Column Norm Sorting Based Successive Interference Cancelation Algorithm For Multi-Beam Satellite Communication System

Jingchao WANG
Peng Cheng Laboratory (PCL)
Shenzhen, China
wangjc61s@163.com

Quan Yu
Peng Cheng Laboratory (PCL)
Shenzhen, China
yuquan61@qq.com

***Abstract*—Multi-beam satellites have the potential to offer high capacity with frequency reuse among different beams. Recently, more radical frequency reuse strategy or even full frequency reuse has been adopted to further improve the system capacity, leading to high co-frequency interference between adjacent beams. Successive Interference Cancellation (SIC) is normally used to deal with the interference. In this paper, we propose an optimized SIC algorithm by user grouping and sorting to cancel the interference in a better way. Simulation results show that the proposed algorithm can improve the bit error rate performance compared with the classic SIC algorithm.**

Keywords—satellite communication; multi-beam satellite; successive interference cancellation algorithm.

I. INTRODUCTION

A multi-beam satellite is defined as a satellite using multi-point beam and frequency reuse techniques. With the same spectrum resources, the capacity of the satellite is several times that of the traditional satellite [1]. When the frequency reuse scheme is more radical, e.g., full frequency reuse, serious interference will be generated between the beams, and interference cancellation is needed to reduce the impact of interference on the system performance. In the literature, Multiuser Detection (MUD) techniques based on Successive interference cancellation (SIC) are usually adopted in the reverse link to combat the interference.

In [2], MUD is proved to be an effective solution to maximize the capacity of multi-beam satellite system. A good review and evaluation of various MUD techniques for broadband multi-beam satellite systems is provided in [3]. It has been shown that the capacity of current multi-beam satellite systems is greatly affected by inter-beam interference, which calls for efficient advanced signal processing techniques to overcome the interference.

In [4], the physical layer performance achievable by a specific algorithm using MUD is evaluated. The results indicate that detecting by two users may be sufficient to greatly improve the spectral efficiency of the link. The authors in [5] analyzed two basic techniques for MUD: theoretically optimal Maximum Likelihood (ML) detection and sub-optimal Minimum Mean-Squared Error (MMSE) detection. The performance of theoretically optimal ML detection is very close to the theoretical single-user limit. As the number of users increases, the performance decreases. For a small number of users, MMSE detection performs very close to ML. When the number of users increases, the performance will drop significantly.

A hybrid QR decomposition with Malgorithm Maximum Likelihood Detection (QRM-MLD) MMSE-SIC adaptive MUD algorithm is proposed in [6]. In contrast to the optimal ML method, QRM-MLD significantly reduces the complexity. A tradeoff between complexity and performance is achieved and the performance is compared with the hybrid ML-MMSE-SIC scheme.

In this paper, the traditional SIC algorithm is optimized in two aspects, which can improve the Bit Error Rate (BER) performance. First, the received signals are sorted by strength before SIC, then the detection is performed in descending order of signal strength. Second, the satellite beams are grouped. In the process of decoding, parallel and serial interference detection are mixed to obtain better performance.

The rest of this paper is organized as follows: Section II provides the system model of the multi-beam satellite system. The classical SIC algorithm is introduced and analyzed in Section III. Two improved SIC algorithms are proposed in Section IV. Simulation results are given in Section V. The conclusions follow in Section VI.

II. SYSTEM MODEL

In this paper, we consider a multi-beam satellite system and focus on the reverse link of the system. Assume the system is based on TDMA, where K users on the ground send data in the same frequency band in the same time slot. In this situation, K ground terminals can be regarded as K transmitting end antennas and the satellite receives signals from multiple users in the coverage area of multiple beams.

Denote by s_j the signal transmitted by user j and h_{ij} the channel coefficient between user j and beam i , the reveiced signal of the ith beam is:

$$y_i = \sum_{j=1}^{K} h_{ij} s_j + n_i \tag{1}$$

where n_i is the additive Gaussian white noise with variance σ^2. Considering K users jointly, the above equation can be expressed in matrix form:

$$Y = Hs + N \tag{2}$$

Where $s = [s_1, \ldots s_K]$ is the signal vector sent by K users. $N = [n_1, \cdots, n_K]$ is the noise vector. $H = [h_1^T, \ldots h_k^T]$ is a $K \times K$ channel coefficient matrix, where the propagation loss, beam antenna gain, rain fading, small-scale fading are considered.

