPACITY PERFORMANCE EVALUATION

This section provides the capacity in terms of bits per channel use. The theoretical expressions are particularized for FR4-PBS-2, FR4-FBS-K, and cooperative NOMA systems.

3.1 Capacity for FR4-PBS-K, with K=2

In order to avoid using a cumbersome notation, a simplified model has been considered to represent the signal of each subcarrier, which is given by:

$$\begin{aligned} y_0 &= h_{0,0}s_0 + h_{0,1}s_1 + u_0, \\ y_1 &= h_{1,0}s_0 + h_{1,1}s_1 + u_1, \end{aligned} \quad (15)$$

where $h_{j,k}$ is the equivalent channel between subcarrier j and subcarrier k , s_j is the signal transmitted in the j -th subcarrier, and u_j is the noise plus the interference term that contaminates the j -th subcarrier. If we consider s_0, s_1 , as useful information signals, the maximum achievable rate is given by these bounds:

$$\begin{aligned} R_0 &\leq I(s_0; y_0, y_1 | s_1) \\ R_1 &\leq I(s_1; y_0, y_1 | s_0) \\ R_0 + R_1 &\leq I(s_0, s_1; y_0, y_1), \end{aligned} \quad (16)$$

being $I(s_j; y_0, y_1 | s_k)$ the mutual information between s_j and y_0, y_1 given s_k . The value of $I(s_0, s_1; y_0, y_1)$ defines the mutual information between s_0, s_1 and y_0, y_1 . If we assume

that the noise and interference signals follow a Gaussian distribution, then the rates are subject to the following constraints:

$$\begin{aligned} R_0 &\leq \log_2(1 + SNR_{0,0} + SNR_{1,0}) \\ R_1 &\leq \log_2(1 + SNR_{0,1} + SNR_{1,1}) \\ R_0 + R_1 &\leq \log_2\left(1 + \sum_{j=0}^1 SNR_{j,0} + \sum_{j=0}^1 SNR_{j,1}\right). \end{aligned} \quad (17)$$

Next, we have assumed that u_j is modelled as a circularly symmetric complex Gaussian variable with zero mean and unit variance, for $i=0,1$. The transmitted signals fulfil this average power constraint $E[|s_i|^2] = 1$, for $i=0,1$. Then, the channel quality metrics can be expressed as $SNR_{i,j} = |h_{i,j}|^2$.

3.2 Capacity for FR4-FBS-K, with K=2

The decoding strategies analysed in this section are listed below:

1. There is one signal per beam and the co-channel interference is treated as noise (FR4-IAN).
2. There are K signals, with $K=2$, that are simultaneously transmitted. The rest of signals that come from other beams are treated as interference (FR4-FBS-K).

The technique FR4-IAN can be considered as a benchmark, because a single signal is decoded and, thus, it relies on single user detection (SUD). On the contrary, FR4-FBS-K systems benefit from MUD. This means that the structure of the interference is exploited to improve the overall system performance.

3.2.1 Rate constraint for FR4-IAN

If we consider the signals that come from other beams as noise, then the received signal becomes

$$y = h_0 s_0 + u, \quad (18)$$

In notation terms, u accounts for the noise plus the residual interference term. The user will be able to decode the corresponding message s_0 when the rate satisfies this constraint:

$$R_0 \leq I(s_0; y). \quad (19)$$

3.2.2 Rate constraints for the FR4-FBS-2

For this situation the signal model at the input of the detector is:

$$y = \rho_0 \cdot s_0 + \rho_1 \cdot s_1 + u, \quad (20)$$

being y the signal at the output of the matched filter. Let s_j and ρ_j be the j -th information signal and its corresponding phase offset, whereas u represents the noise plus the co-channel interference term. If we consider s_0, s_1 as information signals, then the maximum achievable rate is given by

$$\begin{aligned} R_0 &\leq I(s_0; y|s_1) \\ R_1 &\leq I(s_1; y|s_0) \\ R_0 + R_1 &\leq I(s_0, s_1; y) \end{aligned} \quad (21)$$

As we have previously commented, the input-output relation in FR2 and FR4-FBS-2 obey the same model. Therefore, FR2 will be subject to the same rate constraints as FR4-FBS-2. However, in FR2 the rotation angles ρ_j are independent and cannot be optimized.

