Demand-based Scheduling for Precoded Multibeam High-Throughput Satellite Systems

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***Abstract*—The growing demand for broadband applications has driven the satellite communication service providers to investigate High Throughput Satellite (HTS) solutions. While precoding has been identified as the most promising technique to boost the satellite spectral efficiency, new advanced solutions focus on re-configurable demand-driven systems, where throughput delivered aligns with the time and geographical variations of the traffic demand. For such goal, conventional user scheduling algorithms fail to meet the uneven user traffic demand. In this paper, we propose a novel unicast scheduling algorithm that takes into account both the channel orthogonality required for precoding along with the particular user demands. We name such technique as Weighted Semi-Orthogonal Scheduling (WSOS) methodology. Supporting numerical results are provided that validate the effectiveness of the proposed scheduling and quantify the benefits over conventional scheduling techniques.**

***Index Terms*—Multibeam High Throughput Satellite, DVB-S2X, Weighted Semi-Orthogonal Scheduling, Demand Adaptability, Precoding.**

I. Introduction

The trend of user demand shifting from broadcast services to broadband services has made satellite industries investigate High Throughput Satellite (HTS) systems, moving from single-beam to multibeam coverage pattern. Precoding for Multibeam HTS systems has been proposed as an effective co-channel interference mitigation technique able to boost the spectral efficiency and, as a consequence, to improve the overall system throughput performance [1], [2].

However, the performance of precoded Multibeam HTS systems is profoundly affected by the scheduling decisions [3]–[5]. In particular, the achievable throughput decreases whenever the user channel vectors within the adjacent beams are collinear. Therefore, the optimal performance is achieved when proper user scheduling selects users with orthogonal channel vectors to be served simultaneously [6], [7].

The joint user scheduling and precoding problem is non-convex and NP-hard. This means that multiple locally optimal points exists and theoretical guarantees are weak or non-existent. Hence, obtaining the optimal solution requires an exhaustive search-based user grouping and scheduling, which quickly become impractical due to exponential complexity. This was the approach followed in ESA PreDem project [8]. Some recent works have addressed the joint problem by proposing sub-obtimal solutions that reach stationary points of the original problem [9], [10]. Still, the complexity is not negligible and most of the literature have opted to split the design into two steps. As a consequence, channel orthogonality as defined in [11], has been widely used in the satellite community to deal with the scheduling problem. Furthermore, in [12], the authors use the cosine similarity metric to sequentially select the users with most orthogonal channel vectors. In [13], the authors make use of the spectral clustering technique, whose primary goal is to generate clusters of users with orthogonal channel characteristics. As an alternative approach, the authors in [14] propose geographic user clustering approach and use Euclidean distance to relate channel vectors and impose channel orthogonality. In a comparable inclination, the authors in [15] propose a geographical scheduling algorithm and schedule together users belonging to similar locations in their respective beams. Similarly, the authors in [16] propose a user grouping scheme using random pre-processing and the before mentioned Euclidean norm.

On the other hand, the capability to flexibly allocate on–board resources over the service coverage is becoming a must for future broadband multibeam satellites [7], [17]. The primary goal is to assign the system capacity where it is actually needed. In contrast to the majority of recent scheduling studies, in this paper we target the scheduling design not only from the maximum throughput perspective but also considering the aforementioned demand matching problem. In particular, we proposed the so-called Weighted Semi-Orthogonal Scheduling (WSOS) algorithm, which is a sub-optimal low-complexity sequential scheduling that weights the orthogonality coefficient given by the cosine similarity metric with a coefficient computed according to the user demand requirements. The proposed WSOS algorithm can be seen as a method to dynamically allocate bandwidth to users based on user traffic demand and instantaneous queue status. Furthermore, the proposed scheduling mechanism prevents high usage users from starving other users via fairness guarantees.

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During the course of this work Danilo Spano was affiliated to the University of Luxembourg.

The latter can be seen as a minimum resource assignment that ensures the availability of a basic amount of satellite resources no matter how busy the network is.

The rest of the paper is organised as follows: in Section II, the system model has been defined by briefly explaining the Multibeam High Throughput-Satellite channel and Unicast Scheduling; In Section III, the problem statement has been formulated with the semi-orthogonal and demand based scheduling algorithm and furthermore the proposed WSOS solution, which enhances the demand adaptability with good fairness is discussed. Section IV provides the simulation and analyses results which support our arguments in the previous section, and finally, section V concludes the work of this paper along with proposed direction for further analysis.