The reverse link channel coefficient matrix H of the multi-beam satellite communication system can be expressed as:

$$H = BH_R \Phi_{\mathrm{d}} \tag{3}$$

where B is the channel gain matrix, H_R is the small-scale fading matrix, and Φ_{d} is the large-scale fading matrix.

We use diagonal matrix Φ_d to represent the large-scale fading factor of K users, and formula (3)-(5) can be expressed as:

$$\Phi_d = \{\varepsilon_1, ..., \varepsilon_K\} \tag{4}$$

The small-scale fading of the channel can be modeled as Rice distribution. Therefore, channel coefficient matrix H_R is expressed as follows:

$$H_R = \sqrt{\frac{K}{K+1}} H_R^1 + \sqrt{\frac{K}{K+1}} H_R^2 \tag{5}$$

Where K is the Rice factor, H_R^1 represents the light of sight components, and H_R^2 is the matrix containing random interference of scattering components.

III. CLASSIC SUCCESSIVE INTERFERENCE CANCELLATION ALGORITHM

The basic principle of SIC is to reconstruct the successfully decoded signal and eliminate the interference of the signal from the received signal. The SIC detector detects the signals from multiple transmitters through various algorithms. Once a signal is detected, the signal is multiplied by the corresponding column in the channel coefficient matrix, and then the value is subtracted from the original received signal. In this way, the Multiple Access Interference (MAI) caused by the signal is eliminated. Recursing this process, the MAI can be completely eliminated. The performance of the SIC is greatly improved compared with the traditional detector, and the hardware is not changed much, so it is easy to implement. The SIC algorithm is shown in Figure 1.

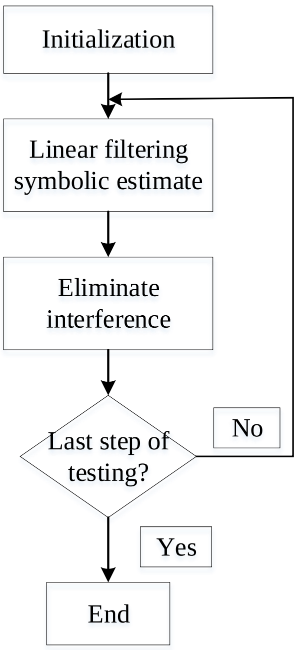

Figure 1. SIC algorithm flow chart

At the satellite receiving side, since the received signal is the sum of signals transmitted from users in multiple co-frequency beams, if the signal cannot be distinguished, the useful information cannot be identified. The SIC detector can first make decision on the strongest signal and obtain its estimated value. If there are N transmitted signals, the multiple access interference cancellation can be performed on other N-1 users in the following stage of detection, that is, the interference caused by the decoded signal is eliminated. It can be seen that the larger the number of detection stages, the better the multiple access interference will be eliminated.

According to the detection algorithm, successive interference cancellation can be divided into ZF-SIC and MMSE-SIC. Both the ZF algorithm and the MMSE algorithm are linear detection algorithms. Their basic principle is to multiply the received signal vector by the filter matrix G to obtain an estimate from which the final solution vector can be determined. There are two different benchmarks when calculating the filter matrix, so the linear detection algorithm can be divided into (ZF) algorithm and minimum mean square error (MMSE) algorithm.

The filter matrix of the ZF algorithm and the MMSE algorithm are:

$$\mathrm{G}_{ZF} = (H^H H)^{-1} H^H \tag{6}$$

$$G_{MMSE} = (H^H H + \sigma^2 I_M)^{-1} H^H \tag{7}$$

The Zero-forcing (ZF) algorithm is simple to implement and has low computational complexity. However, during the detection process, the noise is amplified by multiplication with the pseudo-inverse matrix, which greatly degrades the detection performance. The MMSE algorithm takes into account the amplification effect of noise when designing the filter matrix. Therefore, its performance is improved compared to the ZF algorithm, but its computational complexity is also relatively high. The successive interference cancellation detection algorithm is performed on users one by one, so the SIC algorithm involves the problem of user detecting order. For the SIC algorithm, the detection order is worth further researching.