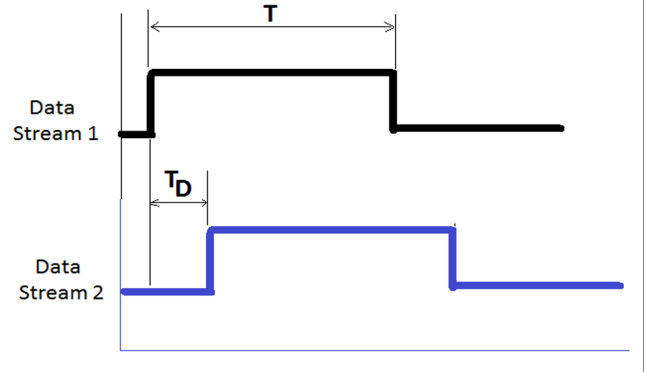


Figure 2: Time delay between the two data streams.

3.2.3 Cooperative NOMA

Based on the proposed cooperative NOMA with two beams cooperation, we assume b_m to be the beam number for which the user $u(b, k)$ receives the dominant interference from. Hence, the signal to noise plus interference ratio ($SNIR$) can be written as:

$$Y_{u(b,k)} = \frac{g_{u(b,k),b}^2 \cdot P_{u(b,k),b} + g_{u(b,k),b_m}^2 \cdot P_{u(b,k),b_m}}{\sum_{b'=1, \neq b, \neq b_m} g_{u(b,k),b'}^2 \cdot P_{u(b,k),b'} + n_{u(b,k)}^*}. \quad (22)$$

Where, the numerator is the addition of received powers from the transmitters in the main and the most dominant interfering beams. The denominator is the addition of channel noise and summation of all interferences, except for the co-operating most dominant interference. The aggregate data rate will be as:

$$R_{sum-rate-overlay} = W \cdot \log_2(1 + Y_{u(b,k)}). \quad (23)$$

In case of asynchronicity, DVB-S2X standard proposes devising the super frame (SF) aligned preambles, for estimation of channel parameters. Based on Annex E.4 of standard DVB-S2X, the pilot fields are constructed by a Walsh-Hadamard (WH) sequence of 32 plus padding of 4 bits, resulting in a set of 32 orthogonal WH sequences. The WH sequences result from the below recursive algorithm: [18]

$$C_{2m} = \begin{bmatrix} C_m & C_m \\ C_m & -C_m \end{bmatrix}, \text{ where } C_1 = 1. \quad (24)$$

The i -th row of the C_{32} , C_i , corresponds to the i -th WH sequence, $i=1, \dots, 32$. Being aware of these C_i sequences, the user terminal can distinguish both its own and the 31 closest interfering beams. The channel coefficient is estimated as:

$$\hat{h}_i = \frac{1}{P_{SF} \cdot N_p} \sum_{k=1}^{N_p} \sum_{j=1}^{P_{SF}} y_k^p(j) \cdot C_i^*(j) \quad (25)$$

Where, P_{SF} is the number of pilots within a block, and N_p is the number of transmitted pilot blocks. Also, y_k^p is the received signal corresponding to k -th pilot block. We have estimated the carrier to interference ratio (CIR) imposed from any interfering beam on the target user by

$$\widehat{CIR}_{i,j} = \frac{|\hat{h}_i|^2}{|\hat{h}_j|^2}. \quad (26)$$

Moreover, the signal to noise ratio (SNR) of the user ter-

minial is estimated as

$$\widehat{SNR}_i = \frac{|\hat{h}_i|^2}{|y|^2 - \sum_{j=1}^{32} |\hat{h}_j|^2}. \quad (27)$$

The numerator in (27) is the received power of the desired signal for user terminal i . The denominator calculates the noise power by subtracting all signals' power from the received signal's power. Thus, in a typical receiver designed for cooperative NOMA, the receiver recovers the clock and phase parameters separately for both the main and the dominant interfering signals. It makes sense to assume frame synchronicity between the two data streams, as either both data streams are sent from one gateway, or the gateways sending these data streams are synchronous. Still, due to distance there might be some time delay between the two data streams. This concept is shown typically in Fig.2, where T is the symbol time and T_D is the time delay between the two data streams.

