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Multi user interference cancellation in satellite to ground uplink system Based on improved WPIC algorithm

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Abstract

An improved optimal weights based on parallel interference cancellation algorithm has been proposed to cancel for interference induced by multi-user access satellite to ground uplink system. Due to differences in elevation relative motion between the user and the satellite, as well as access between users, resulting in multi-user access interference (Multi-user Access Interference, MUI), which significantly degrade system performance when multi-user access. By steepest gradient method, it obtained based on the MMSE criterion, parallel interference cancellation adjust optimal weights to obtain the maximum SINR. Compared to traditional parallel interference cancellation (Parallel Interference Cancellation, PIC) algorithm or serial interference cancellation (Successive interference Cancellation, SIC), the accuracy of which is not high and too many complex iterations, we establish the multi-user access to the satellite to ground up link system to demonstrate that the improved WPIC algorithm could be provided with high accuracy and relatively low number of iterations .

Keywords: WPIC, SINR, MUI, Multi-user access elevation

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1. Introduction

Multi-user access interference for satellite to ground uplink system, not only introduced by the angle of elevation of mobile user access, but also introduced by the different between high-speed satellite and low-speed mobile user. Thus, under these assured conditions including assured system bandwidth, assured total number of carriers, and assured number of uplink access of users, the greater the elevation differences between access mobile users, the greater Doppler shift differences between access mobile users, the more serious multi-user access interference for satellite to ground uplink systems. Because each user has the own Doppler shift, the satellite receiver is difficult for cancellation and compensation. Therefore, multi-user access interference cancellation induced by difference Doppler shift is the key point for satellite to ground for earth uplink user.

For uplink single user detection, XinYu Gao has proposed a training sequence based on Hadamard transform method in literature [1], in order to bring the training sequence against interference during transmission, but the algorithm needs to add too much redundancy during transmission, thus the signal transmission efficiency is low. Because blind user detection does not use training sequences to enhance the utilization of bandwidth, the literatures [2-3] have proposed soft iterative manner to complete the user detection signal, but the soft iteration requires too much user information, and it is not easy to achieve convergence.

Literature [4-5] proposed a second-order statistics for user blind detection, but the convergence time the longer, and has a higher complexity. Currently, the literature [6-9] has proposed space-time processing, interference cancellation and other advanced technology combined to improve the transmission performance of the system. An overview of the multi-user transmission system has been proposed in [10] based on this. An improved Kalman (Kalman Filter, KF) for multi-user detecting has been proposed in [11], but training sequence required is too long, which reduces the signal transmission efficiency of the system. An cancellation algorithm based on LS (Least Square) and MMSE (Minimum Mean Square Error) has been proposed in [12] for multi-user interference, but which need to get more prior knowledge, and eliminate accuracy is not high.

An iterative approach eliminates multi-user access interference has been proposed in [13], which needs cancellation for carrier interference one by one, and has the higher complexity. Literature [14] has proposed a multi-user based on the time domain carrier frequency offset compensation algorithm, but less accuracy. Choi J H has proposed a joint iterative detection algorithm in [15] at each iteration, which needs to do a lot of matrix transpose operations, and has higher complexity. Literature [16] has proposed a multi-user access SIC algorithm to eliminate interference. On this basis, the literatures [17-20] have proposed the cancellation for sub-carriers interference with sequencing in order to improve accuracy.

One by one sub-carrier interference cancellation signal processing increases SIC algorithms delays that each user should estimate the initial offset for higher load requirements of satellite-ground link, it is difficult to achieve for multi-user satellite to ground uplink system. The literature [21] summarizes some of the multi-user interference for satellite communication system Elimination. Compared to the SIC algorithm, PIC algorithm cancels for carrier interference simultaneously. Literature [22-23] have proposed PIC algorithm to eliminate multi-user access interference. On this basis, [24] proposes a PIC algorithm based on the weight of Signal algorithm to eliminate the interference of multi user access, with the influence on Signal to Interference Ratio SINR. Literature [25] has proposed PIC algorithm, which obtains the interference matrix transpose operation, but the complexity is proportional to the subcarrier number. In order to improve the precision of multi user interference cancellation in, it is necessary to improve the traditional user access interference cancellation algorithm in order to meet the needs for satellite to ground uplink system.

2. System model and problem formulation

2.1 Multi-user access elevation model

Fig. 1 shows the mechanism of elevation mode in the satellite to ground system. Due to Multi user access elevation, the relative high-speed movement between satellite and mobile users makes the larger range of Doppler frequency shift. The Multi-users access elevation angle between the user and satellite results in a larger Doppler frequency shift, which is the main reason for Multi-users access interference.

