Research on Continuous Signal Mask Separation in Satellite Communication

Zeng Jing¹, Gengxin Zhang¹ and Ziwei Liu*¹

¹College of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu, 210003, China

First author’s e-mail: 1218012230@njupt.edu.cn

*Corresponding author’s e-mail: lzw@njupt.edu.cn

Abstract. With the rapid development of communication technology, satellite communication has been very popular in our life. However, due to the openness of satellite communication channel, the communication security has been a hot topic. The large signal masking technology is a potential solution to improve the safety of satellite communications in recent years. To achieve this technique, an efficient and reliable signal separation method must be supplemented at the receiver. Based on existing methods, there are problems of low accuracy of parameter estimation and complex estimation process. The improved scheme introduces the Amplitude and Phase Estimation (APES) based parameter estimation procedure, and proposes a new scheme consisting of APES algorithm, Costas loop and Least Mean Square (LMS) adaptive filter. Compared with existing methods, the simulation results show that the proposed method can achieve mask signal separation successfully, and can achieve better separation performance.

1. Introduction

Satellite communication has the advantages of long transmission distance, wide frequency band, large capacity and stable transmission performance. It has become an indispensable part of modern communication[1]. However, due to the characteristics of strong openness and long communication links in satellite communication channels, the security issue is usually a potential problem that satellite communication system faced with.

To alleviate this problem, conventional methods are implemented by spreading spectrum[2], reducing the transmission rate, using array antennas[3] and beamforming[4]. With the development of the intercept technology, conventional methods cannot meet the demand of communication security. In recent years, a new design approach based on large signal masking was proposed. In 2014, Chen Qi analyzed the application of large signal masking technology in information security for the first time and proposed the method of large signal masking[5]. Subsequently, the large signal masking technology has drawn many attentions. Based on [6], Lian C et al. designed a new chaotic mapping function and combined it with coherent chaotic shift keying technology. Spread spectrum modulation is carried out by using the hidden signals to be sent by chaotic sequence, which improves the security of the hidden signals. In [7], Xie T.C et al. superimposed hidden signals on background signals in the time-frequency domain by means of signal overlap, and introduced the transform domain communication system to complete the sending and receiving process of hidden information. Xie A.H et al. adopted a large signal masking with cyclostationary characteristics and a weak signal without
cyclostationary characteristics to realize covert transmission of satellite signals[8]. In [9], He Q.H et al. combined code hopping spread spectrum technology and large signal concealment technology, improved the security of the system.

One of the keys of the large signal masking technology is the mask signal separation technology at the receiver. However, existing methods rarely elaborate on the process of separating the mask at the receiver. To address this problem, based on[10], this paper proposes a new scheme consisting of Amplitude and Phase Estimation (APES) algorithm, Costas loop and Least Mean Square (LMS) adaptive filter. The frequency and phase offset of the signal are estimated and tracked through the APES algorithm and Costas loop, respectively. Then LMS adaptive filtering is used to complete the separation of the mixed signal. The simulation results show the effectiveness of the proposed method.

The rest of this paper is organized as follows. Section 2 presents the system model of using large signal masking technology to improve communication security. Section 3 introduces the proposed adaptive cancellation scheme. Section 4 shows the simulation results. Conclusion is drawn in Section 5.

2. System model

Large signal masking technology uses strong power and significant parameter characteristics to mask useful signals in the channel, increasing the difficulty of interception [11]. The design principle of satellite communication system based on large signal masking technology is shown in figure 1.

![Diagram of large signal masking technology](image)

In figure 1, the uplink signal \(r_1(t)\) sent by ground station B is the masked signal, whose power is larger than the communication signal \(r_2(t)\) sent by ground station A. After transparently forwarded by satellite, mixed downlink signals are separated in the ground station B. For ground station B, the received signal can be expressed as:

\[
R(t) = r_1(t) + r_2(t) + n(t) = h_1 \sqrt{p_1} A_1 \cos(\omega_1 t + \varphi_1) + h_2 \sqrt{p_2} A_2 \cos(\omega_2 t + \varphi_2) + n(t)
\]

(1)

where \(h_1, h_2\) is the channel gain; \(p_1, p_2\) are the transmitter power of masking signal and communication signal, respectively. \(\omega_1, \varphi_1, A_1, \omega_2, \varphi_2, A_2\) are the frequency, phase and amplitude of masking signal and communication signal, respectively. \(n(t)\) is the additive white Gaussian noise introduced in the communication process.

The local signal stored in station B can be written as:

\[
L_0(t) = A_1 \cos(\omega_0 t + \varphi_0)
\]

(2)

where \(\omega_0, \varphi_0, A_1\) are the frequency, phase and amplitude of the local signal respectively.
In the receiver, an appropriate cancellation technique is adopted to excise the masked signal in the mixed signal by local signal, in what follows the communication signal can be demodulated. Due to the existence of local reference signals, the key of separation and cancellation is to estimate and compensate the parameter difference between the masked signal and the local signal in the received signal, so as to improve the relevance of two possible signal before cancellation. The proposed scheme is mainly divided into two parts: pre-compensation and tracking compensation. The scheme will be introduced below in detail.

3. Adaptive cancellation scheme based on reference signal

3.1. Overall receiver design plan
The block diagram of the proposed adaptive cancellation scheme in this paper is shown in figure 2.

![Figure 2. Adaptive cancellation scheme based on reference signal](image)

Considering the transponder frequency error, Doppler frequency shift, channel fading and other factors, the actual received frequency is usually different from the pre-set downlink frequency. First, the mixed signals $R(t)$ and the local signals $L_0(t)$ were used for delay/frequency rough estimation. Then, the APES algorithm was used for accurate frequency estimation to obtain the first-level local recurrence signal $L_1(t)$.

