ABSTRACT
This paper presents a short review on the main high spectral efficient systems for multibeam satellite communications. In this regard, we study the use of Multi-User Detectors (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. 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
Spectral efficiency, NOMA, multibeam satellites, CCI, MUD

1. INTRODUCTION
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 [5],[8]. Recent studies, e.g. [3] 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 is referred to as Time-Frequency Packing (TFP) (See [2],[9],[7]. Next, from the 3GPP arena, systems based on NOMA have shown they provide a larger spectral efficiency than the schemes based on orthogonal ones [6].

Non-orthogonal multiple access (NOMA) has recently been proposed as the means of sharing the limited available resources with more users [10]. 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 [11]. 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.

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
This section shows the signal models of the FR4 systems based on frequency packing and the cooperative NOMA, which it uses full frequency reuse.

2.1 FR4 systems based on frequency packing
In FR4 we have distinguished between two scenarios. In Scenario 1, subcarrier signals are partially overlapped and Scenario 2 where all signals have the same carrier frequency and span the total beams bandwidth.

2.1.1 Scenario 1: FR4 with Partial Bandwidth Sharing of K signals (FR4-PBS-K) (Multi-carrier)
The signal model of this scenario is:

\[ d[k] = Ae^{j\phi} \sum_{m=0}^{K-1} x_m[k] + n[k], \]

where the transmitted signal \( x_m \) expressed in terms of the information data and the pulse-shape one, \( p_m \), is:

\[ x_m[k] = \sum_{n} s_m[n] \cdot p_m[k - n \cdot M], \]
being $M$ the oversampling factor. At the output of the filters, the signal is down-sampled by a factor $M$. By stacking column-wise the signal filtered on each subcarrier, we get

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

where the operator $*$ stands for the linear convolution. The channel matrix $H[n] \in \mathbb{C}^{K \times K}$ is defined as

$$H[n] = \begin{bmatrix}
h_{0,0}[n] & \cdots & h_{0,K-1}[n] \\
h_{K-1,0}[n] & \cdots & h_{K-1,K-1}[n]
\end{bmatrix}. \quad (4)$$

The impulse response between the $q$-th and the $m$-th subcarrier is given by $h_{q,m}[n] = h_c(p_m[k] * p_q[-k])_{k=n,M}$. In order to estimate the transmitted symbols, the received data is MMSE equalized with the following matrix (See [4]):

$$A_{eq} = \left( H_{eq} H_{eq}^H + \frac{R_c}{E_s} \right)^{-1} H_{eq,0}. \quad (5)$$

where $R_c$ is the correlation matrix of the noise plus residual co-channel interference term and $E_s$ is the mean energy symbol. Next, $H_{eq}$ is a convolution matrix defined as

$$H_{eq} = \begin{bmatrix}
H[-L_c] & \cdots & H[L_c] & 0 & \cdots & 0 \\
0 & H[-L_c] & \cdots & H[L_c] & \cdots & 0 \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
0 & \cdots & 0 & H[-L_c] & \cdots & H[L_c]
\end{bmatrix}
$$

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, we can control through the variable $\rho_m[n]$ the channel that undergoes the symbol $s_m[n]$. Then, the $m$-th transmitted signal becomes:

$$x_m[k] = \sum_n \rho_m[n] \cdot s_m[n] \cdot p_k[k - n \cdot M]. \quad (7)$$

Thus the received signal is:

$$d[k] = A c^j \sum_{m}^{K-1} x_m[k] + w[k]. \quad (8)$$

At the receive side, the signal is fed into a filter that is matched to $p[k]$, which is the same for all signals. Thus, the output of the matched filter is

$$r[n] = (d[k] * p^*_[-k]). \quad (9)$$

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 $b$, ($b=1,\cdots,B$), the set of users is provided as $S=[u(b,1), u(b,2), \cdots, u(b,M)]$. The term $u(b,k)$ stands for the $-t$th ($k=1,.,M$) 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:

$$x(t) = \sum_{b=1}^{B} \sum_{k=1}^{M} \sqrt{P_{u(b,k),b}} \cdot S_{u(b,k),b} \cdot p(t - kT). \quad (10)$$

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

$$y_{u(b,k)} = H_{u(b,k)} \cdot x + w_{u(b,k)} \quad (11)$$

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 $N(0,n_{u(b,k)})$ received by the user $u(b,k)$. We define channel parameter as:

$$g_{u(b,k,\lambda)} = \sqrt{|H_{u(b,k)}|^2} \quad (12)$$

So (13) could be written as:

$$y_{u(b,k)} = g_{u(b,k)} \cdot \sum_{b'=1}^{B} \sqrt{P_{u(b,k),b'}} \cdot S_{u(b,k),b'} + n_{u(b,k)} \quad (13)$$

After describing the system model we introduce their performance evaluation metric in terms of capacity.

3. CAPACITY PERFORMANCE EVALUATION

This section provides the theoretical capacity for FR4 and cooperative NOMA systems.

