Successive-Parallel Interference Cancellation Multi-user Detection Algorithm for MUSA Uplink

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Abstract. With the approaching of Internet of Things (IoT), non-orthogonal multiple access technology was proposed in the fifth generation (5G) mobile communication system to improve the system capacity and meet the needs of massive connectivity. Multi-User Shared Access (MUSA) technology is a non-orthogonal multiple access technology of code domain. MUSA receiver adopts multi-user detection algorithm, mainly using interference cancellation based on linear detection. This paper proposes the successive-parallel interference cancellation multi-user detection algorithm for the shortage of typical multi-user detection algorithms of MUSA uplink receiver, and gives the comparison results of the proposed algorithm and typical algorithms. Compared with parallel interference cancellation detection algorithm, the proposed algorithm improves the detection performance greatly. Compared with successive interference cancellation detection algorithm, the proposed algorithm reduces the processing time delay effectively.

Keywords: Multi-User Shared Access · Multi-user detection · Interference cancellation · Time delay

1 Introduction

At this stage, due to the increasing needs of users, as well as the rapid development of Mobile Internet and Internet of Things (IoT), the traditional orthogonal multiple access technology [1] is difficult to meet the enormous demand. Orthogonal technology can effectively avoid multi-access interference (MAI), and design complexity of receiver is low. Therefore, the 4G and previous communication systems adopt orthogonal scheme mainly. However, because orthogonal technology requires different resources to be allocated to different users and different users' resources can not overlap each other, the spectrum utilization is not high enough to meet the huge demand of 5G system [2].

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Therefore, non-orthogonal multiple access technology [3] is proposed in 5G wireless system, which is mainly realized in power domain and code domain. The power domain non-orthogonal multiple access (NOMA) scheme [4] was proposed by NTT DOCOMO, where users data are multiplexed in the non-orthogonal manner in power domain and different transmit power is allocated to different users according to different channel conditions. Sparse Code Multiple Access (SCMA) technology [5] and Multi-User Shared Access (MUSA) technology [6] were proposed by HUAWEI Technology and ZTE Corporation as code domain non-orthogonal multiple access technologies, respectively. SCMA technology [7] replaces the QAM modulation and Low Density Signature (LDS) spread spectrum with a multi-dimensional codebook, providing shaping gain and spreading gain. MUSA technology [8,9] spreads user data through non-orthogonal spreading code sequence, and adopts interference cancellation technology at receiver. The technical difficulty and major breakthrough of MUSA is multi-user detection algorithm of receiver. Researchers have done some research, proposing the parallel interference cancellation detection scheme and the two-successive interference cancellation detection scheme. The two schemes reduce computational complexity and processing time delay, but the detection performance declines as well. Pattern Division Multiple Access (PDMA) technology [10] proposed by Datang Telecom Technology is a non-orthogonal multiple access technique adopting PDMA pattern that defines the mapping of transmitted data to a resource group which can consist of time and frequency resources.

Multi-user detection algorithms mainly adopt linear detection algorithm and non-linear detection algorithm. Linear detection [11] is multiplying the received signal directly with the linear operator, including zero forcing (ZF) detection algorithm and minimum mean square error (MMSE) detection algorithm. The detection scheme is simple, but detection performance is poor because of the effect of noise amplification. Non-linear detection [12] mainly means interference cancellation algorithms, which mainly include successive interference cancellation (SIC) detection algorithm and parallel interference cancellation (PIC) detection algorithm. The difference between interference cancellation technology and traditional detection algorithm is that the other users data are regarded as the interference of the detected user data rather than noise in interference cancellation technology. Then the detected user data can be restored by detecting, reconstructing and eliminating other users' data. In the traditional CDMA system, there will be MAI if orthogonality of the code sequences between users can not be guaranteed, so multi-user detection algorithm is widely used [13].

This paper focuses on the research of multi-user detection algorithm for MUSA uplink receiver. This paper proposes the successive-parallel multi-user detection algorithm for the shortage of typical multi-user detection algorithms of MUSA uplink receiver. The proposed algorithm improves the detection performance greatly comparing with parallel interference cancellation detection algorithm and reduces the processing time delay effectively comparing with successive interference cancellation detection algorithm.

The rest of this paper is organized as follows. In Sect. 2, the previous work is introduced including system model and basic concepts of MUSA uplink. Section 3 introduces multi-user detection algorithms including typical multi-user detection algorithms and the proposed multi-user detection algorithm, and Sect. 4 presents comparison results and the performance analysis of multi-user detection algorithms. Finally, conclusions are drawn in Sect. 5.