Notation: We use upper-case and lower-case bold-faced letters to denote matrices and vectors, respectively. $\circ$ denotes the element-wise Hadamard operations. $(\cdot)^T$ denotes the transpose of $(\cdot)$. $|\,.\,|$ and $\|.\|$ depict the amplitude and Euclidean norm, respectively.

II. System Model

A. Unicast Multibeam Satellite System

Traditional HTS systems consider the use of multiple spot beams to cover a desired service area, with fractional frequency reuse across beams. In particular, several beams can reuse the same frequency band and polarization, as far as they have significant spatial separation to avoid interference. Figure 1 provides the typical 4-color frequency reuse (4CR), where beams with the same color are sharing resources.

In this work, we will consider unicast scheduling, where the DVB-S2X [18] defined XFECFRAME includes data that belongs to a single user. In other words, one user is scheduled per frame. At each time instance, a single XFECFRAME is transmitted per beam, and hence, only one user (denoted in yellow in the Figure 1) is served by a specific beam.

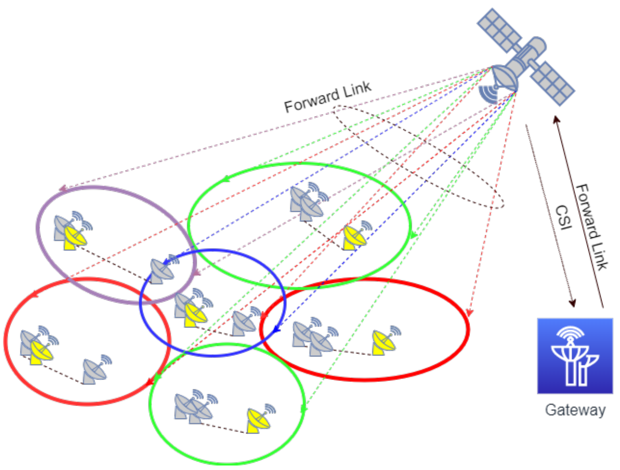

Fig. 1. System Architecture: Multibeam High Throughput-Satellite System with four colour scheme

To further boost the spectral efficiency of the system, full frequency reuse (FFR) combined with spatial interference mitigation techniques has been recently considered [12]. Serving all beams with the same satellite spectral resource facilitate a beam-free scheduling approach, where resources from low demand beams can be exploited by neighboring high-demand beams.

In this paper, we focus on Multibeam HTS architectures operating under FFR and implementing linear precoding as inter-beam interference mitigation technique as shown in Figure 2. Geographically fixed users assuming Fixed Satellite Services (FSS) are considered for simplicity. However, the data requested by the users are independent and mutually exclusive.

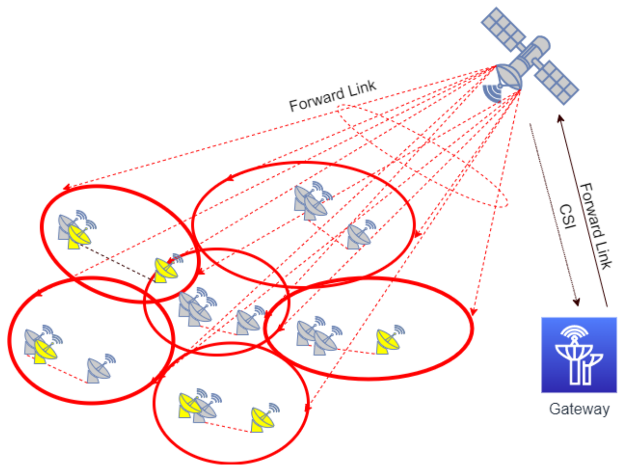

Fig. 2. System Architecture: Precoded Multibeam High Throughput-Satellite System

We assume that the precoding computation and implementation takes place in a single gateway, which uploads the precoded signals to the satellite through an ideal noise-free feeder link. Precoding techniques require full channel state information (CSI) at the gateway side. To this end, DVB-S2X [18] defines SF pilot symbols that are transmitted at specific locations in the downlink frame. In general, users know the value of these pilot symbols a priori. Consequently, the correlation properties of expected values and the received values of these pilot symbols defines the measurements of the channel quality. These measurements will be reported by the UE to the network using the satellite return link. For the sake of simplicity, in this paper, we assume perfect CSI knowledge at the gateway side. The impact of imperfect CSI is kept for future works.