3.1 Capacity for FR4-FBS-K, with $K=2$

The signal model for each subcarrier is given by:

$$y_0 = h_{0,0}s_0 + h_{0,1}s_1 + u_0,$$
$$y_1 = h_{1,0}s_0 + h_{1,1}s_1 + u_1,$$

where $h_{j,k}$ is the equivalent channel between subcarrier $j$ and subcarrier $k$, $s_j$ and $u_j$ are the signal transmitted and the noise in the $j$-th subcarrier. If we consider $s_0,s_1$, as useful information signals, the maximum achievable rate is bounded by:

$$R_0 \leq I(s_0;y_0, y_1|s_1)$$
$$R_1 \leq I(s_1;y_0, y_1|s_0)$$
$$R_0 + R_1 \leq I(s_0, s_1; y_0, y_1),$$

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 $y_0, y_1$.

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

The decoding strategies analysed in this section are: i) FR4-Interference As Noise (FR4-IAN), ii) 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).
3.2.1 Rate constraint for FR4-IAN
In this case the received signal becomes
\[ y = h_0 s_0 + u, \]  
(16)
In notation terms, \( u \) accounts for the noise plus the residual interference term. The user is able to decode the message \( s_0 \) when its rate satisfies:
\[ R_0 \leq I(s_0; y). \]  
(17)

3.2.2 Rate constraints for the FR4-FBS-2
For this situation the signal model is:
\[ y = \rho_0 \cdot s_0 + \rho_1 \cdot s_1 + u, \]  
(18)
being \( y \) the signal at the output of the matched filter. Let \( s_j \) and \( \rho_j \) be the \( j \)-th information signal and its corresponding phase offset, whereas \( u \) represents the noise plus the co-channel interference. Thus the maximum rate is
\[ R_0 \leq I(s_0; y|s_1) \]
\[ R_1 \leq I(s_1; y|s_0) \]
\[ R_0 + R_1 \leq I(s_0, s_1; y) \]  
(19)

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:
\[ Y_{u(b, k)} = \frac{g_{u(b, k), b}^2 P_{u(b, k), b} + \sum_{k' \neq b} g_{u(b, k), b'}^2 P_{u(b, k), b'}}{N_0 + \sum_{k' \neq b, k} P_{u(b, k), b'}^2 + \sigma_{u(b, k)}}. \]  
(20)
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 cooperating most dominant interference. The aggregate data rate will be as:
\[ R_{\text{sum-rate-overlay}} = W \cdot \log_2(1 + Y_{u(b,k)}). \]  
(21)

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 channel coefficient is estimated as:
\[ \hat{h}_i = \frac{1}{T_{SF} \cdot N_p} \sum_{k=1}^{N_p} \sum_{j=1}^{P_{SF}} y_k^i (j) \cdot C_i^j (j) \]  
(22)
Where, \( P_{SF} \) is the number of pilots within a block, \( N_p \) is the number of transmitted pilot blocks and \( C_i^j \) is the \( i \)-th WH sequence. Also, \( y_k^i \) is the received signal corresponding to \( k \)-th pilot block. We have estimated the carrier to interference ratio (CIR) by
\[ \overline{CIR}_{i,j} = \frac{\hat{h}_i^2}{|h_j|^2}, \]  
(23)
and estimated the signal to noise ratio (SNR) as
\[ \overline{SNR}_i = \frac{|\hat{h}_i|^2}{|y|^2 - \sum_{j=1}^{32} |h_j|^2}. \]  
(24)
The numerator in (24) 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 receiver designed for cooperative NOMA, the 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 in Fig.1, where \( T \) is the symbol time and \( T_D \) is the time delay between the two data streams.

4. RESULTS
The following list includes the most relevant metrics: Scenario 1, FR4-PBS-2 with 90% of overlapping. The symbols have been drawn from QPSK, 8PSK, 16APSK and 32APSK alphabets. The roll-off factor is \( \alpha = 0.05 \). The oversampling factor is equal to 4. The MMSE equalizer processes \( 2L_{\text{inc}}+1=41 \) samples. The bandwidth in FR2 systems is \( W_{FR2}=500\text{MHz} \), whereas the bandwidth in FR4 systems is \( W_{FR4}=250\text{MHz} \). Finally, the \( C/I=15 \text{ dB} \) in FR4 systems. Thus Fig.2 shows the envelope of the capacity for all transmission techniques. This translates into representing for each \( P/N \) only the modulation that leads to the highest capacity. 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. 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 duration ($T$). 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: $SNR=7dB$, $CIR=0dB$. Two beams, Two users. The 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.

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

### 5. CONCLUSIONS

In the comparison of FR2 vs FR4 systems we can conclude that FR4 systems saturate at a lower capacity value. However, these systems use MUD. So, 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 [1] or coordination between the gateways. However, due to the distances in satellite communications, slight time misalignment is inevitable. As we have shown this slight symbol asynchronism degrades 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, the design of communications systems with a large spectral efficiency has a side effect that makes difficult the eavesdropping process. 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 one, so-called eavesdropper, $C_E$ [12]:

$$C_S = C_D - C_E$$  \hspace{1cm} (25)

Thus, it is possible to achieve secure communications if the channel of the desired user is better than the eavesdropper one. By doing so, the data rate of the desired user falls in the outage region of the eavesdropper. Results on this area are also part of author’s future work.

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