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Beamforming and Scheduling Techniques for Multibeam DVB-S2X Over Rainy Fading Satellite Channel

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ABSTRACT The extension of the digital video broadcasting second generation standard (DVB-S2X) for transmission over satellite has been introduced recently with its novel superframe structure, which is a key enabler for applying interference management techniques, such as precoding, to multibeam high throughput geosynchronous (GEO) satellite systems operating in the Ka-band. This paper presents the first full design of DVB-S2X system with multi-user-multiple-input-single-output (MU-MISO DVB-S2X), with most of its modulation and coding schemes (MODCODs), over rainy fading channels. The atmospheric impairments on the Ka-band satellite channel are considered, especially the rainfall effect, which is the most effective atmospheric impairment that degrades the system performance. Two rainy fading channels are designed, one for tropical region and the other for temperate region, using real rain data from these areas. In addition, the user scheduling influence on the bit error rate (BER) performance of MU-MISO DVB-S2X system is tested and compared with the conventional MISO DVB-S2X system. Simulation results show that the proposed system can achieve a significant improvement in terms of BER performance with at least 20 dB for 128 amplitude and phase shift keying (128APSK) MODCOD over the tropical channel and 14 dB for 32APSK MODCOD over temperate channel when the number of users is six. The enhancement in error rates proves that MU-MISO DVB-S2X system with scheduling can be the key solution for DVB-S2X system performance degradation in fading channels, especially rainy fading channels.

INDEX TERMS DVB-S2X, multibeam satellite, BER, atmospheric impairments, tropical satellite channel, precoding, user scheduling.

I. INTRODUCTION

With the fast development of satellite technology and the increasing demand for high data rate broadband services in satellite communications, multibeam satellite system in concurrence with aggressive frequency re-use are the most proper candidates for the next generation satellite communications [1], [2]. In this context, MU-MISO techniques with precoding techniques are introduced to manage interferences with the assistance of the new superframe (SF) of DVB-S2X [3], which was designed to be suitable for precoding techniques [4]. In the literature, some precoding techniques for satellite systems have been studied [1], [5], [6], in which they focused on throughput performance and sum rate optimization, however, none of these studies target BER performance. In [2], [4] and [5] DVB-S2X system was

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considered to study the throughput performance. Uncoded BER performance was analyzed in [7] with modulation without taking into account satellite standards, i.e., DVB-S2X, which is considered as the key enabler for implementing the interference mitigation techniques. Fixed satellite communication systems above 10 GHz operate under line of sight (LOS); the satellite channel essentially corresponds to an additive white gaussian noise (AWGN) channel. However, channel and propagation characteristics are the major constituents of a MISO channel matrix at the Ku and Ka bands, which are subjected to various atmospheric fading mechanisms originating in the troposphere that severely degrade the system performance and availability [8]. Although in [6] the rain attenuation was taken into consideration in the satellite channel model to show the impact of channel perturbations on the capacity of the system, the effect of this impairment on the error probability was not studied. In this paper, such analysis is presented, particularly addressing links between multiple satellite antennas in the GEO orbit and ground terminal antennas with the impact of rain fading channel on the BER performance.

A. CONTRIBUTIONS

The main contributions of this paper can be summarized as follows:

- We propose a full MU-MISO-DVB-S2X system with most DVB-S2X MODCODs for a multibeam satellite communication system. In the previous works, only throughput performance is considered for DVB-S2X, which does not require a full system design.
- The atmospheric impairments considered a serious problem in satellite communication in tropical regions, which are mostly characterized by heavy precipitation, especially at high frequencies. For these reasons, we introduce two rainy fading channel models, the first model is designed for tropical regions (high-fading channel), and the second model is designed for temperate regions (low-fading channel). A real measured rain data for two cities are used in our channel models; Penang-Malaysia [9] and Athens-Greece [10] to represent the tropical and temperate regions, respectively.
- Investigate the BER performance of our proposed MU-MISO-DVB-S2X system using the designed channel models, in order to give a prior visualization about DVB-S2X MODCODs functionality and error rates in these areas.
- Finally, a significant enhancement is achieved in terms of BER performance of DVB-S2X system for both tropical and temperate regions, using zero-forcing beamforming (ZFBF) technique and semi-orthogonal user selection (SUS) scheduling algorithm [11].

B. NOTATIONS

The lowercase boldface letters are used to denote vectors, and uppercase boldface letters denote matrices. $(\cdot)^T$ denotes the transpose operation. $(\cdot)^*$, $\|\cdot\|$ and $\odot$ denote the conjugate transpose, the Frobenius norm and Hadamard product operations respectively. $\emptyset$ denotes the empty set and $\mathbf{1}_{N_t}$ denotes an $1 \times N_t$ all-one vector. $\oplus$ denotes the exclusive-or (XOR) operation.

TABLE 1. Summary of important symbol notations.

Symbol	Meaning
k_{bch}	size of frame before bose-chaudhuri-hocquenghem (BCH) encoder
k_{ldpc}	size of the frame after BCH encoder
n_{ldpc}	size of frame after low density parity check (LDPC) encoder
$\boldsymbol{p}$	The nonprecoded pilots
$\boldsymbol{p}_2$	The precoded and modulated pilots

C. PAPER ORGANIZATION

The rest of this paper is organized as follows; Section II introduces end-to-end system model from the gateway terminal, the channel model, and the user terminal. The proposed MU-MISO-DVB-S2X system model is introduced in Section III. Finally, Section IV provides numerical results before giving concluding remarks in Section V.

II. SYSTEM MODEL

We consider a forward link of a multibeam satellite system with full frequency re-use, as depicted in Fig. (1). In this system, a single gateway (GW) with N_t transmit antenna can simultaneously serve N_t fixed user terminals using the ZFBF technique. This system resembles a multi-user MISO downlink beamforming in which N_t users are selected from U users and $(|U| = K)$ using user scheduling. ZFBF is then applied to the scheduled users. Therefore, the received signal at the k-th user terminal is given by

$$y_k = \sqrt{P}\boldsymbol{h}_k \boldsymbol{w}_k x_k + \sqrt{P} \sum_{j=1, j\neq k}^{N_t} \boldsymbol{h}_k \boldsymbol{w}_j x_j + n_k, \tag{1}$$

where $\boldsymbol{h}_k \in \mathbb{C}^{1\times N_t}$ denotes the channel vector which is modeled as rainy fading channel explained in section II-B, $\boldsymbol{w}_k \in \mathbb{C}^{N_t\times 1}$ is the ZFBF vector for the user k, n_k is complex additive white Gaussian noise (AWGN) with distribution $\mathcal{CN}(0, \sigma_n^2)$.