B. Multibeam Satellite Channel

A single feed per beam (SFPB) payload antenna architecture is assumed, where the number of transmitting antennas is equal to the total number of beams denoted by K. The received signal y_k at the user u_k in the k^{th} beam is as expressed in (1), where $\mathbf{h}_k \in \mathbb{C}^{1\times K}$ is the channel vector between the transmitting satellite antennas and the user u_k. $\mathbf{x}_k \in \mathbb{C}^{K\times 1}$ represents the transmitted precoded signal vector from the K satellite antennas, and n_k is a random variable distributed as $\mathcal{CN}(0, \sigma^2)$, modelling the zero-mean Additive White Gaussian Noise (AWGN) measured at the u_k's receiving antenna.

$$y_k = \mathbf{h}_k \mathbf{x}_k + n_k, \quad k = 1, 2, ..., K \tag{1}$$

By rearranging all the users' received signals in a vector $\mathbf{y} \in \mathbb{C}^{K\times 1}$, we can rewrite the above model as,

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

where $\mathbf{H} = [h_1 \dots h_K]^T \in \mathbb{C}^{K\times K}$ represents the system channel matrix, and $\mathbf{n} \in \mathbb{C}^{K\times 1}$ is the AWGN components for all the users.

Since full frequency reuse is considered, the transmitted symbols **x** are precoded to mitigate the co-channel interference. In particular, we define **W** as the precoding matrix and the precoded signal is given by,

$$\mathbf{x} = \mathbf{W}\ \mathbf{s}. \tag{3}$$

In (3), the information vector **s** contains the raw symbols coming from the DVB-S2x modulator and satisfies $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}$. The precoding matrix **W** is assumed to be obtained with the well-known MMSE design [12], [21], which is can be expressed as,

$$\mathbf{W}_{RZF} = \eta' \boldsymbol{H}^{\boldsymbol{H}}(\boldsymbol{H}\boldsymbol{H}^{\boldsymbol{H}} + \boldsymbol{\alpha}\boldsymbol{I})^{-1}, \tag{4}$$

where α is a predefined regularisation factor [21] and η is the power allocation factor defined in (5) with P_{tot} being the total available power.

$$\eta = \sqrt{\frac{P_{tot}}{\text{Trace}(\mathbf{W}\mathbf{W}^\dagger)}} \tag{5}$$

The complex channel matrix **H** stated in (2) is defined as,

$$\boldsymbol{H} = \boldsymbol{\Phi}\boldsymbol{B} \tag{6}$$

where $\mathbf{B} \in \mathbb{R}^{K\times K}$ models the path loss, the satellite antenna radiation pattern, the received antenna gain and the noise power. In particular, the i^{th} and j^{th} components of **B** are given as,

$$b_{ij} = \frac{\sqrt{G_{Rm} G_{km}}}{(4\pi \frac{\mathfrak{D}_{mk}}{\lambda})} \tag{7}$$

where G_{Rm} is the receiver antenna gain (that mainly depends on the receiving antenna aperture) and G_{km} are the gains defined by the multibeam satellite radiation pattern and user locations. $\mathfrak{D}_{mk}$ is the distance between the satellite transmit antenna *k* and the m^{th} user's receiving antenna. Usually, due to the long propagation distance, $\mathfrak{D}_{mk} \approx \mathfrak{D}_m$. Finally, λ is the wavelength of transmission.

The diagonal phase matrix $\Phi \in \mathbb{R}^{K\times K}$ is the signal phase rotations induced by the different propagation paths and is generated as shown in (8) where Φ_x is a uniform random variable in $[2\pi, 0]$ and $[\phi]_{xy} = 0, \forall x \neq y$.

$$[\Phi]_{xx} = e^{i\phi_x}, \forall x = 1...K \tag{8}$$

III. Proposed Demand-based Scheduling

A. Problem Statement

In multibeam HTS using Time Division Multiple Access (TDMA), the resource sharing among different beams and receivers should be designed effectively. Consequently, the goal of the forward link satellite scheduler is to optimise bandwidth utilisation by jointly considering the channel conditions and the different broadband user demands. Such an approach is relatively new and unexplored in the related works.

