Cross-Layer Forward Packet Scheduling for Emerging Precoded Broadband Multibeam Satellite System

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***Abstract*—In this paper, we investigate the forward packet scheduling of a broadband GEO multibeam satellite system that aggressively reuses the user link frequency resources, and thus considers the implementation of interference mitigation techniques at the transmitter side to exploit the multi-antenna multiplexing via precoding. The scheduling and the precoding design are closely coupled with each other, making it very challenging to provide a joint optimal solution that can be implemented in practical systems. On the other hand, future broadband satellite systems have to be capable of accommodating heterogeneous services and guarantee their corresponding uneven Quality of Service (QoS) requirements. As a consequence, we propose a novel cross-layer scheduling algorithm which takes into account the physical layer framing together with the modulator and precoding functionality combined with system constraints imposed by QoS requirements in upper layers. The proposed design is compared and validated using numerical results considering a realistic multibeam satellite system.**

I. INTRODUCTION

Packet scheduling refers to the selection and aggregation of the information to be transmitted in each frame in order to allow efficient non-orthogonal access of the medium. Packet scheduling for the forward satellite link has been studied since the birth of DVB-S2 standard [1] (developed in 2003) in order to fully exploit its new features. In particular, the air interface suggested in DVB-S2 is able to adapt the Code and Modulation (ACM) to the propagation conditions so that the spectral efficiency maximized. This is done by providing to each user with the most suitable modulation and code (ModCod) value according to the measured signal-to-noise-plus-interference ratio (SINR). In the DVB-S2 ACM architecture, however, the choice of the physical layer mode to be used in each frame is necessarily linked to the scheduling process, as all the user packets included in one frame are transmitted with the same physical layer parameters [2]. In order to ensure that all packets can be decoded by their receiver terminals, the satellite encoder selects the ModCod scheme applied to each frame according to the user with minimum SINR included in that frame structure. Therefore, the larger the difference among the users' SINR encoded within a frame, the higher the performance loss. This is the reason why the DVB-S2 standard suggests to group the receivers in a frame according to similarities on the SINR levels. The latter has been considered the main design direction in the forward packet scheduling techniques available in the literature. As an example, the work in [3] selects the packets to be encoded within the same frame based on the definition of Correlated Areas (CA), i.e. geographical area within which channel conditions are highly correlated at a given time.

The scheduling function is also challenged by the need to deliver multimedia services in broadband multibeam satellite system. The nature of the packet traffic in broadband services is bursty, i.e. the data rate needed to support the different services is not constant. As a consequence, the conventional forward link satellite schedulers need to be adapted to optimize bandwidth (capacity) utilization not only based on the propagation conditions but also based on the Quality of Service (QoS), in the presence of traffic flows generated by services with different requirements. This topic has been addressed in [4]–[7], where different DVB-S2 compatible schedulers have been proposed to deal with broadband traffic with divergent QoS requirements.

On the other hand, in order to make the most out of the limited satellite radio resources, satellite systems are moving from conventional 4-color reuse schemes (4 beams served with 2 different frequencies and 2 different polarizations) to more aggressive frequency reuse strategies, where the same spectrum is used for multiple neighboring beams. However, the reuse of spectrum automatically translate into a co-channel interference problem. Linear precoding [8], [9] can effectively manage such interference assuming that the interference channel coefficients are properly estimated at each user terminal and reported back to the satellite gateway, who will exploit this knowledge by appropriately weighting the transmit symbols (precoded symbols).

The combination of precoding implementation with the packet scheduling imposes additional challenges to the satellite system design. In particular, both the precoding and the scheduling design are coupled due to the impact of both designs on the final terminal user performance [8]. On one hand, the precoding weights are designed according to the Channel State Information (CSI) of the user terminal packets that are grouped together within a frame, which is in turn determined by the scheduling algorithm. On the other hand, the scheduling design packs users together within a frame with similar SINR levels, which are determined by the precoding method. Given the aforementioned coupling between the joint

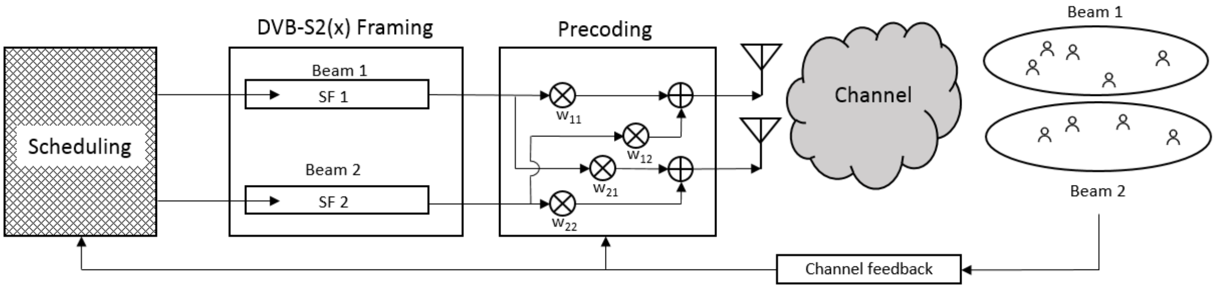

Fig. 1: Multibeam multicast satellite transmission scheme

precoding and scheduling problem is intractable. Computing the optimal solution is very challenging as it involves examining all possible combinations of users' scheduling with their corresponding precoding design. The latter is prohibitive in terms of complexity for practical systems. To relax the implementation complexity of such solution, [8], [10], [11] proposed a sub-optimal heuristic approach which, however, did not consider broadband heterogeneous traffic and thus, is not an appropriate solution when dealing with traffic with uneven QoS requirements.