2 Previous Work

MUSA is a non-orthogonal multiple access technology proposed in 5G system to meet the increasing demand. It can realize grant-free access with a large number of users simultaneously, and is very suitable for IoT. The basic model and concepts of MUSA are introduced in this part.

2.1 Basic Model of MUSA Uplink

MUSA is a NOMA technology based on the complex spreading code sequence, and its uplink access model is shown in Fig. 1. In the transmitter, each user first gets the own modulation data through encoding and constellation mapping. Then each user spreads own modulation data through the spreading code sequence selected randomly. Thus all users' data can be transmitted over a multi-user shared channel and different users data can occupy the same time-frequency resource. In the receiver, the received data is processed first by linear module to get the initial estimation of users' data. Then the detected user eliminates MAI through the interference cancellation module. Finally we can restore the original data for each user through demodulation mapping and decoding.

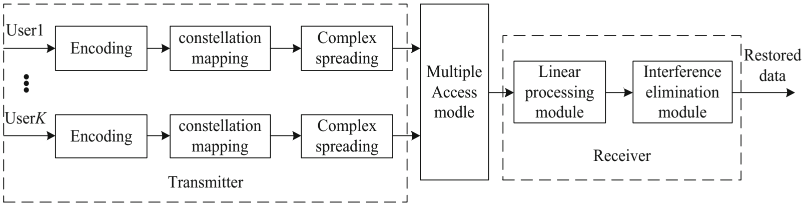

Fig. 1. MUSA uplink access model.

MUSA can be regard as an improvement scheme of CDMA technology. The difference is that MUSA can achieve system overload at transmitter with low cross-correlation complex spreading code sequence. Namely, the number of users accessing at the same time is greater than the length of spreading code sequence. And the spreading code sequences of users need not to be orthogonal.

According to the MUSA uplink access model, each user randomly selects spreading code sequence, then spreads the modulation data to superimposed transmit. The receiving signal after Additive White Gaussian Noise (AWGN) channel can be expressed as

$$\boldsymbol{R} = \sum_{k=1}^{K} \boldsymbol{H}_k \bullet \hat{\boldsymbol{S}}_k + \boldsymbol{N} = \sum_{k=1}^{K} \boldsymbol{H}_k \bullet (\boldsymbol{W}_k \boldsymbol{S}_k) + \boldsymbol{N} \tag{1}$$

where, K is the number of access users. $\hat{\boldsymbol{S}}_k$ and $\boldsymbol{S}_k$ are the spread data and transmitting modulated data, respectively. $\boldsymbol{H}_k$ is channel coefficient and $\boldsymbol{W}_k$ is spreading code sequence randomly selected by user k. $\boldsymbol{N}$ is AWGN, and the symbol "•" represents the multiplication of corresponding position elements of matrices.

Through further deduction, (1) can be written as

$$\boldsymbol{R} = \sum_{k=1}^{K} (\boldsymbol{H}_k \bullet \boldsymbol{W}_k)\, \boldsymbol{S}_k + \boldsymbol{N} = \sum_{k=1}^{K} \boldsymbol{F}_k \boldsymbol{S}_k + \boldsymbol{N} \tag{2}$$

where $\boldsymbol{F}_k$ is defined as the equivalent channel coefficient matrix. Each column of $\boldsymbol{F}_k$ is the result of $\boldsymbol{H}_k$ multiplying corresponding location elements of the column of $\boldsymbol{W}_k$, and symbol "•" represents the multiplication of $\boldsymbol{H}_k$ and corresponding position elements of every column of $\boldsymbol{W}_k$.

2.2 Complex Spreading Code

The MUSA uplink utilizes complex multivariate code sequences [6] as spreading sequences. The cross-correlation of the sequences is low due to the design with real part and imaginary part even though the length of the code sequence is short. Using complex multivariate code sequence as spreading sequences not only satisfies the high overload performance of the system, but also reduces processing complexity, processing time delay and system power consumption effectively.

According to the characteristics of spreading processing, user data will inevitably occupy more time-frequency resources after spreading processing. If the spreading sequence length is L, the time-frequency resources occupied by user data would be expanded to L times. Thus, in MUSA system, the user overloading rate (OR) [6] can be defined as the ratio of the number of users accessing simultaneously to the length of the spreading sequence.

$$\mathrm{OR} = \frac{K}{L} \tag{3}$$

3 Multi-user Detection Algorithm

Complex spreading sequences assigned to each user in MUSA system are non-orthogonal to each other, so there will be MAI at the receiver. Therefore, it is necessary to adopt multi-user detection algorithm to get the original data of each user.