The ZFBF matrix $\boldsymbol{W}$ is given by [12], [13]:

$$\boldsymbol{W} = [\boldsymbol{w}_1, \ldots, \boldsymbol{w}_{N_t}] = \boldsymbol{H}^*(\boldsymbol{H}\boldsymbol{H}^*)^{-1}, \tag{2}$$

where $\boldsymbol{H} = [\boldsymbol{h}_1^T, \cdots, \boldsymbol{h}_{N_t}^T]^T$ denotes the channel matrix of strong users, $\boldsymbol{H}^*$ is the conjugate transpose of $\boldsymbol{H}$ and $(\cdot)^T$ is the transpose operation.

With ZF precoding, the interference is pre-canceled such as:

$$\boldsymbol{h}_k \boldsymbol{w}_j = 0, \text{ for } j \neq k, \tag{3}$$

In this way, the spatial degree of freedom offered by multiple transmit antennas can be exploited such as N_t antennas serves N_t users.

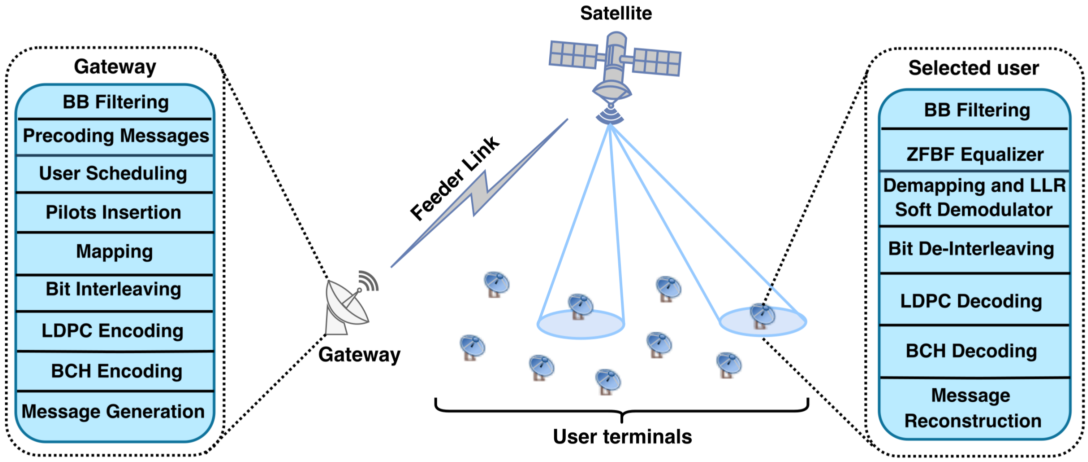

FIGURE 1. The proposed MU-MISO DVB-S2X system model.

TABLE 2. The code rate constant values, q, for LDPC code rates [3].

LDPC Code Identifier	q
11/20	81
23/36	65
128/180	52
13/18	50
132/180	48
135/180	45
140/180	40

A. GATEWAY TERMINAL

At the gateway terminal shown in Fig. (1), the base band frame (BBFRAME) $\boldsymbol{m}$ of size $1 \times k_{bch}$ is created based on the chosen code rate in european telecommunications standards institute (ETSI) [3] and [14], then the forward error correction (FEC) encoding starts with the BCH which represents the outer encoder in the system. BCH encoder generates an error protected packet by multiplying the BBFRAME by BCH polynomials in [3]. The number of multipliers changes with respect to the packet length of the final physical layer frame and the output codeword will be $\boldsymbol{c}$. The LDPC, which represents the inner encoder, generates a parity block of size $n_{ldpc}-k_{ldpc}$ from codeword block $\boldsymbol{c}$ of size k_{ldpc} and constructs the codeword of size n_{ldpc} by gathering the codeword block and parity block. Algorithm 1 shows the steps of parity block generation. The process starts by setting all parity bits to zero then updating the j-th parity bit z_j continually by applying XOR between the parity bit and the codeword bit c_i. Then the next parity bit number j to be calculated is updated using the addresses of the parity bits x and the code rate constant q which is given in Table 2. The output codeword could be either $n_{ldpc} = 64800$ bit or $n_{ldpc} = 16200$ bit long. Afterward, the FECFRAME is interleaved in a pattern depending on the MODCOD of the transmission. Then, M-APSK constellations are composed to n_R concentric rings, each with uniformly spaced PSK points. The signal constellation points are complex numbers, drawn from a set χ which can be represented as [15]

$$\chi = \begin{cases} r_1 e^{j(\frac{2\pi}{n_1}i+\Phi_1)} & i = 0\ldots, n_1-1, \text{(ring 1)} \\ r_2 e^{j(\frac{2\pi}{n_2}i+\Phi_2)} & i = 0\ldots, n_2-1, \text{(ring 2)} \\ \vdots & \\ r_{n_R} e^{j(\frac{2\pi}{n_{n_R}}i+\Phi_{n_R})} & i = 0\ldots, n_{n_R}-1, \text{(ring } n_R\text{)} \end{cases} \tag{4}$$

where n_l, r_l and Φ_l are the number of points, the radius and the relative phase shift corresponding to the l-th ring, respectively. Then, a number of PLFRAMEs are bundled to create a superframe. Each bundle consists of PLHEADER, FECFRAME, 180 modulated pilots $\boldsymbol{p_2}$ from the same FECFRAME constellation format, and 71 pilot fields with 36 symbol in each pilot field $\boldsymbol{p}$. The structure of superframe format specification 2 is depicted in Fig. (2). According to Annex E of the DVB-S2X standard [3], the superframe structure enables the use of precoding techniques for the forward link of a satellite system and it has a constant length of 612540 symbols. The number of pilot fields per superframe is $L = 639$. The pilot fields are determined using walsh hadamard (WH) sequence, and these fields are repeated periodically with a repetition period of 956 symbols, as shown in Fig. (2).

The $\boldsymbol{p_2}$ pilots are generated by mapping between the ψ-bits label ρ_i and constellation points m' using the mapping function f_{mod}. The ψ-bits label ρ_i are determined using the function f_{bin} which return the ψ less significant digits of the integer $v = 180$ which represents the number of $\boldsymbol{p_2}$ pilots in the superframe. Each superframe consists of bundled PLFRAMEs in addition to the preface of 720 symbols, which includes the start of superframe (SOSF) and the super format frame indicator (SFFI) in order to indicate the MODCOD used and the start of the superframe.