IV. OPTIMIZED SUCCESSIVE INTERFERENCE CANCELLATION ALGORITHM

The problem with SIC is that the interference cancellation can only be performed in the order of the transmitting antennas, and the interference intensity caused by the previous signals is not necessarily the largest. When the strongest signal is detected at the end of the detection sequence, the progressive interference cancellation effect will be very limited. Moreover, if strong interference cannot be eliminated in advance, it may also have a bad influence on the bit error rate performance of the entire system. Based on this, we propose an Optimized Successive Interference Cancellation algorithm (Optimized SIC).

A. *Optimized successive interference cancellation algorithm based on column norm sorting*

The sorted successive interference cancellation algorithm can improve the performance of the detection algorithm, improve the accuracy of signal detection, reduce error propagation, and does not significantly increase the complexity.

In a multi-beam satellite communication system, the proportion of the signal transmitted by the ground user i in the received signal is proportional to the column norm corresponding to the channel coefficient matrix, and thus is ordered according to the column norm size. The larger the column norm, the higher the detection priority, so we only need to calculate the *K*-th column norm. The algorithm is as follows:

1. Define the initial variables.

$$H^{(i)} = H(i=1) \tag{8}$$

Here, the transmitted symbol of the user *i* is detected and a hard decision is made. The detection process uses ZF or MMSE detection to obtain ZF-OSIC and MMSE-OSIC detection algorithms. The filtered pseudo-inverse matrix $G^{(i)}$ is:

$$G^{(i)} = (H^{(i)^H} H^{(i)})^{-1} H^{(i)^H} \tag{9}$$

$$G^{(i)} = (H^{(i)^H} H^{(i)} + \frac{\delta_n^2}{\delta_s^2} I)^{-1} H^{(i)^H} \tag{10}$$

2. Sort the column norm for matrix $G^{(i)}$, select the column with the largest column norm value as w_i , multiply the matrix by w_i and y_i , and obtain the estimated value $\hat{x}_i$ of the transmitted signal by hard decision.

$$x_i = \mathrm{Q}(w_i y_i) \tag{11}$$

Eliminating the interference caused by the detected signal in step 2 on the undetected signal from the received signal,

$$\mathrm{y}_{i+1} = y_i - [H]_{:,i} \hat{x}_i \tag{12}$$

3. Set the *i*-th column of $H^{(i)}$ to 0 and remove it from the matrix $H^{(i)}$ to get $H^{(i+1)}$ and updates $i=i+1$.

B. Column Norm Sorting Group Multi-Order Successive Interference Cancellation Algorithm (GOSIC)

When the number of users is too large, the multi-beam satellite communication system needs to process multiple user data, the system complexity of the successive interference cancellation cannot be ignored. The concept of grouping is introduced on the basis of column norm sorting. Grouping based successive interference cancellation divides the entire coverage area into multiple detection groups with a certain spatial isolation by grouping multiple users according to their separated distance. Considering the uplink of the multi-beam satellite communication system, the coverage pattern of the system is illustrated in Figure 2.

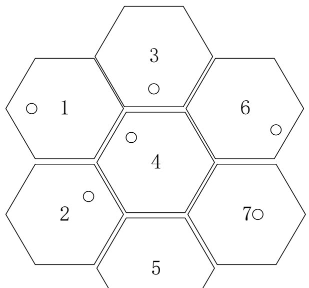

Figure 2. The coverage pattern of satellite multi-beam

Considering the proposed SIC algorithm based on column norm sorting, we introduce multi-level detection using the concept of grouping. Parallel and successive detection are combined in the decoding process to obtain better BER performance.

Due to the directivity of the multi-beam satellite antenna, the interference between the beams with large distance is small. Taking the beam cluster in Figure 2. as an example, the received signal of beam *i* can be expressed as:

$$y_1 = [H]_{1,:} x + n_1 = \sum_{k=1}^{K} h_{1k} x_k + n_1 \tag{13}$$

When considering 7-beam coverage, beam 1 and beam 7 are very far apart, so the interference between them is small. Therefore, the interference of the user 7 to user 1 can be regarded as noise. Then, the computational complexity of the detector can be simplified. Based on the above thoughts, the seven spot beams in Figure 2. are grouped according to the detection order. The following grouping results are obtained to make the interference between groups relatively small: $G(1)=\{1,2\}$, $G(2)=\{3,4,5\}$, $G(3)=\{6,7\}$.