In this paper, we consider the joint scheduling and precoding design in the forward link of a broadband multibeam satellite system by taking into account the severe delay constraints of real-time traffic, while providing acceptable throughput to non-real-time traffic. Clearly, the proposed design claims for a cross-layer scheduling design, where the PHY layer is considered to retrieve the CSI and apply the precoding technique, the MAC layer is considered to retrieve the destination of the packets, and the NET layer is considered to retrieve the traffic class.

The remainder of this paper is organized as follows. Section II introduces the satellite system model and the satellite air interface. After that, Section III presents the proposed joint scheduling and precoding design. Supporting numerical results are provided in Section IV, and Section V states the conclusion.

II. System Model

We consider the forward link of a broadband multibeam satellite system that aggressively reuses the user link frequency resources, where scheduling and precoding are applied. We consider a bent-pipe transparent GEO satellite architecture, which relays the signal from the gateway to the corresponding final receivers.

Fig. 1 illustrates a preliminary scheme of the satellite transmitter functional block diagram based on the DVB-S2(X) and extended to incorporate the advanced interference mitigation block (i.e. precoding). The suggested architecture considers a scheduling block in charge of buffering and processing the data according to the addressed user and its corresponding QoS requirements, prior to conveying them to the ACM modulator. Next, the encoded data is delivered in a frame-by-frame basis to the precoder, which properly weights the information streams before its final transmission to exploit the multi-antenna diversity. We assume that each user monitors its own CSI and reports this information back to the satellite gateway by means of a return link. We assume perfect CSI estimation. The impact of imperfect CSI is kept for future extensions of this work.

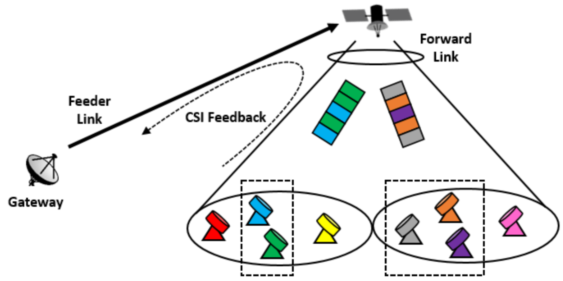

Fig. 2: Multibeam multicast satellite transmission scheme for $N = 2$, $Q = 4$, $|\mathcal{G}_{m,1}| - 2$ and $|\mathcal{G}_{m,2}| = 3$.

This paper focuses on the scheduling strategy, i.e. how to schedule the packets in the DVB-S2 frames in order to access the shared medium in the most efficient way while meeting the users' QoS requirements.

Let us assume the forward link transmission of N satellite beams, which are considered to be equal to the number of transmitting elements on the satellite. For the sake of spectral efficiency, we assume that all beams share the same frequency band B. We assume that each beam provides service to Q terminal users, which are randomly distributed over its coverage area. For each beam n, the Q terminal users are assumed to be orthogonally clustered into M groups, $\mathcal{G}_{1,n}$, $\mathcal{G}_{2,n}$, . . ., $\mathcal{G}_{M,n}$, such that the satellite provides service to one of these groups at a time by means of a DVB-S2 frame. The cardinality of $\mathcal{G}_{m,n}$ is denoted henceforth as $|\mathcal{G}_{m,n}|$. Note that this notation considers that each beam can serve a different number of users simultaneously, as illustrated in Fig. 2.

The received signal at the k-th user located at the n-th beam can be expressed as,

$$y_{k,n} = \mathbf{h}_{k,n}^T \mathbf{x} + n_{k,n}, \tag{1}$$

where $\mathbf{h}_{k,n} \in \mathbb{C}^{N\times 1}$ is the CSI vector corresponding to this particular user, $\mathbf{x}$ represents the vector of N precoded symbols and $n_{k,n}$ is the complex Additive White Gaussian Noise (AWGN) at user k of beam n.

For the sake of clarity, we can rearrange the received signals

(1) by using the following matrix notation,

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{2}$$

where, assuming that the $\mathcal{G}_{m,n}$ cluster of terminal users is served at each beam n, we have the following:

- The received symbols are arranged into $\mathbf{y} = \begin{bmatrix}\mathbf{y}_1^T & \mathbf{y}_2^T & \cdots & \mathbf{y}_N^T\end{bmatrix}^T$, where $\mathbf{y}_n \in \mathbb{C}^{|\mathcal{G}_{m,n}|\times 1}$ is the vector containing the received signal for the $|\mathcal{G}_{m,n}|$ users belonging to the n-th beam.
- The channel matrix $\mathbf{H}$ is defined as $\mathbf{H} = [\mathbf{H}_1 \quad \mathbf{H}_2 \quad \cdots \quad \mathbf{H}_N]^T$, where $\mathbf{H}_n$ refers to the channel matrix corresponding to beam n. In particular, $\mathbf{H}_n = [\mathbf{h}_{1,n} \quad \mathbf{h}_{2,n} \quad \cdots \quad \mathbf{h}_{|\mathcal{G}_{m,n}|,n}]^T$, which contains the CSI vectors of the served user terminals of beam n. The channel model is discussed in section II-A.
- Similarly, the vector $\mathbf{n}$ groups the noise samples in the following way $\mathbf{n} = \begin{bmatrix}\mathbf{n}_1^T & \mathbf{n}_2^T & \cdots & \mathbf{n}_N^T\end{bmatrix}^T$. We assume $\mathbb{E}\left[\mathbf{n}\mathbf{n}^H\right] = \mathbf{I}$.
- The vector $\mathbf{x} \in \mathbb{C}^{N\times 1}$ contains the precoded transmitted symbols. The structure of $\mathbf{x}$ is detailed in section II-B.