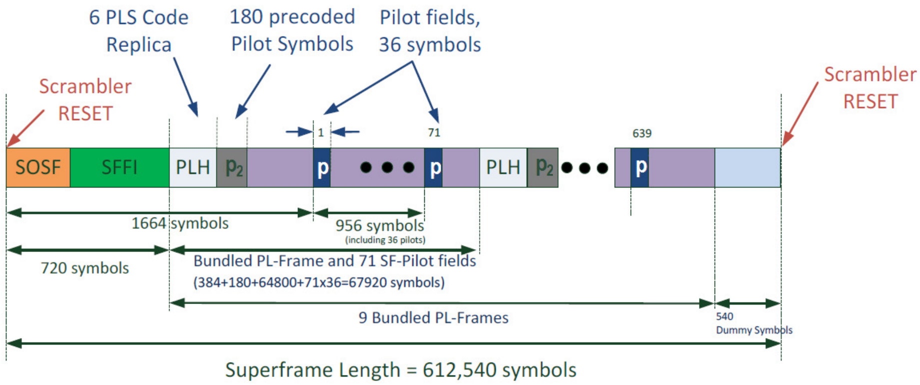

FIGURE 2. DVB-S2X Superframe structure of format specification 2. [3].

Dummy symbols of 540 symbols are added to the end of superframe. Then, after adding the precoded and modulated pilots $\boldsymbol{p_2}$ and nonprecoded pilots $\boldsymbol{p}$ and the superframe preface the GW schedule two users using SUS scheduler in which two semi-orthogonal channels are selected to design zero forcing ZF beams (more details are provided in section III). Finally, the signal is filtered using a square root raised cosine (SRRC) filter with roll off factor 20% in order to be transmitted through the rainy fading channel. The frequency response function $R(f)$ of this filter is given by [16]

$$R(f) = \begin{cases} 1 & |f| \leq f_N(1-\alpha), \\ \sqrt{\frac{1}{2}[1+\sin\frac{\pi}{2f_N}(\frac{f_N-|f|}{\alpha})]} & f_N(1-\alpha) \leq |f| \leq f_N(1+\alpha), \\ 0 & |f| \geq f_N(1+\alpha), \end{cases} \quad (5)$$

where $f_N = 1/2\ T_s = R_s/2$ is Nyquist rate, α is roll-off factor,T_s is symbol period of input signals, R_s is the input symbol rate equal to $1/T_s$. The steps for FEC encoding and superframe constructing that take place in GW terminal are introduced in Algorithm 1.

B. SATELLITE FADING CHANNEL MODEL

The satellite channel characterization is considered one of the main challenges in satellite communications; therefore, the channel has to be properly modeled. For the Ka-band satellite channel, the system performance is severely degraded due to the atmospheric fading effects, especially rain attenuation, which is considered as the dominant factor. The satellite channel model is described in detail in the following paragraph.

1) Rain Fading: To model the effect of rain fading, two rain rate values are used in our channel model. As this study considers the tropical regions and studies the effect of heavy rain rates that these areas suffer from, a real rain rate measured in [9] will be used to calculate the rain attenuation. In order to give a better understanding, another rain rate value for temperate region [10] is considered in order to compare between these two areas in the world. Several models are proposed to calculate the rain attenuation, such as the ITU-R P.618 prediction model [17]. For the sake of accuracy, a real rain rate measurement will be used instead of the predicted one by ITU-R. Table 3 shows the parameters for rain attenuation calculations and the details for the two selected cities in this article. The calculation for rain attenuation are done using equations given in recommendation ITU- R P.618, ITU- R P.839 and ITU- R P.838, [17], [18] and [19] using the parameters from Table 3. Then, the calculated rain attenuation value, A_pdB, is used to find the distribution of the power gain, A_p, using the following equation:

$$A_p\text{dB} = 20\log_{10}(A_p), \quad (15)$$

The corresponding $1 \times N_t$ rain fading coefficients from all antenna feeds towards a single antenna are given in the following vector [20]:

$$\tilde{\boldsymbol{h}}_k = {A_p}^{\frac{1}{2}} e^{-j\phi \mathbf{1}_{N_t}}, \quad (16)$$

where ϕ represents a uniformly distributed phase between 0 and 2π. As we consider line of sight environment and there is no large space between the satellite antennas the phases from all antennas are assumed to be identical [21].

2) Free Space Losses: Due to the long path between the satellite and user terminal, Free Space Losses is considered as an important deterioration factor in the satellite channel and it is not similar for all beams because of the wide coverage area of the satellite and the earth curvature. The free space losses for the k-th user in the j-th beam can be calculated by [6], [22]:

$$b_{max}(k,j) = \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{{d_0}^2 + {d_{k,j}}^2}\right)\left(\frac{G_R^k}{k_b BWT}\right), \quad (17)$$

where d_0 and $d_{k,j}$ are the distance between the GEO orbit and the earth's surface and the distance for the

TABLE 3. Receiving sites parameters for rain attenuation calculations from [9] and [10].

Receiving site location	Region	Latitude deg. N	Longtitude deg. E	Altitude m	Rainfall rate $R_{0.01}$ mm / h	$0°C$ Isotherm height above the sea level h_0
Athens - Greece	Temperate	37.90	23.73	15	24	3
Penang - Malaysia	Tropical	5.17	100.4	57	130	4.5

k-th user from the center of the j-th beam, respectively. k_b represents Boltzmann constant, BW is the noise bandwidth and T is the receiver noise temperature while G_R^k is the k-th user receive antenna gain which for simplicity is assumed to be the same for all user terminals $G_R^k = G_R$.

3) Multibeam Gain: The beam gain matrix is used to model the power level dissimilarity of the received signal on the earth surface and it mainly depends on the satellite antenna beam pattern and the user position. Then the beam gain from the j-th beam to the k-th user can be approximated by [22]

$$[b]_{k,j} = G_s^j \left(\frac{J_1(u_{k,j})}{2u_j} + \frac{36 J_3(u_{k,j})}{u_{k,j}^3} \right)^2, \quad (18)$$

where the auxiliary variable u is defined as $u = 2.07123 \frac{\sin\theta}{\sin\theta_{3dB}}$, θ is the angle between the beam center and the terminal location and θ_{3dB} is the angle which corresponds to 3-dB power loss. In addition, J_1 and J_3 are the first-kind Bessel function of order 1 and 3, respectively.