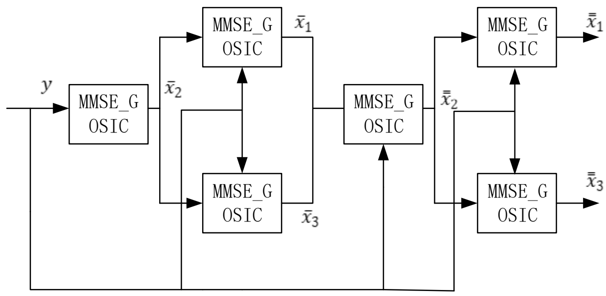

Figure 3. Schematic diagram of multi-stage MMSE-GOSIC algorithm

It can be seen from Figure 2 that users in the second group cause relatively stronger interference to users in the first and third groups. So in the simulation, we first perform interference cancellation on the second group of users, and first make decision on the second group of signals through the original signal. Then, interference cancellation is performed on the first and the third group based on the signal obtained from the hard decision results of the second group and the original signal. In this way, the estimated signals of the first and the third group without interference are obtained. Next, the signals of the second group is re-decoded using the interference-free signals of the first and the third group. Figure 3 shows the block diagram of the algorithm structure.

The estimated signals of the second group are first obtained by the original received signal y by performing column norm sorting successive interference cancellation the second group:

$$\bar{x}_2 = Q(\bar{Q}_2 H^H y) = Q(\bar{G}_2 y) \tag{14}$$

The matrix $[\bar{Q}_2]_i$ is a matrix of columns of the second set of signals in the channel matrix H. Interference cancellation according to the column norm sorting method is to eliminate the interference of the i-th group user to other users, and obtain the updated signal.

$$y_{i+1} = y_i - [\bar{Q}_2]_i \bar{x}_i \tag{15}$$

Where $[\bar{Q}_2]_i$ is a packet channel matrix composed of user columns in the i-th group of the channel coefficient matrix H, and the selected column is sequentially erased in the same manner as before. After the estimated value of $\bar{x}_2$ is obtained, the interference caused by the second group of signals can be eliminated from the received signals of the third group and the first group and updated.

$$\overline{y}_1 = y_1 - H_{12}\overline{x}_2 = H_{11}x_1 + \Delta y_1 + n_1 \quad (16)$$

$$\overline{y}_3 = y_3 - H_{12}\overline{x}_2 = H_{11}x_1 + \Delta y_3 + n_3 \quad (17)$$

Δy_3 and Δy_1 in the equations (16) and (17) represent mutual interference of transmitted symbols between the third group and the first group. However, since the distance between the third group and the first group is far apart, Δy_3 and Δy_1 can be regarded as noise in the respective received signals, respectively, and the receiving algorithm can be simplified. Finally, by eliminating the third group and the first group of received signals $\overline{y}_1$ and $\overline{y}_3$ of the signal interference of $\overline{x}_2$, $\overline{x}_3$ and $\overline{x}_1$ can be respectively estimated by the successive interference cancellation algorithm that performs the intra-group norm sorting.

$$\overline{x}_1 = Q(\overline{Q}_{11}H_{11}{}^H\overline{y}_1) = Q(\overline{G}_{11}\overline{y}_{11}) \quad (18)$$

$$\overline{x}_3 = Q(\overline{Q}_{33}H_{33}{}^H\overline{y}_3) = Q(\overline{G}_{33}\overline{y}_{33}) \quad (19)$$

Among them:

$$\overline{Q}_{11} = (H_{11}{}^H H_{11} + \frac{\delta_n^2}{\delta_s^2}I)^{-1} \quad (20)$$

$$\overline{Q}_{33} = (H_{33}{}^H H_{33} + \frac{\delta_n^2}{\delta_s^2}I)^{-1} \quad (21)$$

Where H_{11} represents the row corresponding to the first group of users in the channel matrix and the column corresponding to the first group of beams. Since the interference caused by $\overline{x}_2$ has been eliminated, the transmitted signals of the second group of users are not considered for the beams in the first group. It has been previously specified that the transmitted signal from the third group of users is considered to be noise. So for signals 1 and 2 in group 1, the specified channel matrix $H_{7;1,2}$ will be reduced to the first group $H_{1,2;1,2}$. That is, H_{11} above.