3.1 Typical Multi-user Detection Algorithm

Three existing typical multi-user detection algorithms of MUSA include MMSE-SIC detection algorithm, MMSE-PIC detection algorithm and the two-successive interference cancellation (MMSE-2SIC) detection algorithm.

Linear processing module of MMSE-SIC multi-user detection algorithm and MMSE-PIC detection algorithm adopt MMSE detection, and interference cancellation module adopt separately successive interference cancellation parallel interference cancellation. The detection performance of MMSE-SIC algorithm is better, but the computational complexity and processing time delay is higher than MMSE-PIC algorithm.

To overcome the high processing time delay of MMSE-SIC algorithm, MMSE-2SIC multi-user detection algorithm was proposed. Its linear processing module adopts MMSE detection, but the interference cancellation module adapts two-successive interference cancellation. The two-successive interference cancellation first calculates the SINR of each user and sorts the users according their SINR. Then the two largest SINR users are selected to detect. This scheme reduces the processing time delay, but the detection performance is worse as well. Next parts mainly introduce the proposed successive-parallel multi-user detection algorithm in this paper.

3.2 Successive-Parallel Multi-user Detection Algorithm

Each iteration of MMSE-PIC detection algorithm needs to detect all users for MMSE detection and eliminate MAI produced by all other users outside themselves. The structure is complex and the performance is poor due to serious MAI. If the strong signal can be detected, reconstructed and eliminated before PIC processing that is equivalent to remove the severe MAI, the data of the rest users would get better detection performance through PIC detection. The essential idea is to detect the users with strong signal through SIC detection firstly, then detect the users with weak signal through PIC detection. That is named as successive-parallel interference cancellation (MMSE-SPIC) multi-user detection algorithm.

The algorithm eliminates the data of users with strong signal, that reduces MAI between users in MUSA uplink receiver and improves the detection performance of users with weak signal. Furthermore, remaining users don't need too many iterations and updates. Its detection performance gets better and processing time delay still is small. The process flow of MMSE-SPIC detection algorithm is shown in Fig. 2.

According to the process flow of Fig. 2, concrete processing steps of MMSE-SPIC detection algorithm is shown in Algorithm 1. In this paper, Cyclic Redundancy Check is used to judge whether the decoding is correct or not.

In SIC processing of Algorithm 1, $\hat{\boldsymbol{\omega}}^n$, $\boldsymbol{R}^n$ and $\boldsymbol{y}^n$ represent MMSE detection coefficient, the receiving signal and the MMSE detecting result in the n-th detection, respectively. $\hat{\boldsymbol{\omega}}^n$ and $\boldsymbol{R}^n$ will be updated when the n-th detection is completed. $\boldsymbol{y}_l^n$ is the portion of $\boldsymbol{R}^n$ involving l, and $\tilde{\boldsymbol{S}}_l$ is the restored signal of user l. Moreover, $\boldsymbol{R}^1 = \boldsymbol{R} = \sum_{k=1}^{K} \boldsymbol{F}_k \boldsymbol{S}_k + \boldsymbol{N}$. In PIC detection, $\hat{\boldsymbol{\omega}}^{K_1}$ is the MMSE detection coefficient for PIC detection, which will not be updated. $\boldsymbol{R}_{k_2}^n$ represents the receiving signal for user k_2 in the n-th iteration, and $\boldsymbol{y}_{k_2}^n$ represents the portion of $\boldsymbol{y}^n$ involving user k_2. $\tilde{\boldsymbol{S}}_{k_2}^n$ is the restored signal for user k_2 in the n-th iteration. Moreover, $K_1 + K_2 = K$.