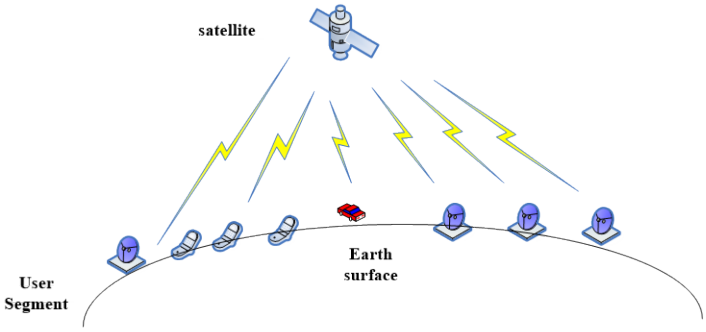

Fig. 1. Multi-user access elevation model

In the satellite to ground uplink system, for the Doppler shift signal exists, the uplink signals received at the satellite deviates from its actual frequency which the user terminal transmits. Doppler Δf of the mathematical model as follows formula (1),

$$\frac{\Delta f}{f} = -\frac{1}{c} \cdot \frac{r_E r \sin(\psi(t) - \psi(t_0)) \cos(\cos^{-1}\left[\frac{r_E}{r} \cdot \cos\theta_{\max}\right] - \theta_{\max}) \omega_F(t)}{\sqrt{r_E^2 + r^2 - 2 r_E r \cos(\psi(t) - \psi(t_0)) \cos(\cos^{-1}\left[\frac{r_E}{r} \cdot \cos\theta_{\max}\right] - \theta_{\max})}} \quad (1)$$

Where, r is the distance between the satellite and the center of the earth, r_E is the radius of the earth, f is the satellite operating frequency, $\theta = \theta_{\max}$ is set the maximum elevation for satellite to ground link system.

$\psi(t)$ and $\psi(t_0)$ are nadir corresponding to the central angle at t and t_0 time. $\omega_F(t)$ is satellite angular velocity in Geocentric coordinate system, ω_S is angular velocity for the satellite in its own orbit, ω_E is rotation angular velocity of the Earth, i is the inclination of the satellite orbit.

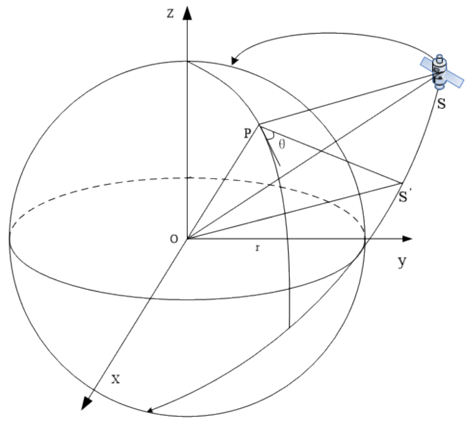

Fig. 2. Doppler shift representation for LEO satellite

From the **Fig. 2**, it can be informed that the greater multi- user access elevation angle, between user and satellite is, the higher satellite working carrier frequency is, the more serious Doppler frequency shift between multi-user access and the satellite.

For a particular Satellite transmission period, its tangential velocity is fixed for each user. Therefore, the Doppler shift due to the satellite motion is the same. While the Tangential velocity and operating frequency variable for satellite are the same, thus the instantaneous Doppler shift in different paths is the same. Thus, the carrier frequency offset and normal frequency offset factors are equal.

The Doppler shift is determined by the user terminal access Elevation angel and the satellite tangential velocity, so Doppler shift in each LEO satellite channel multi-path can be approximated equal. Using LEO satellite communication system to establish satellite to ground system and referring to the maximum elevation of ESA (ESA, European Space Agency) typical parameters after repeated different scenarios in Europe, it has specifically shown in **Table 1.**

Table 1. Biggest elevation angle of different test scene

testing scenarios	Elevation
Open land	15°- 45°
Rural land	15°- 55°
suburbs	15°- 55°
Urban land	15°- 55°
highway	15°- 55°

According to the Global Star satellite reference parameter settings, it is Defined that satellite altitude is 770km, the frequency is L-band, orbital inclination is 52 °, the lowest elevation for communication is 10 °, the average satellite connection time of 8min ~ 12min.