Collecting the beam gain coefficients from all transmit antennas into the $1 \times N_t$ vector $\boldsymbol{b}$, the overall channel for a single user can be expressed as [22]

$$\boldsymbol{h}_k = \tilde{\boldsymbol{h}}_k \odot \boldsymbol{b}^{\frac{1}{2}} \sqrt{\boldsymbol{b}_{max}}, \quad (19)$$

C. USER TERMINAL

The selected user will perform a series of steps in order to get the information. The process for the user terminal shown in Fig. (1) starts from applying the baseband filter to the received signal. Then, the superframe enters to ZF equalizer to get rid of the interference. Then, the received frame is demodulated with log likelihood ratio (LLR) soft demodulator. The general LLR equation is given by [23]

$$LLR(X(j)) = \ln(\frac{P(X(j) = 0|Y)}{P(X(j) = 1|Y)}), \quad (20)$$

where X is the constellation point, Y is the received signal and $X(j)$ is the j-th bit of X. For MISO-ZF based detection with fading channel, the LLR value of the j-th bit in the k-th user can be approximated as [24]

$$LLR_{y_k}^{(j)} \approx \ln \left[\frac{\sum_{a_\tau \in \chi_j}^{1} \exp(-\frac{|y_k - a_\tau|^2}{\sigma_n{}^2} \gamma_k)}{\sum_{a_\tau \in \chi_j}^{0} \exp(-\frac{|y_k - a_\tau|^2}{\sigma_n{}^2} \gamma_k)} \right] \quad (21)$$

where a_τ represents the τ-th signal constellation, and χ_j^1 and χ_j^0 denote the subsets of the constellation candidates whose j-th bit is 1 and 0, respectively. $\sigma_n{}^2$ is the instantaneous noise variance and γ_k is the effective channel gain of the k-th user which can be represented by

$$\gamma_k = \frac{1}{\left[(\boldsymbol{H}^*\boldsymbol{H})^{-1}\right]_{k,k}} \quad (22)$$

After LLR stage, the demodulated frame enters to the LDPC and BCH decoders, respectively. Finally, the message signal will be reconstructed and the error performance is calculated by dividing the number of error bits to the total number of the transmitted bits.

III. THE PROPOSED MU-MISO-DVB-S2X

The proposed system model is introduced in Algorithm 2. In this algorithm, after generating the superframe in the first step, we design the rainy fading channel for all the users K based on each user parameters, i.e., the distance, rain attenuation value and the beam gain in order to determine the user channel vector $\boldsymbol{h}_k$. Then, the user scheduling is done to select the strongest users' channels. In this paper, SUS user scheduling is adopted [11], which proved to give an asymptotic optimal sum-rate performance [25]. First, we initialize the scheduled users set $\Lambda_{zf} = \emptyset$. Then, the first user is selected based on the maximum channel quality $\|\boldsymbol{h}_i\|^2$, whether the rest users' selection depends on maximum semiorthogonality $\|\boldsymbol{g}_k\|^2$. After N_t user selection, ZF beams are generated based on the channels of selected users. The received signal is filtered with SRRC filter and demodulated using LLR demodulator in order to be decoded using LDPC and BCH decoders to reconstruct the BBFRAME. Finally, the BER performance is calculated.

IV. RESULTS AND DISCUSSION

In this section, simulations are conducted to assess the performance of the proposed models in terms of BER versus E_s/N_o[1](dB), where E_s is the average energy per transmitted symbol, N_o is the noise power spectral density. We consider fixed terminals for multibeam satellite system with the detailed parameters listed in Table 4.

The rain has a major effect on the satellite fading channel, especially when the system works at a high frequency, such as the Ka-band. By taking into account the difference between the world regions weather conditions, two different regions are considered in this paper to model the satellite

[1] E_s/N_o is considered by ETSI standard of DVB-S2X [3] for error performace and it is adopted here. $E_s/N_o(\text{dB}) = E_b/N_o(\text{dB}) + 10\log_{10}(\mathcal{N})$ and $\mathcal{N} = \log_2(\mathcal{M}.R_c)$, where E_b is the energy per transmitted bit, $\mathcal{M}$ is the modulation order and R_c is the code rate.

Algorithm 1 Superframe Design for DVB-S2X System

Select the required FEC code rate.

Generate BBFRAME message $\boldsymbol{m} \in \{1, 0\}^{1\times k_{bch}}$

Obtain the output codeword of BCH encoder $\boldsymbol{c} = \left[\boldsymbol{m}\ \boldsymbol{d}\right]$, where $\boldsymbol{d}$ is the reminder which is calculated as [3]

$$d(x) = d_{nbch-kbch-1}x^{nbch-kbch-1}+\ldots+d_1x+d_0, \quad (6)$$

Generate the sparse parity matrix $\boldsymbol{Q}$

$$\boldsymbol{Q}_{(n_{ldpc}-k_{ldpc})\times n_{ldpc}} = [\boldsymbol{A}_{(n_{ldpc}-k_{ldpc})\times k_{ldpc}}\boldsymbol{B}_{k_{ldpc}\times n_{ldpc}}], \quad (7)$$

Initialize the parity bits as

$$z_0 = z_1 = \cdots = z_{n_{ldpc}-k_{ldpc}-1} = 0, \quad (8)$$

for $\forall i \in \left\{1, \ldots, k_{ldpc} - 1\right\}$ **do**

1) Update the parity bits z_j

$$z_j = z_j \oplus c_i, \quad (9)$$

2) Update j according to q

$$j=(x+i \mod 360\times q) \mod (n_{ldpc}-k_{ldpc}), \quad (10)$$

end for

Calculate the parity bits as:

for $\forall i \in \left\{1, \ldots, (n_{ldpc} - k_{ldpc} - 1)\right\}$ **do**

$$z_i = z_i + z_{i-1}, \quad (11)$$

end for

Interleave the FECFRAME with interleaver based on modulation order $\mathcal{M} = \{2, 4, 8, 16, 32, 64, 128, 256\}$

$$\eta = \log_2 \mathcal{M}, \quad (12)$$

where η represents the No. of columns

Map the interleaved FECFRAME into constellation.

Generate pilot fields $\boldsymbol{p}$ using WH sequence of size 32 bits and padding of size 4 bits as

$$\boldsymbol{p} = \left[\boldsymbol{p_{32}}\ \boldsymbol{p_{padding}}\right] \quad (13)$$

for $\forall i \in \{1, \ldots, L\}$ **do**

$$start_{pilot-field}(i) = 1665 + (i - 1 \times 956), \quad (14)$$

1) Append $\boldsymbol{p}$

end for

Generate 2^{nd} type of pilots feilds $\boldsymbol{p_2}$ as

for $\forall i \in \{1, \ldots, v\}$ **do**

1) $\rho_i = f_{bin}(i, \psi)$

2) $\boldsymbol{p}_{2_i} = f_{mod(\rho_i, m')}$ where m' represents the chosen MODCOD

end for

Add SOSF, SFFI and Dummy symbols to the bundled PLFrames to create superframe with size 612540 bits.

Algorithm 2 Proposed MU-MISO-DVB-S2X System Model

1: Generate Superframe SF using Algorithm 1.