4. CONSIDERATIONS ON THE SECRECY CAPACITY

The inherent broadcast communication and the large footprint of the satellite systems make them vulnerable to potential eavesdroppers. As a result, the privacy and security in satellite communications is a critical issue. Usually, the security in satellite communications is guaranteed in the upper layers of the stack by implementing cryptographic protocols. However, it is possible to add a certain level of security if it is used physical layer security (PLS). In this regard, it is possible to achieve perfect secure transmissions when the channel quality of the eavesdropper is lower than the one of the desired users. Specifically, it is well-known that the secrecy capacity, denoted as C_S is equal to the difference between the capacity of the desired receiver, C_D , and the illegitimate receiver, so-called eavesdropper, C_E [22] :

$$C_S = C_D - C_E \quad (28)$$

In this case, it is possible to achieve secure communications only if the channel of the desired user is better than the eavesdropper one. Thus, the transmitter has to encode the data with the maximum data rate that allows its channel. By doing so, the message addressed to the desired user cannot be decoded by the unauthorized eavesdropper since it is encoded with a data rate that falls in the outage region of the eavesdropper. In this regard, the research on high spectral systems, like the ones presented in this paper, reduces the number of potential eavesdroppers since they require a much more complex system to listen the transmitter or be placed in a region of the satellite footprint much closer to position of the desired user, which could not be of interest for the eavesdropper in case of being detected. Therefore, a side effect of high spectral systems in general and in particular for satellite is their close relationship with secure networks since increase the capacity of the desired user, C_D .

5. RESULTS

In this section we provide some numerical results. As for the system parameters, the following list includes the most relevant metrics:

- Scenario 1, FR4-PBS-2 with 90% of overlapping.

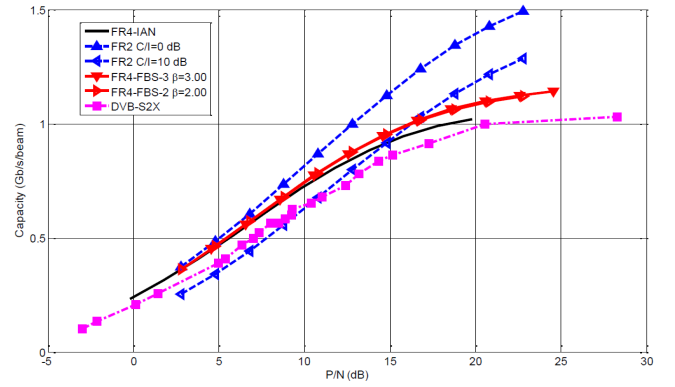


Figure 3: Envelope of capacity in Gb/s/beam.

- Scenario 2, FR4-FBS-2.
- The symbols have been drawn from QPSK, 8PSK, 16APSK and 32APSK alphabets according to DVB-S2X standards.
- The roll-off factor of the pulses is $\alpha = 0.05$.
- The oversampling factor when generating the pulse shape is equal to 4.
- The MMSE equalizer processes $2L_c+1=41$ samples.
- The beam bandwidth in FR2 systems is $W_{FR2}=500\text{MHz}$, whereas the beam bandwidth in FR4 systems is $W_{FR4}=250\text{MHz}$.
- The carrier to interference ratio is $C/I=15\text{ dB}$ in FR4 systems.

As a summary, we have depicted in Fig.3 the envelope of all transmission techniques. This translates into representing for each P/N only the modulation that leads to the highest capacity. Taking into consideration that FR4-PBS-2 and FR4-FBS-2 achieve similar performance, we refrain from representing FR4-PBS-2 for the sake of clarity in the presentation. To determine how close state-of-the art communication systems are able to perform with respect to the theoretical capacity, we have included the spectral efficiency provided by the modulation and coding schemes of the DVB-S2X standard. The DVB-S2X curve has been obtained for the four colour beam pattern under the assumption that the carrier to interference ratio is 15 dB and that the receiver treats the interference as noise. In this case, the gap between FR4-IAN and DVB-S2X is between 1.5 dB and 2 dB.

From Fig.3 it can be inferred that the best candidates are FR2 and FR4-FBS-2. Thus, the two transmission techniques that will be selected to conduct the FER analysis are FR2 with $C/I_1=0\text{dB}$ and FR4-FBS-2. This case is definitely interesting because allows us to draw an analogy between FR2 and FR4. As a result of the similarity between both schemes, the same receiver can be employed. In this regard, we have implemented the iterative detector-decoder scheme described in [1]. It has been considered that the number of LDPC iterations is 50 and that the decoder and the detector exchange extrinsic information in 2 iterations at most.