Fig. 3 is the Doppler frequency shift curve for terrestrial user terminals at different elevation over the top satellite. Learning from the figure, when the user terminal seeing the satellite rising from ground level, We can obtain the maximum positive Doppler shift. When the satellite ground station directly above, the Doppler shift is zero; when the satellite from the ground disappeared, the Doppler shift is the maximum negative Doppler shift. Figure 3 is the Doppler shift for high-speed satellite movement, when satellite, terrestrial user terminals at different elevation.

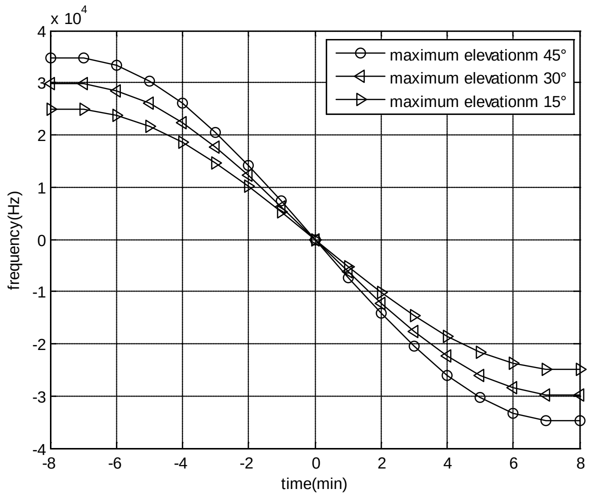

Fig. 3. Changing for Doppler frequency of different biggest elevation angle

Because satellite bandwidth is limited, In order to improve throughput and obtain the maximum bandwidth efficiency for satellite to ground link system, OFDM is selected as the physical layer transmission. **Fig. 4** is a ground satellite uplink OFDM multi-user access system. In this system, each user accesses with the same satellite, the satellite receiver has received multi-user mixed-signal superimposed, including multi-user access interference. We has proposed improved WPIC algorithm to cancel multi-user access interference induced by the Doppler shift, signal processing flow as shown in **Fig. 4.**

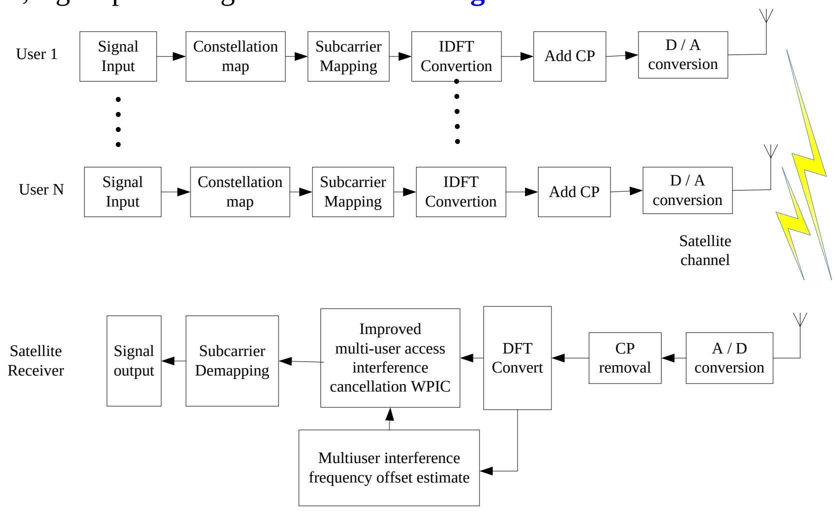

Fig. 4. An improved WPIC algorithm for Multi-user interference cancellation

2.2 Multi-user access elevation model

Due to the different elevation for multi-user access, which could seriously introduce different Doppler shifts, thus introduce carrier frequency offset for satellite to ground uplink system. For particular user, the tangential velocity, and the carrier frequency within one symbol remain unchanged, so the frequency offset introduced within one symbol period can be seen as constant. Thus, the regularization frequency offset factor remains unchanged.