A. Channel Model

In this section, we explain the model of the channel matrix $\mathbf{H}$, which gathers the forward link budget information and phase rotations introduced by the over-the-air propagation. In particular,

$$\mathbf{H} = \mathbf{P}\hat{\mathbf{H}} \tag{3}$$

where the matrix $\mathbf{P}$ models the phase variations due to the different propagation paths and its components $[\mathbf{P}]_{x,y}$ are defined as,

$$[\mathbf{P}]_{x,y} = \begin{cases} e^{j\phi_x} & \text{if } x = y \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

being ϕ_x a uniform random variable between $-\pi$ and π.

The matrix $\hat{\mathbf{H}}$ represents the real CSI contribution, which is determined by the satellite antenna gain, the path loss, the received antenna gain and the noise power. More precisely, the (k, n)-th component of $\hat{\mathbf{H}}$ is given by,

$$\left[\hat{\mathbf{H}}\right]_{k,n} = \frac{\sqrt{G_R G_{k,n}}}{4\pi \frac{d_k}{\lambda}\sqrt{K_B T B}} \tag{5}$$

where G_R is the user terminal antenna gain, $G_{k,n}$ denotes the gain from the n-th satellite antenna towards the k-th user served within the n-th beam and d_k is the slant range between the satellite and the k-th user. The term $\sqrt{K_B T B}$ represents the noise contribution, where K_B is the Boltzmann constant and T is the receiver noise temperature. It is common practice to include the noise contribution into the channel model [8], [10], [11] in order to proceed with the assumption of unit-variance noise.

B. Precoded Signal Model

In order to minimize the co-channel interference impact, the transmitted signal is formed as,

$$\mathbf{x} = \mathbf{W}\mathbf{s} \tag{6}$$

where the length N information vector $\mathbf{s}$ contains the raw symbols coming from the DVB-S2 modulator and satisfies $\mathbb{E}\left[\mathbf{s}\mathbf{s}^H\right] = \mathbf{I}$. The matrix $\mathbf{W}$ denotes the multicast precoding matrix. Note that the transmitted symbols are precoded in a frame-by-frame basis and thus, the same precoding vector applies to the multiple users scheduled within each particular frame. Given that we transmit a single frame per antenna, the precoding design consists in obtaining the precoding vectors $\mathbf{w}_n \in \mathbb{C}^{N\times 1}$ for each n-th transmitted frame, such that the precoding matrix $\mathbf{W}$ is build as,

$$\mathbf{W} = [\ \underbrace{\mathbf{w}_1 \ \ \ldots \ \ \mathbf{w}_1}_{\text{Repeated } |\mathcal{G}_{m,1}| \text{ times}} \cdots \ \underbrace{\mathbf{w}_N \ \ \ldots \ \ \mathbf{w}_N}_{\text{Repeated } |\mathcal{G}_{m,N}| \text{ times}}]. \tag{7}$$

The design of the multicast precoding matrix $\mathbf{W}$ has been addressed in [8], [10]. In this paper, we follow the Minimum Mean Squared Error (MMSE) design, which coincides with the popular Regularized Zero Forcing (RZF) approach [9], [12]. In particular, and for the multicast case, the MMSE design corresponds to the following expression,

$$\tilde{\mathbf{W}}_{\text{MMSE}} = [\mathbf{w}_1 \quad \mathbf{w}_2 \quad \cdots \quad \mathbf{w}_N] = \tilde{\mathbf{H}}^H\left(\tilde{\mathbf{H}}\tilde{\mathbf{H}}^H + \alpha\mathbf{I}\right)^{-1} \tag{8}$$

where $\alpha = 1/P$, being P the total power available at each satellite beam, and $\tilde{\mathbf{H}}$ denotes the $N \times N$ channel matrix, which is a function of the original multicast channel matrix $\mathbf{H}$. In particular, one common way to reconvert the multicast channel matrix $\mathbf{H}$ into a square unicast-like channel matrix $\tilde{\mathbf{H}}$ is to take the average over the amplitude and over the phase of the CSI vectors corresponding to the users included in each frame. Let us denote $\tilde{\mathbf{H}} = \begin{bmatrix}\tilde{\mathbf{h}}_1 & \tilde{\mathbf{h}}_2 & \cdots & \tilde{\mathbf{h}}_N\end{bmatrix}^T$, the mean channel vector per beam $\tilde{\mathbf{h}}_n$ is given by,

$$\left[\tilde{\mathbf{h}}_n\right]_x \begin{cases} \left|\left[\tilde{\mathbf{h}}_n\right]_x\right| = \frac{1}{|\mathcal{G}_{m,n}|}\sum_{i\in\mathcal{G}_{m,n}} \left|\left[\mathbf{h}_{i,n}\right]_x\right| \\ \angle\left[\tilde{\mathbf{h}}_n\right]_x = \frac{1}{|\mathcal{G}_{m,n}|}\sum_{i\in\mathcal{G}_{m,n}} \angle\left[\mathbf{h}_{i,n}\right]_x, \end{cases} \tag{9}$$

where $\left[\tilde{\mathbf{h}}_n\right]_x$ denotes the x-th element of $\tilde{\mathbf{h}}_n$ and $\left[\mathbf{h}_{i,n}\right]_x$ denotes the component x of vector $\mathbf{h}_{i,n}$.

However, in practical systems, the precoding matrix have to be designed subject to individual per-antenna power constraints of the form,

$$\mathbb{E}\left[|[\mathbf{x}]_n|^2\right] = \left[\tilde{\mathbf{W}}_{\text{MMSE}}\tilde{\mathbf{W}}_{\text{MMSE}}^H\right]_{n,n} \leq \frac{P}{N}, \tag{10}$$

where $[\mathbf{x}]_n$ denotes the n-th component of vector $\mathbf{x}$ and P denotes the total available power at the satellite.