Algorithm 1. MMSE-SPIC detection algorithm

Require: Channel matrices $\boldsymbol{H}$; Spreading sequence matrices $\boldsymbol{W}$; Received signals $\boldsymbol{R} = \sum_{k=1}^{K} \boldsymbol{H}_k \bullet (\boldsymbol{W}_k \boldsymbol{S}_k) + \boldsymbol{N}$; SINR threshold value M_1; PIC iteration times N;

Ensure: Reconstructed signals $\tilde{\boldsymbol{S}}_k$;

STEP1 (Initialization)

Equivalent channel matrices $\boldsymbol{F}_k = \boldsymbol{H}_k \bullet \boldsymbol{W}_k$; Received signals $\boldsymbol{R} = \sum_{k=1}^{K} \boldsymbol{F}_k \boldsymbol{S}_k + \boldsymbol{N}$; MMSE detection coefficient $\boldsymbol{\omega} = \left(\boldsymbol{H}^H \boldsymbol{H} + \sigma^2 \boldsymbol{I}\right)^{-1} \boldsymbol{H}^H$, $\hat{\boldsymbol{\omega}} = \left(\boldsymbol{F}^H \boldsymbol{F} + \sigma^2 \boldsymbol{I}\right)^{-1} \boldsymbol{F}^H$;

SINR calculation $\mathrm{SINR}_k = \frac{\|\boldsymbol{F}_k \boldsymbol{\omega}_k\|^2}{\|\boldsymbol{F}_k\|^2 \sum_{k=1}^{K} \|\boldsymbol{\omega}_k\|^2 + \boldsymbol{N}_k}$;

STEP2 (SIC processing)

All SIC users K_1, $K_1 = \{k | \mathrm{SINR}_k \geqslant M_1, k \in K\}$;

for $n = 1 : \mathrm{length}\,(K_1)$ **do**

  (Choose the detected user)

  Choose user l, meets $\mathrm{SINR}_l = \max_{i \in K_1} \mathrm{SINR}_i$;

  (MMSE detection) $\boldsymbol{y}^n = \hat{\boldsymbol{\omega}}^n \boldsymbol{R}^n$;

  (Demodulation&Decoding) $\tilde{\boldsymbol{S}}_l = (\mathrm{Dem\&Dec})\, \boldsymbol{y}_l^n$;

  (Update)

  if Decoding correct **then**

    $\boldsymbol{R}^n = \boldsymbol{R}^{n-1} - \boldsymbol{F}_l \tilde{\boldsymbol{S}}_l$;

  end if

end for

All users with correct decoding L;

(Updating) $\boldsymbol{R}^{K_1} = \boldsymbol{R}^1 - \sum_{m \in L} \boldsymbol{F}_m \tilde{\boldsymbol{S}}_m$;

STEP3 (PIC detection)

All PIC users K_2, $K_2 = \{k | \mathrm{SINR}_k < M_1, k \in K\}$;

for $n = 1 : N$ **do**

  (MMSE detection) $\boldsymbol{y}^n = \hat{\boldsymbol{\omega}}^{K_1} \boldsymbol{R}_{k_2}^n$;

  (Demodulation&Decoding) $\tilde{\boldsymbol{S}}_{k_2}^n = (\mathrm{Dem\&Dec})\, \boldsymbol{y}_{k_2}^n$;

  All users with correct decoding L;

  (Update) $\boldsymbol{R}_{k_2}^n = \boldsymbol{R}^{K_1} - \sum_{m \in L, m \neq k_2} \boldsymbol{F}_m \tilde{\boldsymbol{S}}_m$;

end for

$\tilde{\boldsymbol{S}}_{k_2} = \tilde{\boldsymbol{S}}_{k_2}^N$;

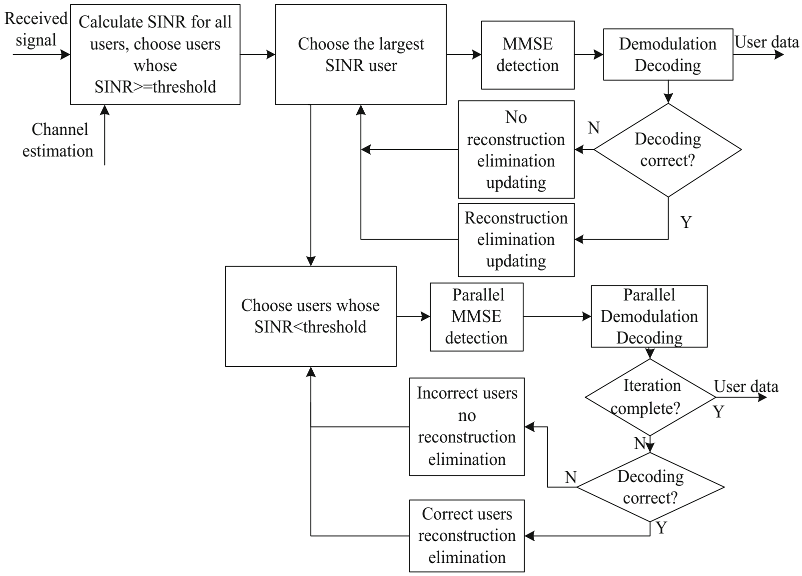

Fig. 2. MMSE-SPIC processing flow.