Define ξ_i as the regularization frequency offset factor for user *i*, *T* as the number of users for access satellite uplink, *L* as the order time-domain channel impulse response $h(m,l)$. After signal $d(k)$ through the *N* orthogonal subcarriers modulated, the time-domain signals received by satellite receiver may represent for,

$$y_i(m) = \sum_{k=0}^{N-1} d(k) \sum_{l=0}^{L-1} h(m,l) \exp(j2\pi k(m-l)/N) \exp(j2\pi k \xi_i m/N) \tag{2}$$

$$y(k') = \frac{1}{M} \sum_{k=0}^{M-1} \sum_{m=0}^{M-1} D(k)H(k) \exp(j2\pi mk/M) \cdot \exp(j2\pi \xi m/M) \cdot \exp(-j2\pi mk'/M) \tag{3}$$

The frequency-domain signal $y_i(k')$ for user *i* after satellite receiver demodulating, can be combined with multi- user access interference. In order to facilitate research, the separation interfering induced by carrier frequency offset can obtain as,

$$\begin{aligned} y_i(k') = & \frac{1}{N} \sum_{m=0}^{M-1} \sum_{k=0}^{M-1} D(k')H(k') \exp(j2\pi \xi^i m/M) \\ & + \sum_{\substack{k=0, \\ k \neq k'}}^{M-1} D(k)H(k') \frac{\sin \pi(k-k'+\xi^i)}{N \sin \frac{\pi}{N}(k-k'+\xi^i)} \cdot \exp(j\pi(k-k'+\xi^i)(M-1)/M \\ & + z(k') \\ & k' = 0,1,\cdots,M-1, \end{aligned} \tag{4}$$

The first term of these is the interference introduced by users carrier leakage, the second term is the inter-carrier interference between users leakage, the third term is the white Gaussian noise. The separation for multi-user interference can be obtained by the following formula,

$$\begin{aligned} Y(k') = & \frac{1}{M} \sum_{m=0}^{M-1} \sum_{k'=0}^{M-1} D(k')H(k') \exp(j2\pi \xi^i m/N) \\ & + \sum_{\substack{i \in M \\ j \neq i}} \sum_{\substack{k=0, \\ k \neq k'}}^{M-1} D(k)H(k) \frac{\sin \pi(k-k'+\xi^i)}{M \sin \frac{\pi}{M}(k-k'+\xi^i)/M} \cdot \exp(j\pi(k-k'+\xi^i)(M-1)/M \\ & + \sum_{\substack{j \in T \\ j \neq i}} \sum_{\substack{j=0, \\ j \neq k'}}^{M-1} D(j)H(j) \frac{\sin \pi(j-k'+\xi^j)}{M \sin \frac{\pi}{M}(j-k'+\xi^j)} \cdot \exp(j\pi(j-k'+\xi^j)(M-1)/M \\ & + z(k') \\ & k' = 0,1,\cdots,M-1, \end{aligned} \tag{5}$$

Where, $y(k')$ is the received multi-user mixed signals. From the formula (6), we can obtained, when multi-users with different elevation access to the same satellite, interference between users will be introduced, which thereby reducing the satellite receiver performance.

Equation (6) also show the influence due to the frequency offset, leakage of energy from the subcarrier k to subcarrier l. we can also conclude that the energy leakage depends on the difference between the number of the carrier spacing, and the normal carrier frequency offset factor. Define the relative frequency offset factor ξ, then the leakage induced from kth carrier to the lth carrier can be expressed as,

$$\Gamma = \frac{\sin^2(\pi\left[(l-k)+\xi\right])}{N^2 \cdot \sin^2(\pi\left[(l-k)+\xi\right]/N)} \tag{6}$$

Define that the carrier number is 1024, **Fig. 5** shows the energy leakage caused by near the subcarrier k. As the normal frequency offset factor increasing, and the serial number of the carrier spacing is reduced, the energy leakage is more serious interferencu indcued by subcarrier k. At the same number subcarrier interval, normal carrier frequency offset factor can seriously increase power leakage.

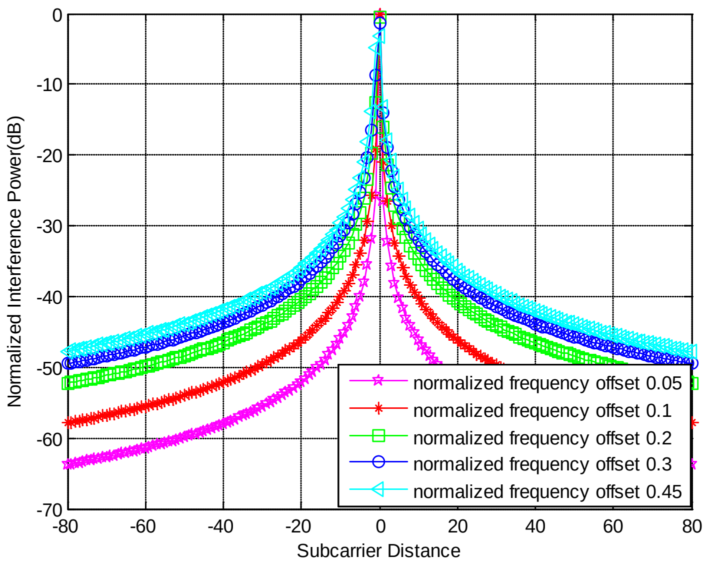

Fig. 5. Energy leakage introduced by subcarrier frequency deviation

3. Improved WPIC algorithm

The proposed algorithm is based on the goal for optimizing SINR, which is to find the optimal SINR corresponding to WPIC interference cancellation algorithm weights. Thus multi-user interference signal received by satellite is expressed as,