To meet the sum-power and per-antenna constraints at the satellite, we apply the following heuristic normalization to the rows of matrix $\tilde{\mathbf{W}}_{\text{MMSE}} = [\mathbf{a}_1 \quad \mathbf{a}_2 \quad \cdots \quad \mathbf{a}_N]^T$,

$$\mathbf{a}_n = \mathbf{a}_n / \|\mathbf{a}_n\|_2 \quad \text{for} \quad n = 1, \ldots, N \tag{11}$$

Hereafter, this precoding design is referred to as normalized MMSE scheme (NMMSE).

C. Signal-to-Interference plus Noise Ratio

All user terminals within a beam are time division multiplexed (TDM) on a single downlink carrier and, thus, they do not interfere with each other [1], [2]. According to the previous statement and (1), (6), the signal received at the k-th terminal belonging to the n-th beam can be modeled as,

$$y_{k,n} = \mathbf{h}_{k,n}^T \mathbf{w}_n s_n + \mathbf{h}_{k,n}^T \left(\sum_{j \notin n}^{N} \mathbf{w}_j s_j \right) + n_{k,n}. \quad (12)$$

As a consequence, the instantaneous SINR at the k-th terminal belonging to the n-th beam can be expressed as,

$$\text{SINR}_{k,n} = \frac{\left|\mathbf{h}_{k,n}^T \mathbf{w}_n\right|^2}{\sum_{j \neq n}^{N} \left|\mathbf{h}_{k,n}^T \mathbf{w}_j\right|^2 + 1}. \quad (13)$$

III. Proposed Scheduling

Assuming a NMMSE precoder designed to minimize the inter-beam interference, here we focus on the packet scheduling design. In particular, a new packet scheduler capable to maximize the efficiency of the satellite forward link and to satisfy different QoS requirements taking into account the ACM policy of the DVB-S2 standard is proposed.

The proposed scheduler aims at:

- Grouping the users within a frame according to similar channel conditions. Since all packets in a frame are served using the ModCod imposed by the worst user contained in that frame, significant performance gains are expected from a scheduler that groups the terminals according to similar propagation conditions.
- Minimizing the inter-beam interference by scheduling users within adjacent synchronous frames according to orthogonal channel conditions. This is expected to ease the work of the precoder, which is implemented after the scheduling block.
- Giving priority to delay-sensitive real-time traffic (QoS-1 class), while ensuring an acceptable throughput to non-real-time packets (QoS-2 class).

As mentioned before, precoding and scheduling are coupled in the sense that precoding drastically affects the SINR, which is used to determine the packet grouping at the scheduling part. One way to solve this issue is to try all possible combinations of groups with the corresponding precoders and feed the output back to the scheduler in order to choose the best combination. Clearly, exhaustive or brute-force search over all permutations has exponential complexity and thus, it is not efficient in practical systems. Here, we proposed an heuristic scheduling solution with the main goal of maximizing the overall satellite forward link performance.

The proposed scheduler for a particular beam is illustrated in Fig. 3, and works as follows. When a packet enters the scheduler, it is first classified according to its traffic class and its destination. For each traffic class (QoS-1 and QoS-2) and for each m-th group, we assume a FIFO (first-in first-out) buffer associated, which is assumed to be properly dimensioned according to the average traffic demand. As an example, Fig. 3 depicts the proposed scheduler for $M = 2$.

The proposed scheduling is divided into 2 steps, which are described in the following sections.

A. Scheduling - Step 1

The first step, represented by **step 1** in Fig. 3, merges the packets from different traffic classes in a second queuing model, thus resulting in a FIFO queue for each group of terminals. For this first step, we propose a Weighted Round Robin (WRR) which gives priority (i.e. more weight) to QoS-1 traffic. For instance, the WRR can be designed such as it takes 1 packet from the QoS-2 queue for each 2 packets from the QoS-1 queue.

The similarity-based groups are formed using the cosine similarity metric. Considering the channel matrix of a particular beam $\mathbf{H}_n$, the similarity vector of the q-th user within the n-the beam $\mathbf{u}_q \in \mathcal{C}^{Q \times 1}$ is defined as,

$$[\mathbf{u}_q]_i = \frac{\mathbf{h}_{q,n}^H \mathbf{h}_{i,n}}{\|\mathbf{h}_{q,n}\|_2 \|\mathbf{h}_{i,n}\|_2}, \quad i = 1, \ldots, Q, \quad (14)$$

where $[\mathbf{u}_q]_i$ denotes the i-th component of $\mathbf{u}_q$. We can rearrange the similarity vectors in a similarity matrix $\mathbf{S}_n = [\mathbf{u}_1 \quad \mathbf{u}_2 \quad \cdots \quad \mathbf{u}_Q]$. Since the components of $\mathbf{S}_n$ are complex, we build the corresponding angle and magnitude matrices based on $\mathbf{S}_n$ as follows,

$$\mathbf{S}_{n,\text{phase}} = \cos\left(|\angle \mathbf{S}_n|\right) \in [0, 1], \quad (15)$$

$$\mathbf{S}_{n,\text{mag}} = |\mathbf{S}_n| \in [0, 1]. \quad (16)$$

Ideally, we want to cluster user terminal such that they have similar CSI vectors both in phase and in magnitude. The combination of both similarity matrices is done as follows,

$$\hat{\mathbf{S}}_n = [\mathbf{s}_1 \quad \mathbf{s}_2 \quad \cdots \quad \mathbf{s}_Q] = \frac{1}{2}\left(\mathbf{S}_{n,\text{phase}} + \mathbf{S}_{n,\text{mag}}\right) \in [0, 1]. \quad (17)$$