2: Design the Rainy Fading Channel Model for each user

3: **for** $\forall k \in \{1, \ldots, K\}$ **do**

1) Calculate the rain fading coefficients $\tilde{\boldsymbol{h}}$ for user k according to (16)
2) Compute the free space losses b_{max} for each user k using (17)
3) Design the multibeam gain matrix using (18)
4) Determine the channel vector $\boldsymbol{h}$ for user k according to (19)

4: **end for.**

5: Schedule N_t users set $U = \{1, \ldots, K\}$, $\Lambda_{zf} = \emptyset$ and $k = 1$, using SUS and select the first user in user group Λ_{zf} from the initial user set U by using this criterion:

$$\begin{aligned} \Lambda_{zf}(1) &= \arg\max_{i\in U} \left(\|\boldsymbol{h}_i\|^2\right), \quad (23)\\ \Lambda_{zf} &\leftarrow \Lambda_{zf} \cup \{\Lambda_{zf}(1)\}\\ k &\leftarrow k+1 \end{aligned}$$

6: Calculate the subspace semiorthognal component $\boldsymbol{g}_i$ for the remaining users set $C_k = U - \Lambda_{zf}$ as

$$\boldsymbol{g}_i = \boldsymbol{h}_i - \sum_{j=1}^{k-1} \frac{\boldsymbol{h}_i\boldsymbol{g}^*_{(j)}}{\left\|\boldsymbol{g}_{(j)}\right\|^2}\boldsymbol{g}_{(j)}, i \in C_k, \quad (24)$$

7: Find the k^{th} user, from the user set C_k as

$$\begin{aligned} \Lambda_{zf}(k) &= \arg\max_{i\in U} \left(\left\|\boldsymbol{g}_i\right\|^2\right), \quad i \in C_k, \quad (25)\\ \Lambda_{zf} &\leftarrow \Lambda_{zf} \cup \{\Lambda_{zf}(k)\} \end{aligned}$$

8: Update the user set C_{k+1} as:

$$C_{k+1} = \left\{ i \in C_k, i \neq \Lambda_{zf}(k), \frac{\boldsymbol{h}_i\boldsymbol{g}^*_{(k)}}{\|\boldsymbol{h}_i\|\ \|\boldsymbol{g}_{(k)}\|} < a \right\}, \quad (26)$$

where $a \in [0, 1]$ is the correlation factor used to test the orthognality between users' channels and we set it $a = 0.3$ [11].

$$k \leftarrow k+1$$

9: If $k \leq N_t$, then go to 6. Otherwise, users scheduling is completed.

10: Generate ZFBF matrix $\boldsymbol{W} = \{\boldsymbol{w}_1, \boldsymbol{w}_2, \ldots, \boldsymbol{w}_{N_t}\}$.

11: Apply baseband filtering with rolloff factor 20%

12: Demodulate the received signal using (21)

13: Decode the received SF using LDPC and BCH decoders in order to remove the parity bits and reconstruct the BBFRAME.

14: Calculate the BER performance.

fading channel: the tropical area which suffers from severe weather conditions and heavy rainfall and the temperate area to represent the light rainfall. A comparison between these two regions is introduced in this paper in order to analyze the BER performance of the multibeam multi-user MISO system using different fading channels.

TABLE 4. System parameters.

Parameter	Value
Orbit	GEO , $d_0 = 35788$Km
Frequency Band	Ka-band $f = 20$GHz
No. of beams	2, 4
Boltzmann constant	1.38×10^{-23}J/m
Noise Bandwidth	50 MHz
Satellite antenna gain	$G_s = 52$dBi
User terminal antenna gain	$G_r = 41.7$dBi
Clear sky temperture	207°K
3 dB angle	$\theta_{dB} = 0.4$
Elevation angle	45°
Rician factor	$Kr = 8$

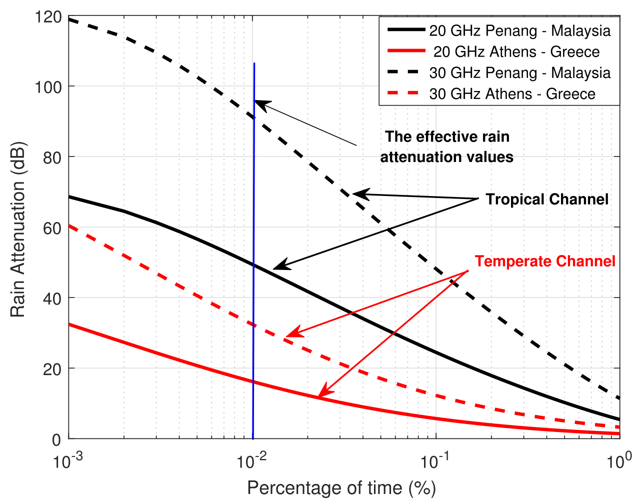

FIGURE 3. The rain attenuation for two cities: Athens and Penang.

Based on ITU-R, the effective rainy time percentage of a year is less than 1% ($\mathcal{P} \leq 1\%$). However, the heavy rainfall that causes a serious problem to the received signal quality is usually happening in 0.01% of the year time. Therefore, the 0.01% of the annual period of time is the typical percentage when analyzing the effect of heavy or highly effective rain attenuation, particularly in Ku and Ka bands [9], [17]. For this reason, this percentage at $\mathcal{P} = 0.01\%$ is considered for effective rain attenuation values in our simulation as shown in Fig. (3). The figure also shows the rain attenuation at the effective rainy percentage of the annual time $\mathcal{P} \leq 1\%$, for both cities: Athens and Penang with two frequencies, 20 GHz and 30 GHz, in order to show the effect of increasing the frequency on the rain attenuation values. The rain attenuation values at all the rainy percentages of time are obtained using the ITU-R rain attenuation prediction model based on the rainfall rates shown in Table 3. It is clear that the rain attenuation for the tropical city is much higher for both frequencies than the temperate city attenuation values. This is owing to the fact that tropical areas suffer from worse climatic conditions than the temperate areas.

A. SATELLITE FADING CHANNEL VS. OTHER CHANNELS

The most important factor affects the BER performance is the atmospheric impairments. Fig. (4) shows a comparision between four types of channels in order to show the effect of fading channel comparing with other kind of channels. In addition, Fig. (4) shows the BER performance of QPSK 11/20 MODCOD using AWGN channel and Rician channel. Basically, AWGN channel gives the best performance among other channels. Fig. (4) also shows the BER performance for two fading channels, the temperate fading channel in which the rain rate of Athens, a city in Greece, is used. Temperate fading channel shows a better performance than the tropical fading channel in which the rain rate of Malaysian city, Penang, is used as an example for a tropical region that gives the worst behavior among all channels because of the high rain rates and its worse weather conditions in the area.