$$Y^i = D^i H^i \Theta_{i,i} + D^i H^i \Theta_{i,k} + D^j H^j \Theta_{i,j} + Z$$
$$k, i = 0, 1, \cdots, N-1, \quad j = 0, 1, \cdots, M-1 \tag{7}$$

In accordance with the multi-carrier modulation user allocation, this processing can be a multi-user signal separation. First, each user should be according to the traditional WPIC algorithm for cancellation. After a user *i* through WPIC algorithm, it can be expressed as,

$$Y_m^i = Y_{(m-1)}^i - w\Theta_{i,l} Y_{m-1}^j \tag{8}$$

Where, m is the number of cancellation, w is the weight. Define $\Lambda_{k,l}$ as the interference induced by subcarrier *i* of user *j* and carrier *k* of uer *i*, which can be expressed as,

$$\Theta_{k,l} = \sum_{j=1}^{N-1} \sum_{j \neq k'}^{N-1} \frac{\sin \pi (j - k' + \xi^j)}{N \sin \frac{\pi}{N} (j - k' + \xi^j)} \cdot \exp(j\pi (j - k' + \xi^j)(N-1)/N \tag{9}$$

Where, $w\Theta_{i,l} Y_{m-1}^j$ is expressed as the previous term of the interference term, Y_m^i is the *m*-th detection signals of user *i*, $Y_{(m-1)}^i$ is the $(m-1)$-th received signal for the user *j*. Putting the formula (9) into the PIC judgment, we can obtained,

$$Y_2^i = D^i(k) H^i(k) \left(1 - w\Theta_{k,l}^2\right) + I \tag{10}$$

Where, I is the second interference judgments, Y_2^i is the received signal after cancellation, which can be obtained as,

$$I = \sum_{\substack{l=1 \\ l \neq k}}^{N-1} \sum_{l \in j} D^i(l) H^i(l) (\Theta_{k,l}(1-w) - w\Theta_{k,l}^2) \tag{11}$$

Analyzing the received signal SINR after the PIC cancellation, it can be expressed as,

$$SINR^i \propto (1 - w\Theta_{k,l}^2)^2 \tag{13}$$

Formula (13) is a function with relationship about the signal SINR about the second cancellation and the value w, which can be expressed as convex function. SINR could be obtained the best, when *w* is extreme value. The improved WPIC algorithm is based on the PIC algorithm to select the optimal weights in iteration, which can greatly reduce the number of iterations and improve the accuracy. A comb or block pilot signal can be used for initial signal to interference ratio. The optimum signal to interference ratio can be obtained by training the initial weights in iteration, in order to approach the optimum.

Define the number of user is 4, the number of subcarrier is 512. In the condition of AWGN, E_b / N_0 =15dB, The allocation is OFDM, The normalized frequency offset is 0.1，0.05，0.15，0.2。**Fig. 6** is the curve of the relationship between average SIR and weight *w*.

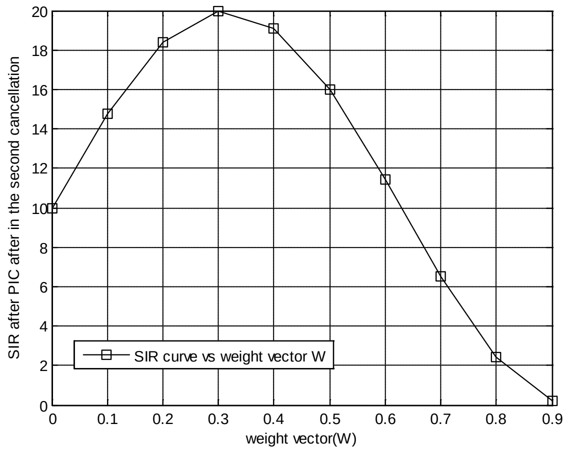

Fig. 6. SINR performance of different weights in PIC in two iterations

It could obtained from **Fig. 4**, convex function can be received. PIC algorithm could adjust weighted w to obtain optimal SIR value, SIR can take the extreme. The improved WPIC algorithm is based on PIC, choosing the optimal weights to improve the PIC removal precision, and reducing the number of iterations with the algorithm PIC. This paper uses the massive pilot signals the user frequency offset estimate and access user optimum user signal SIR; Optimal weights are iterated to approximate with setting the initial weights. It is the specific way of obtaining the optimal weights below.