Furthermore, satellite operators and service providers are compelled to provide any agreed throughput to broadband users. Such agreed throughput will be defined in a legal contract termed as the Service-Level Agreement (SLA). Consequently, the satellite operators are obliged to provide every broadband user with the agreed levels of the metrics defined in the SLA. This further pushes the need for improved scheduling algorithms which jointly intends to achieve the SLA defined user demand.

B. Proposed WSOS Solution

While most of the literature focused on scheduling designs that maximize the achievable capacity of the system, very few research has been done in demand-based scheduling. Herein, we propose an iterative sub-optimal scheduling method, which on the one hand intends to orthogonalize as much as possible the users' channels, while on the other hand prioritizes the users demanding higher traffic. The orthogonality-based user selection was initially proposed in [11], which highlighted the importance of selecting users with orthogonal channels in order to not compromise the channel matrix inversion procedure in (4).

Given a cluster of *K* beams, the goal is to select *K* users from the user pool of *M* users at each scheduling time, $t = 1, ..., T$. We assume the users' demand to be denoted as $(d_1, \dots, d_M)$.

The proposed method is summarized in **Algorithm 1**. In order to take into account the traffic demand d_m in the scheduling, we associate to the generic user *m*, a coefficient $\alpha_m \in [0, 1]$ as defined in (9), which shall be seen as the priority that a given user *m* has in the initial scheduling time $t = 1$. Such coefficient is simply a normalised version of the demand d_m and is expressed in (9), for each *m = 1,2,3 . . . , M*. Thus, $\alpha_m = 1$ is associated with the highest traffic demand and $\alpha_m = 0$ with the lowest.

$$\alpha_m = \frac{d_m}{\max_m(d_m)} \tag{9}$$

In the following, we explain the procedure in **Algorithm 1**. The first scheduled user U_1 is the one maximizing the metric defined in (10).

$$U_1 = \max(\alpha_m \cdot \|\mathbf{h}_m\|) \tag{10}$$

After the first user has been scheduled, in order to schedule the remaining *K-1* users, the metric w_m in (11) is sequentially calculated for each user m = 1, ..., M, with Λ denoting the set of indexes of the previously scheduled users.

$$w_m = \max(\alpha_m.(1 - \sum_{j \in \Lambda} \frac{| \mathbf{h}_j \mathbf{h}_m^H |}{\|\mathbf{h}_j\| \|\mathbf{h}_m\|})) \quad (11)$$

At each step the scheduled user U_k is the one maximizing the metric w_m, which jointly accounts for the priority and for the orthogonality to the previously scheduled users. The WSOS scheduling is followed by precoding to mitigate the interference of the semi orthogonal scheduled channels.

Algorithm 1 Proposed WSOS algorithm

Input: *m = 1,2,3 ..., M* $\leftarrow$ Users, $d_m \leftarrow$ Demand in *bps*, $k = 1, 2, 3 \ldots, K \leftarrow$ beams,

Procedure WSOS(Input)

$\alpha_m(t=1) = \frac{d_m(t=1)}{max_m(d_m(t=1))} \leftarrow \forall m$ where $\alpha_m \in [0,1]$

Set $\Lambda = \emptyset$

for $t = 1$ to T **do**

  for $m = 1$ to M **do**

    $U_1 = \max(\alpha_m(t).\|\mathbf{h}_m\|)$

  end for

  Update set: $\Lambda = \Lambda \in U_1$

  for k = 2 to K **do**

    for m = 1 to M **do**

      $w_m = \max(\alpha_m(t).(1 - \sum_{j \in \Lambda} \frac{|\mathbf{h}_j \mathbf{h}_m^H|}{\|\mathbf{h}_j\| \|\mathbf{h}_m\|}))$

    end for

    U_k is the user *m* of w_m. Update set: $\Lambda = \Lambda \in U_k$

  end for

  Update α_m such that $\alpha_m(t) = \frac{d_m(t)}{E_m[R_m(t)]}$

end for

End Procedure

At some point, it is important to update the priority coefficients α_m, and specifically to rescale it to account for those users which have low demand and have not been yet scheduled. In this paper, we propose the priority update based on the average offered rate, where the priorities in a given instant are updated considering the average rate provided to the users until that particular time instant. This approach, which requires the storage of the offered rates for a specific temporal window, can dynamically account for the average demand satisfaction at each user. More specifically, the coefficient of a served user *m* at the scheduling instance *t* is updated as per (12), with d_m denoting the demand and $E_m(R_m)$ the average rate until instant *t*.

$$\alpha_m^{new}(t) = \frac{d_m(t)}{E_m(R_m(t))} \quad (12)$$

The temporal window *T* is heuristically chosen based on the reduction rate of the priority coefficients. In the numerical simulations, *T* is fixed to 100. Further, the performance of the scheduling procedure is enhanced by promoting the underserved users when restoring the priorities (every *T* scheduling instances), in order to improve fairness.