In this paper, we make use of graph theory to do the clustering of users. The motivation behind this decision is that graphs are a convenient mathematical representation, which provides a global view of the similarity metrics within a beam. Graphs are structures formed by a set of vertices and a set of edges that are connections between pairs of vertices. Here, the set of vertices correspond to the Q terminals within a beam, and the connections between them are determined by the similarity measurements in $\hat{\mathbf{S}}_n$. Once the graph is generated, several graph clustering tools are available to perform the user clustering. Graph clustering is the task of grouping the vertices of the graph into clusters taking into consideration the edge structure of the graph in such a way that there should be many edges within each cluster and relatively few between the clusters. Finding the optimal partitioning is NP-complete and, therefore, heuristic methods are commonly used [13]. Here, we use the spectral clustering method, which is based on eigen-decomposition of the Laplacian matrix of the graph under consideration [14].

The spectral clustering method makes use of the Laplacian matrix associated to the n-th beam, which we define as $\mathbf{L}_n \in \mathbb{R}^{Q \times Q}$, and whose elements are defined as,

$$[\mathbf{L}_n]_{q,i} = \begin{cases} \sum_{k=1, k \neq q}^{Q} [\mathbf{s}_q]_k & \text{if } q = i \\ -[\mathbf{s}_q]_i & \text{otherwise,} \end{cases} \quad (18)$$

where $[\mathbf{s}_q]_k$ denotes the k-th element of the q-th column vector of $\mathbf{s}_q$. By definition, the Laplacian matrix is positive semidefinite and, as a consequence, its eigenvalues are non-negative $0 \leq \lambda_1 \leq \lambda_2 \leq \ldots \leq \lambda_Q$. The spectral clustering

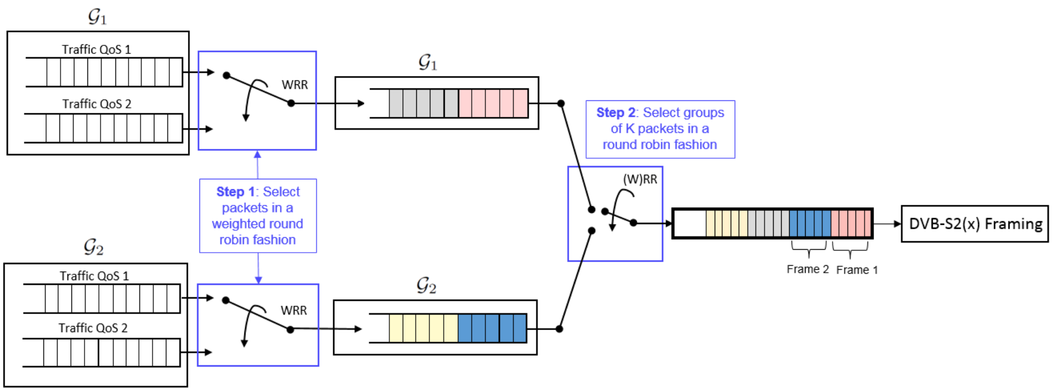

Fig. 3: Proposed two stage scheduler scheme for a beam and for $M = 2$

$$\hat{\mathbf{S}}_n = \begin{bmatrix} 1 & 0.6 & 0.7 & 0.4 & 0.9 \\ 0.6 & 1 & 0.8 & 0.9 & 0.5 \\ 0.7 & 0.8 & 1 & 0.4 & 0.8 \\ 0.4 & 0.9 & 0.4 & 1 & 0.7 \\ 0.9 & 0.5 & 0.8 & 0.7 & 1 \end{bmatrix}$$

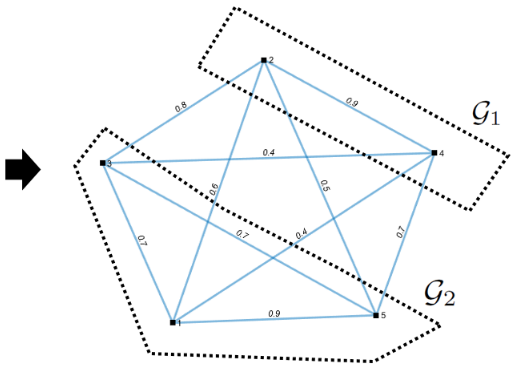

Fig. 4: Graph partitioning example using spectral clustering method for a particular similarity matrix $\hat{\mathbf{S}}_n$.

Algorithm 1 Spectral Clustering

1: **Require**:
- Laplacian matrix: $\mathbf{L}_n$
- Number of clusters: M

2: **Do:**
- Compute the M first eigen-vectors $\mathbf{u}_1, \dots, \mathbf{u}_M$ of $\mathbf{L}$
- Let $\mathbf{U} \in \mathbb{R}^{Q \times M}$ be the matrix containing the M eigenvectors as columns
- For each row of $\mathbf{U}$, apply the k-means algorithm [15], with $k = M$, to cluster the Q points into M clusters.

3: **Return:** Clustering groups $\mathcal{G}_{1,n}, \dots, \mathcal{G}_{M,n}$.

algorithm is based on the algebraic connectivity of the graph, which is given by the eigen-decomposition of $\mathbf{L}_n$. Algorithm 1 provides the spectral clustering procedure, which gives as output M groups of terminal users. Fig. 4 illustrates a graph and the corresponding user clustering ($M = 2$) using the method in Algorithm 1 for a particular similarity matrix $\hat{\mathbf{S}}_n$.