4 Simulation Results

The proposed multi-user detection algorithm and the three existing typical multi-user detection algorithms will be compared in this part. The simulation parameters [6] are shown in Table 1, and the relationships of average block error rate (BLER) and user overload rate of different algorithms are shown in Fig. 3.

From the simulation result of Fig. 3, the conclusion can be concluded that the detection performance of MMSE-SIC detection algorithm is the best and MMSE-PIC detection algorithm is the worst. That is consistent with theoretical result. About the two rest multi-user detection algorithms, results of the two algorithms are different in different range of users' overload rate.

When the user overload rate is low, the BLER of MMSE-SPIC detection algorithm is lower in the range of 100%–180%. For example, when the user overload rate is 125%, the average BLER is 1.0×10^{-2} for MMSE-2SIC and 2.5×10^{-3} for MMSE-SPIC. When the user overload rate is high, the BLER of MMSE-2SIC detection algorithm is lower in 180%–300%. For example, when the user overload rate is 200%, the average BLER detection is 6.0×10^{-2} for MMSE-SPIC and 4.0×10^{-2} for MMSE-2SIC.

For a small number of access users, MMSE-SPIC detection algorithm firstly detects the users with strong signal through SIC detection, then the remaining few users are for PIC detection. The number of remaining users is small and MAI is weak, so the detection performance is good. When the number of access users is large, the remaining number of users for MMSE-SPIC is large and MAI is strong, so the detection performance becomes poor.

Table 1. The simulation parameters for performance comparison of multi-user detection algorithm.

Simulation parameters	Parameters configuration
Coding scheme	Turbo, code rate 1/2
Modulation method	QPSK
Spreading sequence category	Tri-level complex spreading code sequence
Spreading sequence length	4
Number of access user	4, 6, 8, 10, 12
Antenna configuration	1Tx,1Rx
Channel noise	Gaussian white noise
Transmit power	Fixed
SNR condition	All users 4–20 dB uniform distribution
Channel estimation	Ideal
Receiver	MMSE-SPIC, MMSE-2SIC, MMSE-SIC, MMSE-PIC

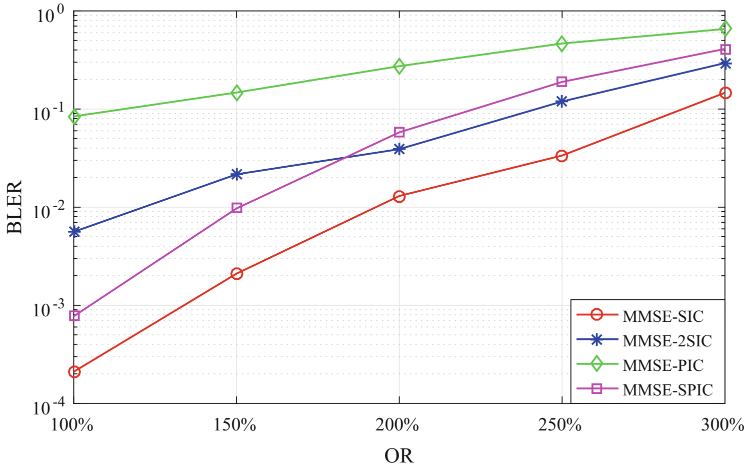

Fig. 3. Performance comparison for multi-user detection algorithms.

According to above description about the proposed algorithm, the choice of SINR threshold value will affect the detection performance of the proposed algorithm. Therefore relevant simulation results are provided in Fig. 4. In this simulation, the overload rate is set to 150% or 200% and that is the number of access users is 6 or 8. The other parameter configuration is similar to Table 1.