According to Fig.4, which depicts the FER results when the two streams of interest are assigned QPSK 2/5 and

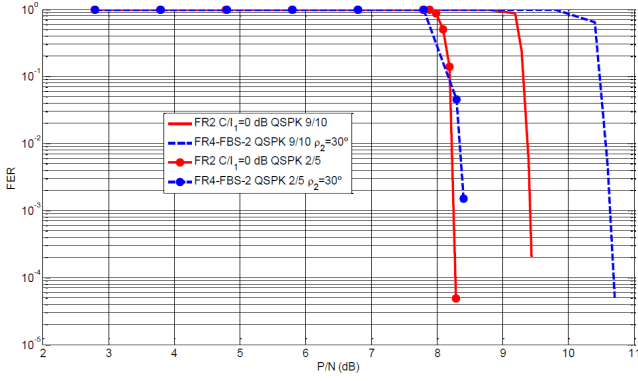


Figure 4: FER against P/N. a) Stream 1 is assigned QPSK 2/5 b) Stream 2 is assigned QPSK 9/10.

QPSK 9/10, FR2 and FR4-FBS-2 are able to guarantee a $FER = 10^{-3}$ when P/N is equal or higher than 9.5 dB and 10.7 dB, respectively. The throughput that can be achieved in both schemes is $(1-10^{-3}) \cdot \frac{0.5}{2 \cdot (1+\alpha)} \cdot (0.789 + 1.788) = 0.613$ Gb/s. The theoretical capacity determines that the maximum achievable rate in FR2 at $P/N=9.5$ dB is $\frac{0.5}{2 \cdot (1+\alpha)} \cdot 2.805 = 0.668$ Gb/s. Therefore, the rate could be increased up to 9%. Concerning FR4-FBS-2, the relative difference between the theoretical bound and the achievable rate is equal to 18%. We have experimentally verified that the following combinations do not converge: 8PSK 3/5+8PSK 3/5, 8APSK 5/9+8APSK 5/9 and 16APSK 1/2+16APSK 1/2. This highlights that the best strategy to target a given FER when two streams are received with the same energy is to select a combination of low and high order modulation formats, such as QPSK+16APSK or QPSK and 32APSK.

Considering the SIC block in cooperative NOMA receiver, even the slight time delay, T_D , would result in residual error when the recovered, reconstructed signal is going to be subtracted from the aggregate received signal. We evaluated the effect of this residual error by simulating different values of T_D . In this simulation, we assume the two data streams to be "quasi synchronous", i.e., the relative time delays (T_D) are within one symbol time (T). We have simulated the two-beam, two-user scenario with different time delays to find out the effect of non-symbol synchronous reception of the two data streams on cooperative NOMA. The performance is evaluated by:

- $SNR=7$ dB, $CIR = 0$ dB
- Two beams, Two users
- Symbol delay offset: 25%, 50%, and 75% of symbol time duration (T_D/T)

The aggregate data rate achieved based on simulation results are provided in Table 1. It is clear that without symbol synchronicity between the two received data streams, the performance will be degraded due to residual error in SIC. However, the performance is still acceptable; hence, cooperative NOMA is possible in case there is no strict alignment of the two data streams.

6. CONCLUSIONS

Table 1: Time Delay Impact on Overlay Coding Performance

| Concept | $T_D=0$ | $\frac{T_D}{T}=0.25$ | $\frac{T_D}{T}=0.5$ | $\frac{T_D}{T}=0.75$ |
|----------------|---------|----------------------|---------------------|----------------------|
| A. data rate | 2.53 | 2.44 | 2.36 | 2.36 |
| Data rate Loss | - | 3.6% | 6.7% | 6.7% |

In the comparison of FR2 vs FR4 systems we can conclude that the larger the number of points in the constellation, the lower the minimum distance between symbols. This means that the residual interference and the co-channel interference become the dominant sources of distortion as the cardinality of the alphabet increases. In the light of this observation, together with the fact that the level of the interference is higher in FR4 than in FR2 systems, it follows that FR4 systems saturate at a lower capacity value. Furthermore, when we evaluate the FER of two streams received with the same energy consists on combining low and high order modulation formats, such as QPSK+16APSK or QPSK and 32APSK. However, we have to take into account that these systems use MUD. Consequently, it means that the two streams that are jointly detected have to be perfectly aligned in time, which is not a minor observation for satellite communications. This constraint could be alleviated if satellite communications resort to Time Advance techniques as terrestrial 3GPP LTE based systems do [20],[21] or coordination between the gateways. However, due to the distances in satellite communications, slight time misalignment is inevitable. As we studied in this paper this slight symbol asynchronism would cause degradation in the systems performance. Investigating the effect and solution for symbol asynchronicity in cooperative NOMA in multibeam satellite forward link is left as part of authors future work. Finally, comment that the design of communication systems with large spectral efficiencies difficults the task of the eavesdroppers since the messages of the desired users are encoded with large data rates. Results on this area are also part of author's future work.