In (16) and (17), we consider Δy_3 and Δy_1 to be noise in order to simplify the reception signals of the third and the first group. At the same time, we ignore the estimation error of $\overline{x}_2$. This will affect the performance of the algorithm, so we introduce the concept of multi-stage detection. We will use the estimated signals of the third and the first group in the first stage and the original received data to perform a second-stage detection on the estimation signals sent by the users in the second group, and update $\overline{x}_2$:

$$\overline{\overline{y}}_2 = y - H_1\overline{x}_1 - H_3\overline{x}_3 \quad (22)$$

$$\overline{\overline{x}}_2 = Q(\overline{Q}_2 H_2^H \overline{\overline{y}}_2) = Q(\overline{\overline{g}}_2\overline{\overline{y}}_2) \quad (23)$$

Among them:

$$\overline{Q}_2 = (H_2{}^H H_2 + \frac{\delta_n^2}{\delta_s^2}I)^{-1} \quad (24)$$

Next, use the updated second-stage $\overline{\overline{x}}_2$ and the first-stage $\overline{\overline{x}}_1$ and $\overline{\overline{x}}_3$ to eliminate interference from the received signals of the third and first groups again:

$$\overline{\overline{y}}_1 = y_1 - H_{12}\overline{\overline{x}}_2 - H_{13}\overline{x}_3 \quad (25)$$

$$\overline{\overline{y}}_3 = y_3 - H_{32}\overline{\overline{x}}_2 - H_{31}\overline{x}_3 \quad (26)$$

$\overline{\overline{y}}_1$ and $\overline{\overline{y}}_3$ are used again to detect and estimate the transmitted signals of the group, and update $\overline{x}_1$ and $\overline{x}_3$. The second order detection signals $\overline{\overline{x}}_1$ and $\overline{\overline{x}}_3$ are obtained. At this point, all transmitted symbols complete the second-order detection.

V. SIMULATION

In this paper, the successive interference cancellation technique of multi-beam satellite reverse link is studied. The multi-beam satellite system model is established according to the diagram in section 2. Considering the seven spot beams in the cluster and adopting TDMA access, the performance of the algorithm studied in this paper is evaluated by comparing simulation with the classical SIC.

TABLE 1. MULTI-BEAM SATELLITE REVERSE LINK SYSTEM PARAMETERS

Link parameter	Value	Link parameter	Value
Satellite orbital altitude (Km)	35786	Maximum satellite antenna gain (dBi)	52
Carrier frequency (GHz)	2.2	Maximum terminal antenna gain (dBi)	20
Number of beams	7	Receiver noise power (dBw)	-118
Free space loss (dB)	190	Half power beam width (°)	0.6

Therefore, the scenario of multi-beam satellite reverse link is established. The various parameters of multi-beam satellite reverse link simulated by SIC algorithm are shown in Table 1.

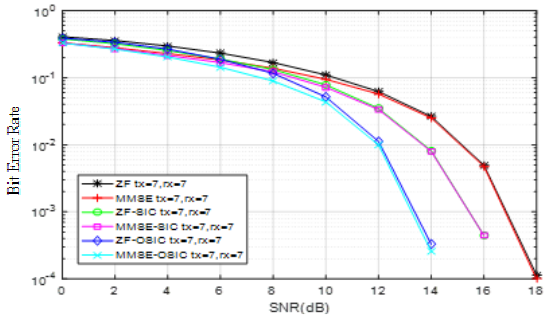

Figure 4. Bit error rate of ZF-OSIC/MMSE-OSIC detection algorithm

Figure 4. shows the bit error rate simulation of the classical linear detection ZF algorithm, MMSE algorithm, nonlinear detection ZF-SIC algorithm, MMSE-SIC algorithm and the optimized interference cancellation algorithm based on column norm sorting.

It can be seen from the Figure 4. that the performance of the MMSE algorithm is significantly better than the ZF algorithm at low SNR. This is because the noise is amplified by multiplying the pseudo-inverse matrix in the detection process in ZF algorithm, resulting in a poor performance. On the contrary, the MMSE algorithm takes the problem of noise into account. When the SNR value is high, the influence of noise becomes small, and the performance of the two linear detection algorithms is close. Combining SIC, the bit error rate of both ZF and MMSE is significantly reduced and the performance is significantly improved. This is because SIC algorithm is an iterative process. After each iteration, a signal is detected and eliminated to reduce the impact on subsequent signal detection. With the increase of SNR, the bit error rate of the six algorithms tend to decline, but the bit error rate of the OSIC algorithm drops the fastest. When the SNR value is high, the bit error rates of the six algorithms are obviously