Define $SINR_{opt}$ as the optimal $SINR$ after PIC algorithm cancellation. Since $SINR_{opt}$ is the convex function with $w(n)$, the optimal SINR could be obtained when w has the extreme value. Define the initial value for $w=1$. In this case, the algorithm becomes the traditional PIC algorithm, which also can be the next iteration w value.

Define e_{SINR} is error between $SINR_{opt}$ and $SINR_{out}$ after cancellation with PIC algorithm, which also can be expressed as,

$$e_{SINR} = SINR_{out} - SINR_{opt} \tag{14}$$

So the algorithm for the optimization goal is $\min\left\{E\left|SINR_{out} - SINR_{opt}\right|^2\right\}$, In accordance with $SINR_{out}$, at the point of $SINR_{opt}$ in the first order with Taylor expansion, which can be obtained,

$$SINR_{out} \approx SINR_{opt} + \nabla(w_{out} - w_{opt}) \tag{15}$$

where,

$$\nabla \approx \left[\frac{\partial SINR_{out}}{\partial w_{out1}}, \cdots \frac{\partial SINR_{out}}{\partial w_{outk}}\right] \tag{16}$$

The formula (16) is substituted by J, which can be obtained,

$$\begin{aligned}&\min\left\{E(\left|SINR-SINR^{(i+1)}\right|^2)\right\}\\&\approx\min\left\{E(\left|SINR_{out}^{i}+f(w_{opt}-w_{out}^{(i)})-SINR_{out}^{(i+1)}-f(w_{out}^{(i+1)}-w_{out}^{i})\right|^2)\right\}\end{aligned} \tag{17}$$

In order to minimize the objective function, using linear search from the weights w_{out} to approximate the optimal value w_{opt}. From the current direction M^i, we could optimize from ith iteration w_{out}^i weights to the optimal weight $w_{out}^{(i+1)}$, then the weight approximation process can be expressed as,

$$w_{out}^{(i+1)}=w_{out}^{i}+\mathrm{M}^{i}\cdot e_{SINR}^{i} \tag{18}$$

Approach the direction M^i, we need as,

$$\begin{aligned}\mathrm{M}^i&=\arg\min_{T^i}E\left(\left|SINR_{out}^{i}-SINR_{out}^{(i+1)}\right|^2\right)\\&=\arg\min_{T^i}E\left[(w_{out}^{i}-w_{out}^{(i+1)})^H(\nabla^i)^H\nabla^i(w_{out}^{i}-w_{out}^{(i+1)}\right]\end{aligned} \tag{19}$$

The formula (19) can be obtained after expansion,

$$\begin{aligned}&E\left[(w_{out}^{i}-w_{out}^{(i+1)})^H(\nabla^i)^H\nabla^i(w_{out}^{i}-w_{out}^{(i+1)})\right]\\&=E\left[(w_{opt}-w_{out}^{i}-\mathrm{M}^i(SINR_{opt}-SINR_{out}^{i})^H(\nabla^i)^H\nabla^i(w_{opt}-w_{out}^{i}-\mathrm{M}^i(SINR_{opt}-SINR_{out}^{i})\right]\end{aligned} \tag{20}$$

Substitution $k=(w_{opt}-w_{out}^{i})$, which can be obtained as,

$$\begin{aligned}&E\left[(w_{opt}-w_{out}^{(i+1)})^H(\nabla^i)^H\nabla^i(w-w_{out}^{(i+1)})\right]\\&\approx E\left[((I-T^i\nabla^i)k^i)^H(\nabla^i)^H\nabla^i(I-\mathrm{M}^i\nabla^i)k^i\right]\end{aligned} \tag{22}$$

To find the T^i derivative, which can be obtained as,

$$\mathrm{M}^i=\left[(\nabla^i)^H\nabla^i+\sigma^2(k^i(k^i)^H)^{-1}\right]^{-1}(\nabla^i)^H \tag{23}$$

formula (23) is the direction from w_{out}^i obtained weights to the optimal weights w_{opt}, in the ith iteration, which can be expressed as,

$$k^i(k^i)^H=\eta I \tag{24}$$

Where, η is a constant, formula (24) can be simplified as,

$$\mathrm{M}^i=\left[(\nabla^i)^H\nabla^i+\sigma^2(\eta I)^{-1}\right]^{-1}(\nabla^i)^H \tag{25}$$

Formula (25) can be obtained for optimal approximation of optimal SINR direction from the ith iteration.