B. Scheduling - Step 2

The second step, represented by **step 2** in Fig. 3, is responsible of taking packets from the same group of terminals and send them to the final FIFO buffer, which will be used as input for the DVB-S2 framing module. The main goal of **step 2** is to achieve similar SINR within a frame, leading to a fair ModCod allocation. Here, we assume that the frame length is fixed and set equal to K packet units. Therefore, and as illustrated in Fig. 3, we proposed a Round Robin (RR) scheduler which takes K packets from each queue in a sequential manner. Optimization of the scheduler for a particular frame length is kept for future work.

In addition, it is relevant to coordinate with the other satellite transmitting elements such that the group of users served by one beam is as orthogonal as possible (in the channel condition sense) to groups simultaneously served in other beams. Assuming that each beam clusters their users using M groups, we will need M sequential frame transmissions to serve all the users within a beam, each serving a different cluster. At each frame transmission, N beams are transmitting in parallel using the same spectrum. As a result, the scheduler needs to design the serving pattern for M sequential transmissions, making sure that all users are illuminated in the serving period. As an example, Fig. 5 shows the procedure for $N = 2$ beams and $M = 3$ groups per beam. At the first transmission frame, M^N scheduling combinations are possible. However, once one is chosen (indicated in blue in Fig. 5), the number of options for the next transmission frame is reduced to $(M-1)^N$ and so on. To select the scheduling combination from all the possibilities, we proposed to use the cosine similarity metric (14) and apply it to the different mean

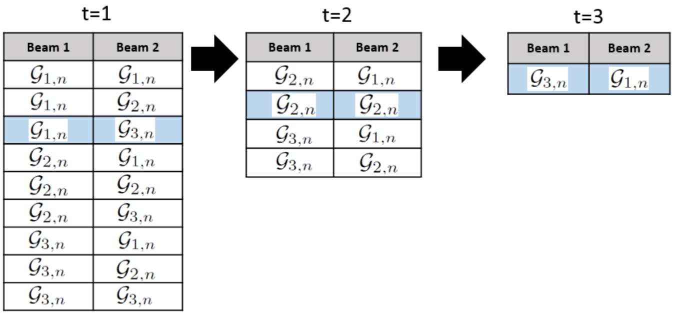

Fig. 5: Intra-beam scheduling options for $N = 2$ beams with $M = 3$ groups per beam.

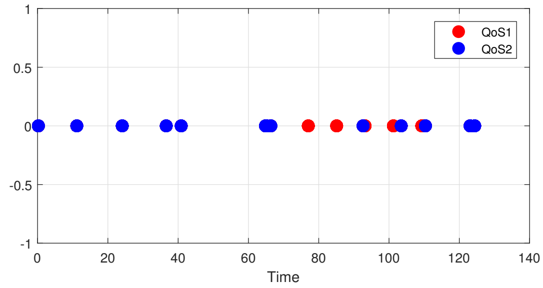

Fig. 6: Example of arriving packets for a particular user terminal.

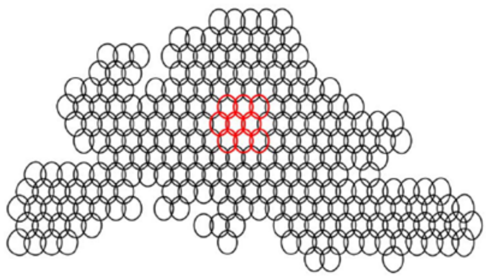

Fig. 7: Beam pattern covering Europe, with the $N = 9$ beams considered herein.

channel vectors $\tilde{\mathbf{h}}_{n(m)}^T$ defined in (9). More precisely, for a particular intra-beam scheduling $\mathbf{m} = [m_1 \quad m_2 \quad \cdots \quad m_N]^T$, with $m_n \in \{\mathcal{G}_{1,n}, \mathcal{G}_{2,n}, \ldots, \mathcal{G}_{M,n}\}$, we define the associated similarity matrix $\mathbf{U}(\mathbf{m}) \in \mathcal{R}^{N \times N}$, whose element $[\mathbf{U}(\mathbf{m})]_{n,n'}$ is defined as,

$$[\mathbf{U}(\mathbf{m})]_{n,n'} = \frac{\tilde{\mathbf{h}}_{n(m)}^H \tilde{\mathbf{h}}_{n'(m)}}{\left\|\tilde{\mathbf{h}}_{n(m)}\right\|_2 \left\|\tilde{\mathbf{h}}_{n'(m)}\right\|_2}. \tag{19}$$

Note that the diagonal elements $\mathbf{U}(\mathbf{m})$ are equal to one, and ideally, we would like the non-diagonal elements to be zero (orthogonal). Based on the previous reasoning, we proposed to select the scheduling combination $\mathbf{m}^*$ that provides the minimum Frobenius norm between the matrix $\mathbf{U}(\mathbf{m})$ and the ideal identity matrix of dimension N, i.e. $\mathbf{I}_N$. The latter can be formulated as,

$$\mathbf{m}^* = \min_{\mathbf{m}} \|\mathbf{I}_N - \mathbf{U}(\mathbf{m})\|_F. \tag{20}$$

IV. Results

For the sake of simplicity and for simulation purposes, we will assume that the WRR of **step 1** takes 2 packet units from traffic class QoS-1 and one packet unit from traffic class QoS-2 in a sequential manner. A smarter solution which adapts the weights according to traffic classes and instantaneous queue lengths is kept for future work.

We consider a full frequency reuse broadband multi-beam satellite with 245 beams that employs frame-based precoding. For the purposes of the present work, only a subset of $N = 9$ beams will be considered, as illustrated in Fig. 7. We assume $K = 10$ users per beam. For the scenario at hand, we assume perfect CSI available at the satellite gateway. The true satellite beam gain per user location, i.e. $G_{k,n}$, has been provided by the European Space Agency (ESA). In addition, we consider $G_R = 40.7$ dBi, carrier frequency of 20 GHz, user bandwidth of $B = 500$ MHz, a roll-off factor of 0.2, a satellite terminal noise temperature of $T = 235.3$ K and the true slant range distance for d_k. Regarding the satellite transmitted power, we assume 90 W per beam and an OBO of 3 dB.