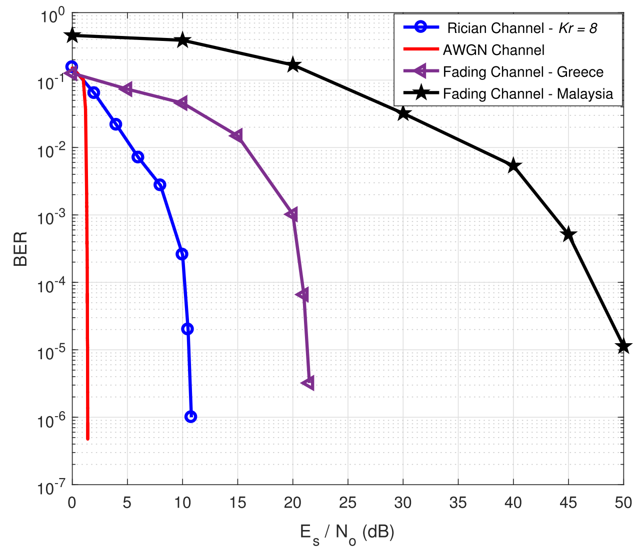

FIGURE 4. BER performance for QPSK 11/20 MODCOD using different channels.

B. KA BAND VS. KU BAND

Another factor that affects the BER performance in satellite fading channel is frequency. Although increasing the frequency offers higher data rates, it also causes system performance degradation due to the rise in atmospheric impairments that the channel suffers from in high frequencies. Fig. (5) shows the BER performance for QPSK 11/20 MODCOD using tropical and temperate fading channels for three different frequencies. The error rates for all frequencies using tropical channel are higher than values that achieved using a temperate channel. This is because of the high fading that tropical channel suffers from compared with the temperate channel.

The lowest frequency $f = 12$ GHz gives the best performance in both channels and achieves BER $= 10^{-6}$ with $E_s/N_o = 12$ dB and $E_s/N_o = 25$ dB for temperate and tropical channels, respectively. While in the second frequency $f = 20$ GHz error probability becomes worse as we get the

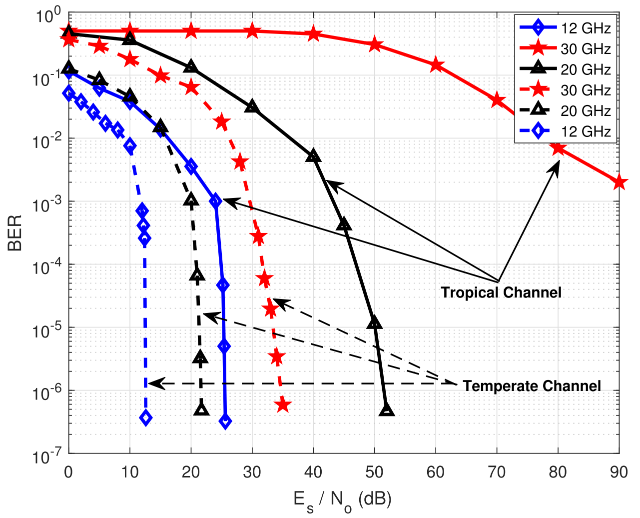

FIGURE 5. BER performance for QPSK 11/20 MODCOD for different frequency values using tropical and temperate fading channels.

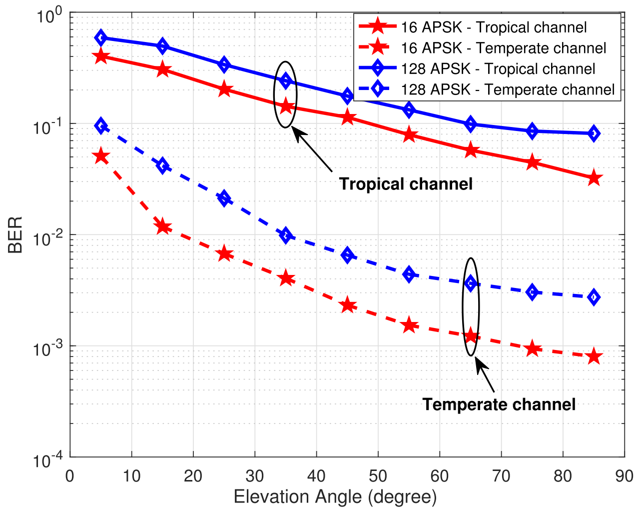

FIGURE 6. BER performance with different values of Elevation angle (θ) using temperate and tropical Fading channels with E_s/N_o = 20 dB.

same BER value with higher E_s/N_o equals to $E_s/N_o = 52$ dB for tropical channel and $E_s/N_o = 22$ dB for the temperate channel. The worst BER is come by the highest frequency $f = 30$ GHz, and the same BER value required a very high E_s/N_o value greater than 90 dB for the tropical channel, but for the temperate channel, E_s/N_o value equals to $E_s/N_o = 35$ dB.

C. ELEVATION ANGLE EFFECT ON BER PERFORMANCE

The effect of the elevation angle on the system performance is shown in Fig. (6). Since the rain attenuation value depends on the elevation angle of the earth terminal antenna, increasing the elevation angle means reducing the length of the path that the signal propagates through which in turn decreases the rain attenuation values and leads to better BER performance. As the figure shows, two types of MODCODs are used 16APSK 130/180 and 128APSK 135/180 using temperate and tropical fading channels. The increment in the elevation angle gives a lower error rate in both MODCODs for the same E_s/N_o.

D. SCHEDULING IN HIGH FADING SATTELITE CHANNEL: SCENARIO 1

High fading channel (tropical channel) is used in this scenario in order to analyze the BER performance of the multi-beam MISO DVB-S2X system, taking into account the ZFBF receiver and SUS scheduler. The tropical fading channel model is designed based on real measured rain data for a tropical city (Penang-Malaysia) to analyze the effect of high fading, that the tropical areas suffer from, on BER performance of DVB-S2X MODCODs. A scheduler is used in our proposed system model in order to analyze the effect of scheduling on BER performance. The BER performance of 2 × 2 MISO DVB-S2X system for different MODCODs using a tropical fading channel is shown in Fig. (7). The result shows enhancement in BER performance for all MODCODs when comparing the system with and without scheduling. It can be declared that the BER decreases after employing the scheduling technique. The effect of the number of users on scheduling is also considered in this work. Fig. (7) also shows a comparison between two number of users 20 and 6, and we can see as the number of users goes higher, the BER performance decrease respectively, this is because increasing the number of users gives more tolerance for the scheduler to choose the best users with the best channel quality. Fig. (7) (a) shows that the E_s/N_o value for QPSK 11/20 MODCOD is $E_s/N_o = 50$ dB for the MISO system without scheduling to achieve BER $= 10^{-5}$. This value decreases to lower than half $E_s/N_o = 23$ dB to get the same error performance after applying scheduling in the system with a total number of users equals to 6 users. E_s/N_o value decreases more to reach $E_s/N_o = 18$ dB when the number of users increases to 20 user. The same results are shown in Fig. (7) (b,c,d) for different MODCODs. E_s/N_o values for the MISO system without scheduling is $E_s/N_o = 52$ dB for 16APSK and $E_s/N_o = 54$ dB for 128APSK and $E_s/N_o = 56$ dB for 256APSK, which is the highest MODCOD in DVB-S2X system, to achieve BER $= 10^{-5}$. These values decrease after applying scheduling with a total number of users equal to K= 6 users in the MISO system, and the same error rate is achieved with lowest $E_s/N_o = 28$ dB, $E_s/N_o = 32$ dB and $E_s/N_o = 35$ dB for 16APSK, 128APSK and 256APSK, respectively. With K= 20 user, the multi-user diversity gain increased, and hence the system performance is enhanced. Therefore, a BER $= 10^{-5}$ can be obtained with $E_s/N_o = 20$ dB, $E_s/N_o = 25$ dB and $E_s/N_o = 27.5$ dB for 16APSK, 128APSK and 256APSK, respectively.