Copyright (c) IARIA, 2020.

divided into three groups. The linear detection algorithm has the highest bit error rate, the SIC algorithm has the second bit error rate, and the OSIC algorithm has the lowest bit error rate. This is because the received signals are sorted according to the column norm before the detection so that the strong signal is first detected and cancelled. Compared with the disordered SIC algorithm, the OSIC can eliminate the interference to a greater extent. Therefore, the bit error rate of the OSIC algorithm is significantly lower than the bit error rate of the SIC algorithm.

Figure 5. adopts the concept of grouping and multi-stage. Combined with the MMSE multi-user detection algorithm based on the column norm sorting, the MMSE-GOSIC algorithm is close to the bit error rate of the MMSE algorithm at low SNR. As the SNR increases, the bit error rate of the MMSE-GOSIC algorithm decreases rapidly, and its advantages gradually emerge. At high SNR, the bit error rate of the MMSE-GOSIC algorithm is the lowest compared to other algorithms, and its performance is better than other algorithms.

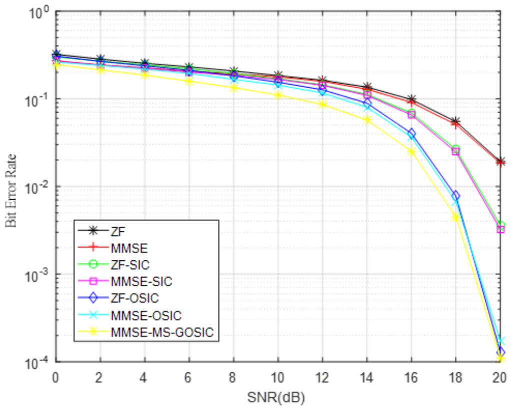

Figure 5. Bit error rate graph of MS-F-MMSE-GOSIC detection algorithm

VI. CONCLUSION

In this paper, the SIC algorithm of the multi-beam satellite system is simulated by establishing a multi-beam satellite reverse link. By investigating advantages and disadvantages of the SIC algorithm and the multi-beam satellite system, two optimization algorithms are proposed. A successive interference cancellation detection algorithm based on column norm sorting is proposed. Then, considering the high complexity as the number of user increases, the concept of grouping is proposed. The combination of grouping successive detection and multi-stage detection is used to reduce the complexity of the satellite side algorithm while ensuring accuracy. The simulation proves that the satellite MMSE multi-stage MUD algorithm based on the column norm sorting can achieve excellent performance compared with traditional SIC based detector. In the future, we will evaluate the proposed algorithm under the environments with rain fading.

ACKNOWLEDGMENT

The research content of this paper is funded by the National Natural Science Foundation of China (Project No.: 91538104, 91438205).

REFERENCES

[1] O. Vidal, G. Verelst, and J. Lacan. “Next generation High Throughput Satellite system”, IEEE First Aess European Conference on Satellite Telecommunications. IEEE, 2012:1-7.

[2] G. Colavolpe, A. Modenini, and A. Piemontese. “Multiuser Detection in Multibeam Satellite Systems: Theoretical Analysis and Practical Schemes”, IEEE Transactions on Communications, 2017, 65(2):945-955.

[3] F. Lombardo, E. A. Candreva, and I. Thibault, “Multi-user interference mitigation techniques for broadband multi-beam satellite systems,” 2011 Conference Record of the Forty Fifth Asilomar Conference on Signals, Systems and Computers (ASILOMAR), pp. 1805-1809, 2011

[4] S. Andrenacci, M. Angelone, and E. A. Candreva., “Physical Layer Performance of Multi-User Detection in Broadband Multi-Beam Systems based on DVB-S2,” 20th European Wireless Conference, pp. 1-5, 2014

[5] C. Stallo and C. Sacchi, “Link performance analysis of multi-user detection techniques for W-band multi-beam satellites,” IEEE Aerospace Conference.pp. 1-6, 2016.

[6] U. Yeşilyurt, “Hybrid QRM-MLD-MMSE with SIC adaptive multiuser detection for SDMA-OFDM systems,” 26th Signal Processing and Communications Applications Conference, pp. 1-4, 2018