4. Experimental Classification Results and Analysis

In order to research on the improved WPIC algorithm for multi-user access interference cancellation performance. Establishing that the orbital altitude 1100km for satellite to ground uplink system model. Setting satellite beam spot beam with the number is 5, and the diameter of covering is 450km, satellite running tangential speed is 7.15km / s (according to the Globe star). Using S-band carrier frequency, and 3 channel model path model which has the direct component, and the second delay is 100ns, the longest diameter expansion 180ns delay. Setting the number of 4 for uplink user, with employing OFDM access mode, the pilot block type information transmission, and cyclic prefix length is longer than the multi-path channel delay spreading. For analysis, users can access the maximum elevation 25 °, 15 °, 5 °, 5 ° . Signal bandwidth is 50MHz, the number of subcarriers is 1024, and signal mapping method is QPSK.

Fig. 7 shows simulation BER results about the proposed improved WPIC algorithm based on multi-user interference cancellation, which is compared with the proposed PIC algorithm proposed in literature [25].

At the same time, with the optimal weights, the improved WPIC algorithm were made with two iteration iterations. The simulation results can be seen from the graph. After the first iteration, its interference cancellation algorithm is similar with the performance of WPIC algorithm. But after the second iteration, the weights *w* converge close to the inflection point convex function of location, then we can get close to the optimal elimination of weight, so it is possible to obtain optimum performance of the BER performance for multi-user. The system has been enhanced under conditions of 10e-3 bit error rate of the proposed algorithm performance after the second iteration compared with the second iteration of the algorithm PIC performance improved by nearly 3dB.

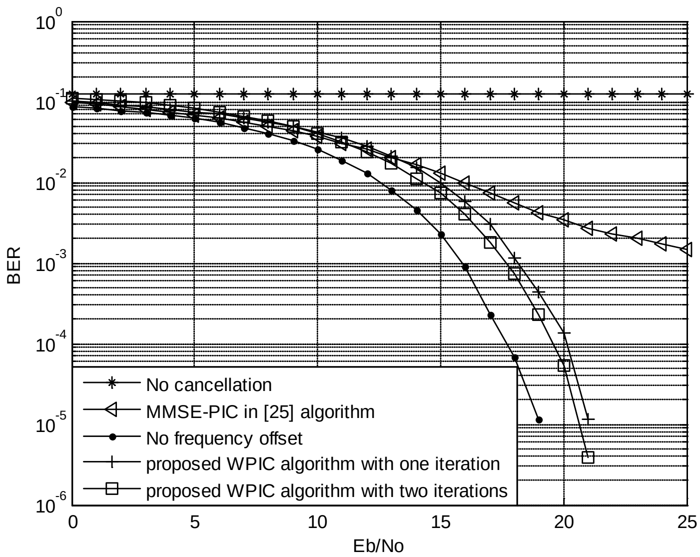

Fig. 7. BER curves under different SNR

Fig. 8 shows SINR performance comparison between PIC algorithm proposed in literature [25] and the proposed improved WPIC algorithm. Since the improved WPIC algorithm is to eliminate the sub-carrier frequency offset interference due to the differences in the introduction, such SINR system can get the optimal, when weight value *w* approach optimum,.

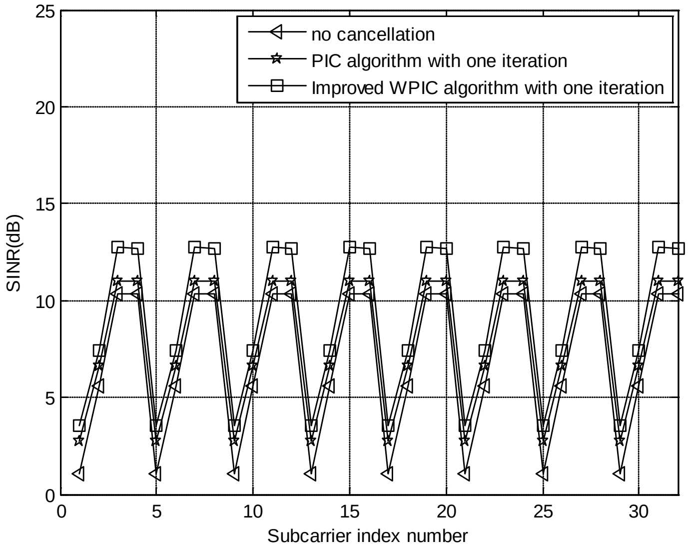

Fig. 8. SINR performance of different subcarrier

(within OFDM subcarrier allcation, normalized frequency offset is 0.25、0.15、0.1、0.1)