To model the class QoS2 packet arrivals we use a Poisson process with an average arrival rate $\lambda_2 = 0.16$ and we allow arrival traffic between $[0, T_{\max}]$, with $T_{\max} = 125$. As a consequence, the average number of class QoS2 packets after $T_{\max}$ is equal to $\lambda_2 T_{\max} = 20$. To model the class QoS1 packet arrivals we use a uniform process with arrival rate $\lambda_1 = 0.04$ resulting in a $\lambda_1 T_{\max} = 5$ class QoS1 packets. The latter is in-line with the expected traffic load ratio of probability $1/5$ for delay-sensitive packets versus probability $4/5$ for non-delay-sensitive packets [16]. The inter-packet spacing for QoS1 packets is randomly taken from the interval $(0, 10]$. An example of the packet arrivals for a particular user terminal is depicted in Fig. 6. Each user has an associated packet arrival model, which differs from the one of the other users in the scenario.

Fig. 8 illustrates the average sum-rate achieved considering the 9 beams under evaluation. In particular, Fig. 8 compares the proposed scheme with a First-In-First-Out (FIFO) scheduling with and without precoding capabilities. For the proposed scheme, we illustrate results for $M = 2$ and $M = 3$, i.e. when the users within a beam are clustered into 2 and 3 clusters, respectively. From Fig. 8, it can be observed the gains in terms of rate achieved with the proposed scheduling, which is of the order of $+22\%$ with respect to the conventional FIFO with precoding for $M = 2$, and of the order of $+50\%$ for the case $M = 3$. These gains remain even when precoding is not considered, resulting in $+17\%$ for $M = 2$ and $+48\%$ for $M = 3$ if we compare it with FIFO without precoding.

Furthermore, we have computed the Jain Fairness Index

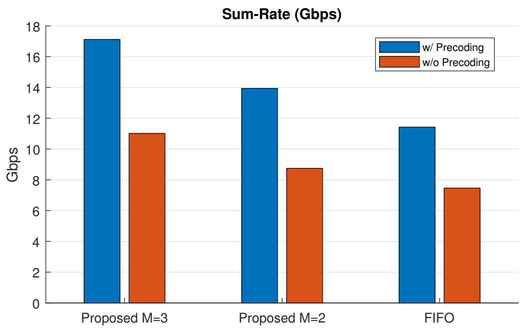

Fig. 8: Average sum-rate per frame transmission

defined as,

$$\mathcal{J} = \frac{\left(\sum_{n=1}^{N}\sum_{k=1}^{Q}\mathrm{R}_{k,n}\right)^2}{Q\cdot N\cdot\sum_{n=1}^{N}\sum_{k=1}^{Q}\mathrm{R}_{k,n}^2}. \quad (21)$$

Assuming normalization of $\mathcal{J}$ to $\tilde{\mathcal{J}} \in [0, 1]$, and focusing on the precoded case, we have obtained $\tilde{\mathcal{J}} = 0.85$ for the proposed scheme ($M = 2$) versus $\tilde{\mathcal{J}} = 0.79$ obtained with the FIFO benchmark, which highlights the user fairness provided by the novel scheduling proposed in this paper.

Having demonstrated the gains in terms throughput, we now focus on the evaluation of the performance of the proposed scheduling in terms of guaranteeing short delivery delay for the traffic class QoS1. Here, we focus on the delay introduced by the scheduling mechanism rather than the propagation delay which is due to the geometry of the scenario and cannot be avoided.

There are two key performance metrics when dealing with delays. One is the reception time which is defined as the time difference between first and last received packet of a particular service, and the second one is the variations between the delays experienced by packets in a single connection (usually known as delay jitter). While certain applications such as non-interactive television and audio broadcasting are not sensitive to these delay performance metrics, the later are crucial for achieving acceptable QoS for interactive applications.

Here we focus on the delays introduced by the scheduling. Fig. 9 shows the histogram of delay between the first and the last received packet, where the results obtained with the proposed scheme (in yellow) are compared with the conventional FIFO scheduling (in purple). From Fig. 9, it can be observed that $+50\%$ of the users received all packets belonging to QoS1 in less than 5 transmission slots, while the FIFO benchmark requires 10 transmission slots to achieve the same percentage. Fig. 10 shows the average inter-packet reception delay, both for traffic class QoS1. It can be observed that the proposed scheduling provides values which concentrate around 0 and 2 transmission slots, while the FIFO benchmark average inter-packet delay spreads out along higher values.

V. Conclusion

In this paper, a cross-layer scheduling design has been proposed for the forward link of a broadband multibeam satellite system with aggressive frequency reuse. Linear precoding is considered to minimize the interference caused by the frequency reuse, while the proposed packet scheduling takes into account the DVB-S2 framing, takes into account the severe delay constraints of real-time traffic (QoS-1 class), and ensures an acceptable throughput to non-real-time packets (QoS-2 class). Numerical simulations have confirm the advantages of the proposed scheduling scheme, showing the throughput gain achieved with the proposed user clustering and the adjacent synchronous inter-beam scheduling design when compared with a conventional FIFO scheduler. Unlike previous works devoted to the join scheduling and precoding design, the proposed method is able to deal with broadband heterogeneous traffic, including traffic with uneven QoS requirements.