IV. Simulation and Result Analysis

A. Performance Metrics definition

1) Jain's Fairness Index: The Jain's Fairness Index [24] is a well-known fairness metric, which in this context measures how the provided rate matches the demand at a user level. Specifically, defining the satisfaction u_m of the generic user *m* as the ratio between the offered rate s_m and the demanded rate d_m, the Jain's fairness index is defined as per the (13) and ranges between $\frac{1}{M}$ and 1 where M defines the total number of users.

$$J = \frac{(\sum_{m=1}^{M} u_m)^2}{M \sum_{m=1}^{M} u_m^2} \quad (13)$$

2) Sum Rate: The Sum Rate (*C*) as defined in (14) is the average sum throughput delivered by the multibeam system in a particular window of time, where C_k represents the average beam throughput.

$$C = \sum_{k=1}^{K} C_k \quad (14)$$

B. Simulation results

In this section, we present numerical results of the Monte Carlo simulations to validate the proposed Weighted Semi-Orthogonal Scheduling (WSOS) scheme.

The considered benchmark is Semi-Orthogonal Scheduling (SOS) as defined in [11], [12] which is not designed to account for user demand. Another benchmark is the Demand-Based Scheduling (DBS) which is purely designed to satisfy the demand without considering the channel orthogonality. The Geographical scheduling is intentionally not included, as its performance is expected to be worse than SOS, since the phase of the channel components are ignored.

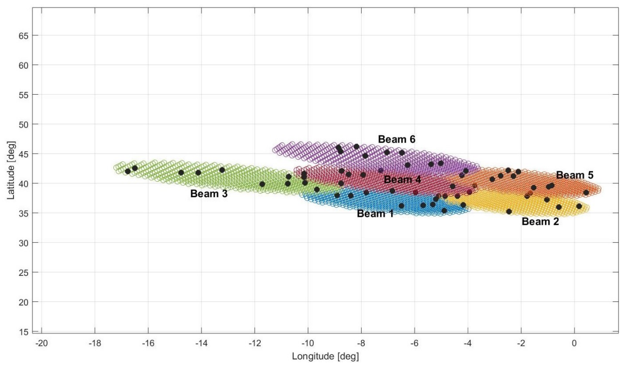

Fig. 3. Considered beam cluster, with users' positions considered for scheduling.

The antenna pattern corresponds to a 71-beam GEO 13E satellite operating at the Ka exclusive band 19.7 to 20.2 GHz in accordance to [7], [19], [20] and the simulation parameters are as shown in Table I. Also, we consider a total number of $M = 60$ users distributed across $K = 6$ beams as shown in Figure 3. Users locations and demands have been extracted from the SnT traffic simulator [23]. Furthermore, we consider a sum power-constrained system with a per-beam power of 20 dBW and a bandwidth of 500 MHz.

TABLE I
SIMULATION PARAMETERS

Satellite longitude	13 degree East (GEO)
Satellite total radiated power, P_T	6000 W
Total Number of Beams, N_B	71 (Only 6 beams are considered)
Number of HPA, N_{HPA}	36 (2 beams per HPA)
Beam Radiation Pattern	Provided by ESA
Downlink carrier Frequency	19.5 GHz
User link bandwidth, B_W	500 MHz
Roll-off Factor	20%
Duration of time slot. T_{slot}	1.3 ms
Number of time slots	100
Antenna Diameter	0.6
Terminal antenna efficiency	60%
DL wavelength	0.01538 m

The scheduling performance is assessed both at beam and user level, by evaluating the average per-beam user rate as well as the rate for each user, and by comparing them with the demand.