Figure 4 shows the impact of the choice of SINR threshold value on BLER in MMSE-SPIC detection algorithm. As can be seen from the curves, BLER

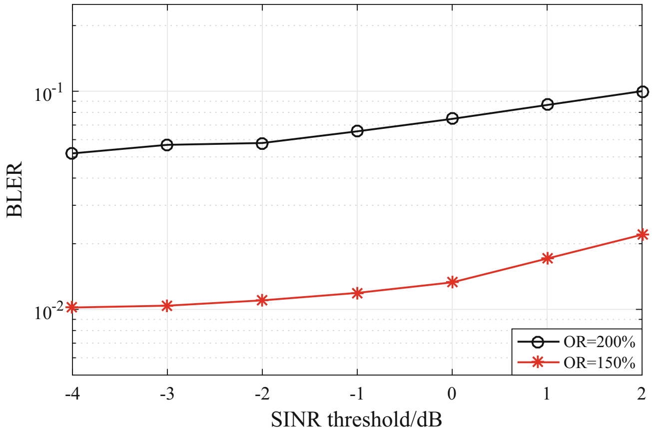

Fig. 4. Impact of the choice of SINR threshold value on BLER.

becomes higher and higher with the increase of SINR threshold. This is because the higher the SINR threshold, the less the number of users doing SIC detection. Thus the more serious the MAI, the worse the performance of the system. If SINR threshold is too high to no user reaching the SINR threshold, all users would do PIC detection. If SINR threshold is too low to all users reaching the SINR threshold value, all users would do SIC detection. System performance is the better when lower overload rate, but processing time delay will be higher because of more users doing SIC detection.

In addition, it can be seen from the curves that the relationship between SINR threshold and BLER is analogous when the overload rate is 150% and 200%. Therefore, considering time delay and detection performance, -2dB is selected as the SINR threshold value of MMSE-SPIC detection algorithm in this paper.

The following is the analysis of the processing time delay of several multi-user detection algorithms. According to the processing flow of detection algorithms, assume that the processing time for SINR calculating and sorting, MMSE detection, demodulation and decoding and reconstruction and elimination are τ_1, τ_2, τ_3, and τ_4, respectively. Thus it is easy to get the processing time delay of MMSE-SIC detection. That is $\tau_{\mathrm{SIC}} = \sum\limits_{i=1}^{K} \tau_{1i} + K\left(\tau_2 + \tau_3 + \tau_4\right)$, where K is the number of access users and τ_{1i} is the τ_1 for the ith time detection. The processing time delay of MMSE-PIC detection is $\tau_{\mathrm{PIC}} = N\left(\tau_2 + \tau_3 + \tau_4\right)$, where N is the iteration times, $N < K$. The processing time delay of MMSE-2SIC detection is $\tau_{\mathrm{2SIC}} = \sum\limits_{i=1}^{K/2} \tau_{1i} + \frac{K}{2}\left(\tau_2 + \tau_3 + \tau_4\right)$. The processing time delay of MMSE-SPIC detection is $\tau_{\mathrm{SPIC}} = \tau_{11} + K_1\left(\tau_2 + \tau_3 + \tau_4\right) + N_1\left(\tau_2 + \tau_3 + \tau_4\right)$, where N_1 is the iteration times, $N_1 \ll K$, and K_1 is the number of users for SIC detection. Thus we can draw that $\tau_{\mathrm{SIC}} > \tau_{\mathrm{2SIC}} \approx \tau_{\mathrm{SPIC}} > \tau_{\mathrm{PIC}}$.

According to the simulation result and analysis above, the comparison results for multi-user detection algorithm is shown as Table 2.

Table 2. Indicators comparison for multiuser detection algorithm.

Algorithm indicators	Comparison result
Processing time delay	MMSE-PIC < MMSE-SPIC ≈ MMSE-2SIC < MMSE-SIC
BLER	Overload is less than 180%: MMSE-SIC < MMSE-SPIC < MMSE-2SIC < MMSE-PIC Overload is greater than 180%: MMSE-SIC < MMSE-2SIC < MMSE-SPIC < MMSE-PIC

5 Conclusion

As a code domain non-orthogonal multiple access technology, MUSA can effectively improve spectral efficiency and enhance system capacity, and is suitable for IoT services in 5G communication system.

This paper mainly studies the multi-user detection algorithms for MUSA uplink receiver. The successive-parallel interference cancellation multi-user detection algorithm is proposed to overcome the shortage of the typical algorithms. Compared with MMSE-PIC multi-user detection algorithm, the proposed MMSE-SPIC detection algorithm improves detection performance well and ensures low processing time delay in addition. Compared with MMSE-SIC multi-user detection algorithm, MMSE-SPIC detection algorithm effectively reduces processing time delay and ensure good detection performance simultaneously. Moreover, MMSE-SPIC detection algorithm can achieve better detection performance than MMSE-2SIC detection algorithm under the condition that overload rate is below 180%, and the detection performance is acceptable when overload rate more than 180%.

In the future, we can try to combine MUSA with power domain NOMA technology or MIMO technology to further enhance system capacity.

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