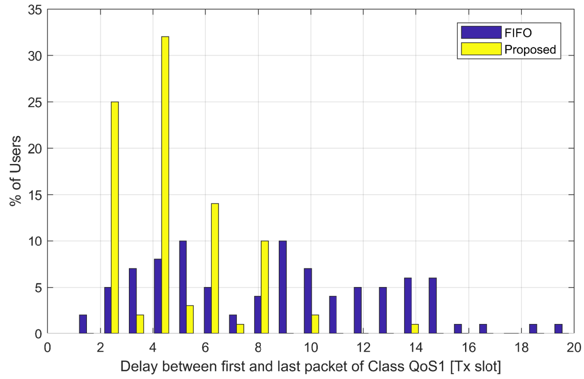

Fig. 9: Histogram of the delay between the first and the last packet of class QoS1

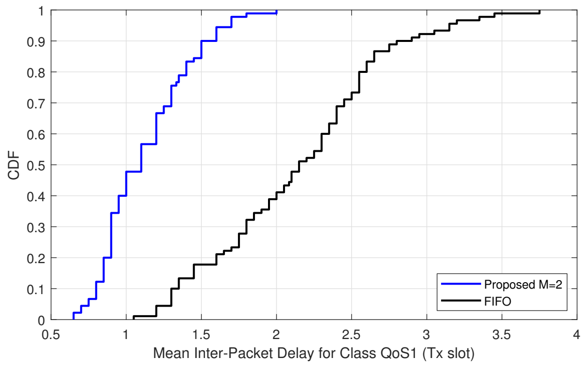

Fig. 10: CDF of the average inter-packet delay for class QoS1

Acknowledgment

This work has received funding from the European Space Agency (ESA) funded activity SatNEx IV Call of Order 2 (Part 1), Work Item 4 entitled “Forward Packet Scheduling Strategies for Emerging Satellite Broadband Networks”. The views of the authors of this paper do not necessary reflect the views of ESA.

REFERENCES

[1] ETSI-EN-302-307-1, "Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broadband Satellite Applications," *Digital Video Broadcasting (DVB)*, 2014.

[2] ETSI-TR-102-376, "User guidelines for the second generation system for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications," *Digital Video Broadcasting (DVB)*, 2005.

[3] M. Vazquez-Castro and G. Seco-Granados, "Cross-layer packet scheduler design of a multibeam broadband satellite system with adaptive coding and modulation," *IEEE Trans. Wireless Communications*, vol. 6, no. 1, pp. 248–258, Jan. 2007.

[4] M. Tropea, F. Veltri, F. De Rango, A. Santamaria, and L. Belcastro, "Two step based qos scheduler for dvb-s2 satellite system," *IEEE International Conference on Communications (ICC), Kyoto, Japan*, Jun. 2011.

[5] E. Rendon-Morales, J. Mata-Díaz, J. Alins, J. Muñoz, and O. Esparza, "Adaptive Packet Scheduling for the Support of QoS over DVB-S2 Satellite Systems," *Int. Conf. Wired/Wireless Internet Communications (WWIC), Vilanova i la Geltrú, Spain*, pp. 15–26, Jun. 2011.

[6] J. Dupe, E. Chaput, C. Baudoin, E. Bes, A. Deramecourt, and A. Beylot, "Rule-based packet scheduling for dvb-s2 through generic stream encapsulation," *EEE International Conference on Communications (ICC), Sydney, Australia*, pp. 3576–3581, 2014.

[7] M. A. Vazquez Castro and F. Vieira, "DVB-S2 full cross-layer design for QoS provision," *IEEE Communications Magazine*, vol. 50, no. 1, pp. 128–135, 2012.

[8] D. Christopoulos, S. Chatzinotas, and Ottersten, "Multicast Multigroup Precoding and User Scheduling for Frame-Based Satellite Communications," *IEEE Trans. Wireless Communications*, vol. 14, no. 9, pp. 4695–4707, Sept. 2015.

[9] M. Vazquez, A. Perez-Neira, D. Christopoulos, S. Chatzinotas, B. Ottersten, P. Arapoglou, A. Ginesi, and G. Tarocco, "Precoding in multibeam satellite communications: Present and future challenges," *IEEE Wireless Communications*, vol. 23, no. 6, pp. 88–95, Dec. 2016.

[10] V. Joroughi, M. Vazquez, and A. Perez-Neira, "Cross-layer packet scheduler design of a multibeam broadband satellite system with adaptive coding and modulation," *IEEE Trans. Wireless Communications*, vol. 16, no. 2, pp. 952–966, Feb. 2017.

[11] A. Guidotti, A. Vanelli-Coralli, G. Taricco, and G. Montorsi, "User Clustering for Multicast Precoding in Multi-Beam Satellite Systems," *ArXiv e-prints*, Jun. 2017.

[12] A. Wiesel, Y. Eldar, and S. Shamai, "Zero-Forcing Precoding and Generalized Inverses," *IEEE Trans. Signal Processing*, vol. 56, no. 9, pp. 4409–4418, Sept. 2008.

[13] A. Pothen, H. Simon, and K. Liou, "Partitioning Sparse Matrices with Eigenvectors of Graphs," *SIAM Journal on Matrix Analysis and Applications*, vol. 11, no. 3, pp. 430–452, 1990.

[14] U. Luxburg, "A Tutorial on Spectral Clustering," *ACM Journal on Statistics and Computing*, vol. 17, no. 4, pp. 395–416, Dec. 2007.

[15] J. MacQueen, "Some Methods for Classification and Analysis of Mltivariate Observations," *Proc. Fifth Berkeley Symp. on Math. Statist. and Prob.*, pp. 281–297, 1967.

[16] ITU Recommendation ITU-T Y.1541, "Network Performance Objectives for IP-based Services." *International Telecommunication Union (ITU)*, Dec. 2011.