E. SCHEDULING IN LOW FADING SATTELITE CHANNEL: SCENARIO 2

A low fading satellite channel (temperate channel) is designed and used in this scenario in order to test the BER

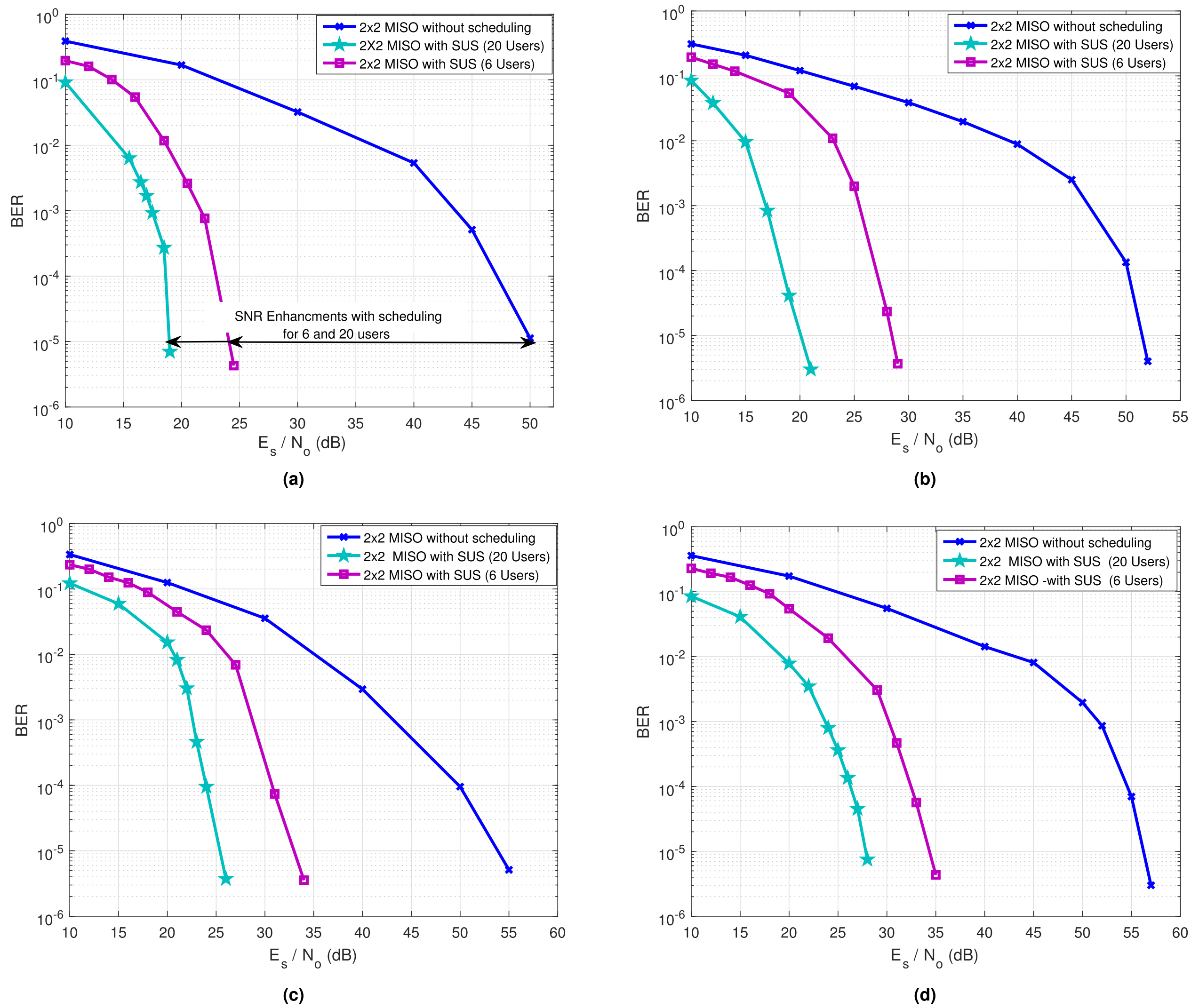

FIGURE 7. **BER performances in tropical fading channel with and without scheduling for different MODCODs: (a) QPSK with code rate 11/20 (b) 16APSK with code rate 130/180 (c) 128APSK with code rate 135/180 (d) 256APSK with code rate 128/180.**

performance of the multibeam MISO DVB-S2X system with this channel taking into account ZFBF and SUS scheduler. The rain rate of the temperate city (Athens-Greece) is used to design the temperate fading channel. Fig. (8) shows the BER performance for different DVB-S2X MODCODs 8PSK, 32APSK, 64APSK, and 256APSK with code rate 23/36, 7/9, 132/180, and 128/180. The result shows a huge enhancement in error rates when applying scheduling to the system for both numbers of users 6 and 20 users. Fig. (8) (a) represents 2×2 MISO DVB-S2X system with 8PSK MODCOD. The E_s/N_o value need to get error rate BER $= 10^{-5}$ is $E_s/N_o =$ 23 dB, while this value reduced to $E_s/N_o = 9$ dB after applying scheduling with 6 users only and it is reduced more to $E_s/N_o = 4$ dB with 20 user. The same results for Fig. (8) (b,c,d) in which the E_s/N_o values for the system without scheduling are $E_s/N_o = 25$, 27 and 33 dB to achieve BER $= 10^{-5}$ for 32APSK, 64APSK, and 256APSK respectively. After applying scheduling for 6 users, we observe the same BER with lower E_s/N_o values equals to $E_s/N_o = 11$, 12.5, and 15 dB, and it is reduced more with 20 users scheduling to $E_s/N_o = 6$, 7.5 and 8 dB. In order to show the effect of heavy fading, a comparison between Fig. (7) (d) from scenario 1 and Fig. (8) (d) from scenario 2 for the same MODCOD 256APSK. It is clear that the BER performance for tropical fading channel is much worse than temperate fading channel for the same MODCOD, we can see that in scenario 1 to get BER $= 10^{-5}$ it is required $E_s/N_o = 56$ dB while in scenario 2 it is required approximately half the value $E_s/N_o = 33$ dB to get the same error rate.