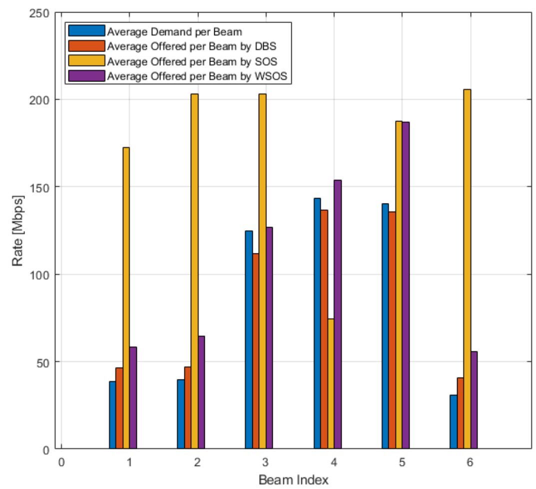

Fig. 4. Per-beam Average User Rate vs. Average Demand

The per-beam average user rate is shown in Figure 4 and compared with the average per-beam demand. It can be observed from Figure 4 that the proposed scheme satisfies the requested beam demand for all beams. On the other hand, the benchmarks achieve an offered rate either completely mismatched from the demand as in the case of SOS scheme or not meeting the demand in all the beams as in the case of the DBS. Furthermore, even though the DBS attains a rate that follows quite well the average demand, at many instances the demand is not satisfied (Beam 3, 4 and 5). This is because the cluster demand is too high to be met without proper precoding-tailored user scheduling.

Figure 5 provides the results at user level. In particular, Figure 5 compares the average offered user capacity versus

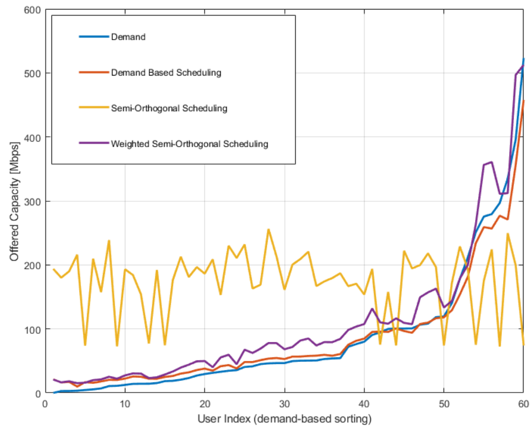

Fig. 5. Per-user Rate vs. Demand

the user requested demand for the proposed WSOS scheme as well as the two considered benchmarks, i.e. DBS and SOS. Clearly, the conventional SOS is not matching the user demands, resulting on some users receiving capacity that is not requested and some others where the offered capacity falls short is satisfying the users' demands. The DBS scheme provides a quite accurate demand matching but it faces some issues in satisfying the high demand requests. Finally, the proposed WSOS is shown to provide a good trade-off between demand satisfaction and the offered capacity.

Additional insights are given in Table II, where the sum rate and the Jain's fairness index of users' satisfaction are provided for the considered scheduling schemes. The obtained Jain's indexes clearly show that the proposed scheme provides greater fairness in comparison to the benchmarks (i.e. index is always close to 1). Also, the achieved sum rate is higher than the DBS scheme. As expected, SOS has a better sum rate in comparison to the proposed WSOS. Nonetheless, the proposed scheme offers better trade-off in terms of fairness, which is considerably more crucial and demand dependent.

TABLE II
SUM RATE AND JAIN'S FAIRNESS INDEX OF USERS' SATISFACTION FOR THE CONSIDERED SCHEDULING SCHEMES, WITH PRIORITY UPDATE BASED ON AVERAGE OFFERED RATE.

	WSOS	**SOS**	**DBS**
Sum Rate (Gbps)	6.2749	10.8339	5.6286
Jains's Fairness Index	0.9102	0.0169	0.8317

V. CONCLUSIONS AND FUTURE WORK

This paper proposed a novel user scheduling algorithm for precoded-based multibeam GEO satellite communications systems, including the design perspective of allocating resources according to the users' demands. The proposed Weighted Semi-Orthogonal Scheme (WSOS) provides a trade-off between the channel orthogonality needed for effective precoding performance and the user demand requirements. Numerical simulations conducted in MATLAB have evidenced better performance of the WSOS algorithm with respect to benchmark schemes in terms of balancing the demand satisfaction, user fairness and offered throughput.

A possible extension of this work would be the adaptation to multicast systems, where more than one user is scheduled at the physical frame defined by the standard DVB-S2X [18]. For sharing the frame, multiple users are usually grouped based on similar SNIR, and the modulation and coding scheme is selected based on the SNIR of the weakest user. Such grouping is necessary in order to guarantee that all the users, sharing the XFECFRAME, can decode the frame correctly. Hence, the proposed WSOS algorithm can be enhanced to face such challenges.

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