Fig. 9 and **Fig. 10** is E_b / N_0=10dB， E_b / N_0=20dB, each user of the uplink access of different BER curves, as the relative interference carrier frequency offset increments user error rate increases, which is due to the introduction of the user to access the multi-user access system is poor due to interference of reception.

Because the improved WPIC algorithm performance is poor, the weight is not the best at this time, its performance and the performance of the algorithm is similar to the conventional PIC, which is due to the residual carrier frequency offset introduced multi-user access interference. After the second iteration with the improved WPIC algorithm, the weights at this time is close to the optimum value, then the system is close to the maximum SINR optimization.

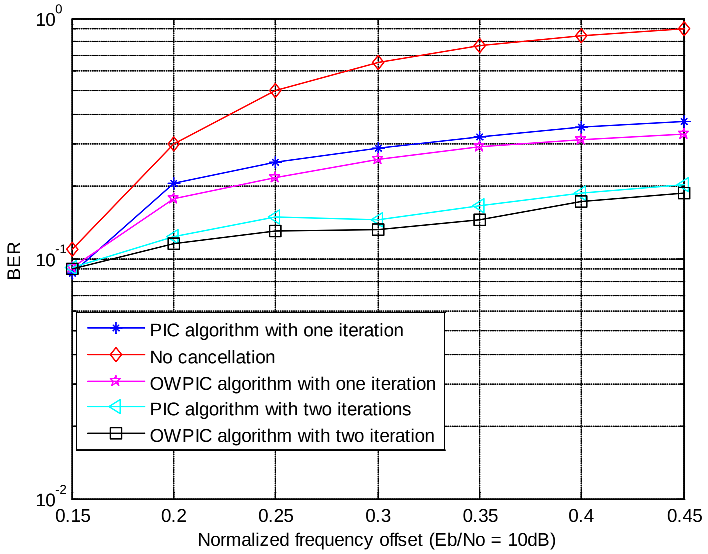

Fig. 9. BER performance of different normalized frequency offsets

(E_b / N_0 =10dB, within OFDM subcarrier allocation)

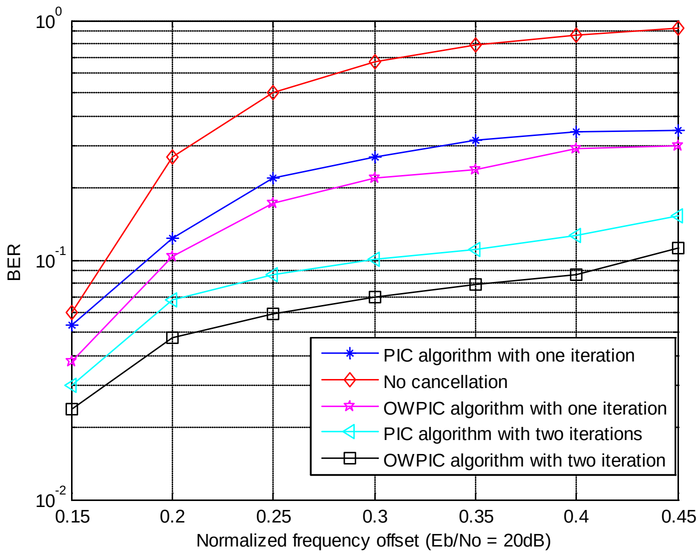

Fig. 10. BER performance of different normalized frequency offsets

(E_b / N_0 =20dB, within OFDM subcarrier allocation)

5. Conclusion

The improved WPIC algorithm has been proposed to cancel interference induced by multi-user access in satellite to ground uplink system. Since the introduction of multi-user Elevation angle differences for users in satellite-ground uplink system, traditional PIC or SIC algorithm to eliminate accuracy is not high, huge iterations, the proposed algorithm using the optimal weight value parallel for multi-user cancellation algorithm. Theoretical analysis and simulation of the algorithm to eliminate the high precision step iterative simplify conducive algorithm can be realized.

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