In Fig. (9), the BER performance is tested with different numbers of transmit antennas N_t. It is clear that the BER performance, for both channels, became worse as the number of transmit antennas increased from 2 to 4. This degradation is caused by the decrement in multi-user diversity gain with increasing the number of transmit antennas N_t. Furthermore, this degradation is less with 20 users compared to that of 6

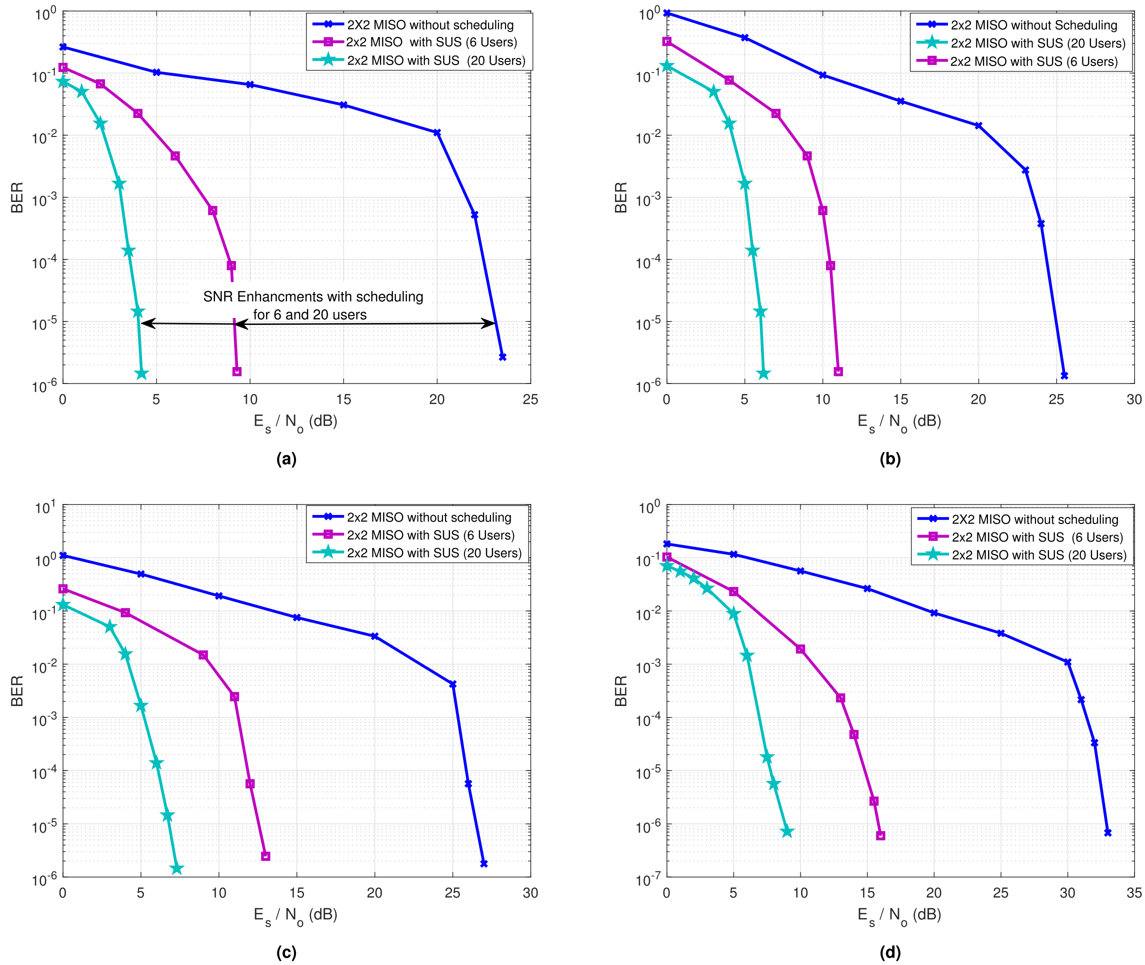

FIGURE 8. BER performances in temperate fading channel with and without scheduling for different MODCODs: (a) 8PSK with code rate 23/36 (b) 32APSK with code rate 140/180 (c) 64APSK with code rate 132/180 (d) 256APSK with code rate 128/180.

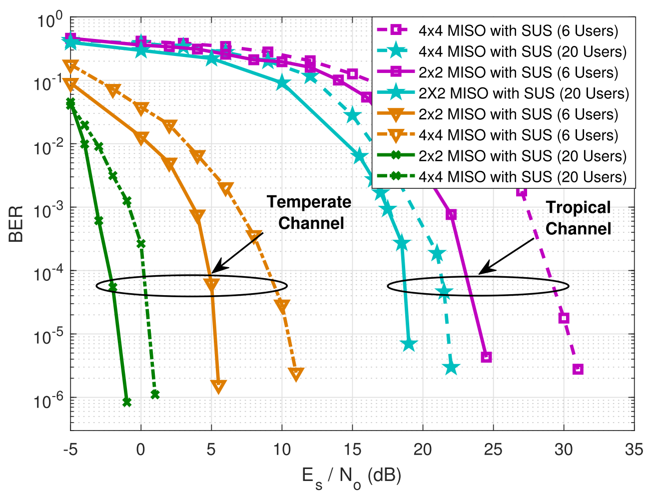

FIGURE 9. The effect of increasing the number of transmit antennas on BER performance for QPSK 11/20 MODCOD in tropical and temperate regions.

users, as the multi-user diversity gain for 20 users is higher than that of 6 users. For example, in tropical channel, the BER performance at 10^{-5} with $N_t = 4$ is worse with around 3 dB compared to that with $N_t = 2$ antennas when the scheduling is done between 20 user. On the other hand, the difference is increased to 6 dB when the scheduling is done between 6 users only.

V. CONCLUSION

This paper considered the effect of rainy fading channels on BER performance of DVB-S2X system in tropical and temperate areas. A model for rainy satellite fading channel is designed using real measured rain rate data from the tropical city with a very high rain rate in order to evaluate the effect of heavy fading on DVB-S2X system performance in terms of bit error rate using Ka frequency. The rain rate data of temperate city is used to design the low fading channel in this work to compare between these two channels with different fading levels on the error rates of the system. We considered user scheduling as a solution to reduce the effect of heavy fading on BER performance by exploiting multi-user diversity. The results show that the effect of scheduling is enormous on BER performance for all MODCODs in both types of channels. Finally, the results verified that our proposed system could significantly improve the BER performance of DVB-S2X system in heavy and low fading channels. Since we assume perfect CSI at the gateway terminal in this paper, future work includes the study of channel estimation techniques using the non-precoded pilots $\boldsymbol{p}$ that included in the superframe.

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