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8. REFERENCES

- [1] G. Colavolpe, A. Modenini, A. Piemontese and A. Ugolini, On the application of Multiuser Detection in multibeam satellite systems, ICC 2015.
- [2] M. Caus, A. I. Perez-Neira, M. Angelone, and A. Ginesi, An innovative interference mitigation approach

- for high through-put satellite systems, in IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications, June 2015.
- [3] G. Colavolpe, A. Modenini, A. Piemontese, and A. Ugolini, Multiuser Detection in Multibeam Satellite Systems: Theoretical Analysis and Practical Schemes, in IEEE 16th International Signal Processing Advances in Wireless Communications Conference (SPAWC), pp.525-529, 2015, Stockholm, Sweden.
 - [4] M. Angelone, A. Ginesi, N. Alagha Advanced Physical Layer Techniques: Performance Limits within Future Multi-spot Ka-band Networks in the Proceedings of IEEE First AESS European Conference on Satellite Telecommunications (ESTEL), Oct. 2012, Rome, Italy
 - [5] F. Rusek, J. B. Anderson The Two Dimensional MIMO Limit, In Proc. Inter. Symp. on Inf. Theory (ISIT), pp.970-974, 2005.
 - [6] A. Modenini, Advanced transceivers for spectrally-efficient communications, Ph.D. dissertation, Jan. 2014.
 - [7] T. Delamotte, G. Bauch Receiver Design for GEO Satellite Systems Using MIMO and Time-Frequency Packing, In Proc. Inter. OFDM Workshop, pp.9-15, 2014.
 - [8] S. Chatzinotas, S. K. Sharma, B. Ottersten, Frequency Packing for Interference Alignment-based Cognitive Dual Satellite Systems, In Proc. Veh. Techn. Conf. (VTC Fall), pp.1-7, 2013.
 - [9] M. Caus, M. A. Vazquez, A. P. Neira, NOMA and interference limited satellite scenarios, In Proc. Asilomar Conference on Signals, Systems and Computers, pp. 497-501, 2016.
 - [10] E. Casini, R. De Gaudenzi, A. Ginesi, DVB-S2 modem algorithms design and performance over typical satellite channels, In Proc. International Journal of Satellite Communications and Networking. Vol.22, pp. 281-318, 2004.
 - [11] Z. Ding, M. Peng, H. Vincent Poor, Cooperative non-orthogonal multiple access in 5G systems, in IEEE Commun. Letters, Vol.19, No.8, Aug. 2017, pp. 1462-1465
 - [12] N. Khan Beigi, M. R. Soleymani, Interference management using cooperative NOMA in multibeam satellite systems, accepted in IEEE International Conference on Communications (ICC), May 2018
 - [13] H. Chaouech, R. Bouallegue, Channel estimation and detection for multibeam satellite communications, in IEEE Asia Pacific Conf. on Circuits and Systems, 2010, pp. 366-369
 - [14] W. Gappmair, M. Bergmann, B. S. Rechberger, New results on location aware channel estimation for multibeam satellite links, in IEEE Commun. Letters, vol. 18, No. 8, Aug 2014, pp.1355-1358
 - [15] L. Xiao, L. Cottatellucci, Contention resolution and channel estimation in satellite random access channels, in IEEE Int. Conf. on Commun. in China, 2012, pp.562-567
 - [16] ETSI EN 302 307 v1.2.1, Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2).
 - [17] Gappmair, W., and Ginesi, A., Cramer-Rao lower bound and parameter estimation for multibeam satellite links, in Int. J. Satell. Commun. Network, 2016.
 - [18] Digital Video Broadcasting (DVB), Implementation guidelines for the second generation system for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 2 - S2 Extensions (DVB-S2X)
 - [19] J. Bas, M. Caus, A. Perez, M. Angelone, A. Ginesi, A. Modenini, J. Ebert, A. G. Armada, Mutual Information Analysis of Frequency Packing Schemes in Multi-Beam Satellite Systems, In Proc. Ka-Band Conference, Trieste, 2017.
 - [20] 3GPP specification 36.133, Requirements for support of radio resource management, v15.3, 2018.
 - [21] 3GPP specification 36.321, Medium Access Control (MAC) protocol specification, v15.2, 2018.
 - [22] S. K. Leung-Yan-Cheong, M. E. Hellman, The Gaussian wiretap channel, IEEE Trans. Infor. Theory, vol.24, n 4, pp.451-456, Jul. 1978.