Considering the effects of frequency and phase time-varying characteristics such as Doppler jitter during the communication process. The Costas loop is used to dynamically track the frequency and phase differences between $L_1(t)$ and the masked signal in the mixed signal. The result is compensated into $L_1(t)$ to obtain the second-level local recurrence signal $L_2(t)$.

When the Costas loop is locked, the LMS adaptive filter module is started to complete more precise frequency and phase compensation, and the separation and cancellation of masking signal and communication signal are completed to obtain the adaptive offset signal $S(t)$.

3.2. Adaptive cancellation plan
The adaptive cancellation plan mainly includes four modules: delay/frequency rough estimation, APES spectrum estimation, Costas loop tracking and LMS adaptive filtering

3.2.1. Delay/Frequency rough estimation. Due to the large frequency difference between the local signal and the masked signal, the correlation decreases severely. The delay/frequency rough estimation module provides initial parameter estimation to enter the more accurate estimation module later. The commonly used algorithm for estimating the delay and frequency difference is a natural extension of the correlation function. The rough estimation can be expressed as:

$$B(\tau, f) = \int_0^\tau R(t)L_0(t + \tau)\exp(-j2\pi ft)dt$$  (3)
where $\tau, f$ respectively represent delay and frequency difference, $R(t)$ is the envelope of the mixed signal, $L_o(t)$ is the envelope of the local signal, to make $B(\tau, f)$ peak of $\tau, f$ is the time delay and frequency offset we are looking for.

Equation (3) can be regarded as the accumulated result of two signals at different delay and frequency offset. Firstly, the cumulative time length $T$ is determined according to the estimated accuracy requirements, and then the frequency slots are divided according to $T$. After the frequency slot is divided, the sliding correlation value is directly calculated and the maximum correlation peak is found within a short pre-detection integration time. When all the correlation peaks in the frequency slots are found, the exact frequency difference can be considered to be within this range.

### 3.2.2. APES spectrum estimation

APES spectrum estimation algorithm can be used to estimate the frequency offset and phase offset between local signals and masked signals. It is first proposed by Li in the 1990s [12]. It was originally derived by approximate maximum likelihood method, and requires no prior knowledge.

Estimation of $R(t)$ use APES spectrum can be expressed as:

$$\alpha(\omega) = \frac{a^H(\omega)Q^{-1}(\omega)g(\omega)}{a^H(\omega)Q^{-1}(\omega)a(\omega)}$$  \hspace{1cm} (4)

where $a(\omega)$ is the frequency vector of the signal.

$$Q(\omega) = K - g(\omega)g^H(\omega)$$  \hspace{1cm} (5)

$$g(\omega) = \frac{1}{L} \sum_{n=M-1}^{N-1} d(n)e^{-j\omega n}$$ \hspace{1cm} (6)

where $K$ is the correlation matrix of the input samples, $M$ is the tap of the filter, $d(n)$ is the input sample, $L = N + M - 1$. Since the power of the masked signal in the mixed signal is greater than that of the communication signal, the masked signal is more sharp than the spectrum peak of the communication signal. Therefore, the APES spectrum estimation method can be used to estimate the frequency difference and difference between the local signal and the masked signal in the mixed signal. At the frequency difference $\omega$, $|\alpha(\omega)|$ will show a peak, while at other frequencies, $|\alpha(\omega)|$ will be flat. After obtaining the frequency estimation result of the signal, it can be substituted into equation (4) to obtain the amplitude and phase of the signal at the frequency difference $\omega$.

### 3.2.3. Costas loop

To track the frequency and phase changes in a continuously transmitted signal, the phase-locked loop can be considered. In this plan, Costas loop is used to track the frequency and phase of the carrier. Its structure is shown in figure 3.
In the Costas loop, the frequency $\omega_i'$ and phase $\phi_i'$ estimated by the APES spectrum estimation algorithm are compensated into the frequency $\omega_0$ and phase $\phi_0$ of the local signal, which are used as the initial frequency and phase of the Costas loop. Then the two orthogonal signals $L_i(t)$ and $L_q(t)$ are generated through modulation. After passing through the discriminator, $L_i(t)$ and $L_q(t)$ generate the error signal $r_n(t)$. Then, through the loop filter, only the low-frequency component $r_e(t)$ is left in $r_n(t)$. Under the control of $r_e(t)$, the frequency and phase of Voltage Controlled Oscillator (VCO) output are approximately equal to the frequency and phase of the masked signal. The output signal $L_i(t)$ is the second-level local recurrence signal $L_2(t)$.

3.2.4. LMS adaptive filtering. After using Costas loop to obtain accurate frequency and phase tracking, the mixed signal is separated based on Minimum Mean Square Error (MMSE) criterion by using the correlation between the second-level local recurrence signal $L_2(t)$ and the mixed signal $R(t)$. This scheme uses LMS adaptive filtering algorithm, which was first proposed by Widrow and Hoff. Its structure is simple and easy to implement, so it is widely used. Its structure is shown in figure 4.
The second-level local recurrence signal $L_2(t)$ is taken as the input signal of the adaptive filter, and the expected signal is the received mixed signal $R(t)$, then the error signal can be expressed as:

$$e(t) = R(t) - y(t) = R(t) - w^T L_2(t)$$

(7)

Where $w$ is the weight vector of the filter. The key to the LMS algorithm is to solve $w$. For the solution of $w$, an initial value of $w(0)$ is generally adopted by iteration method, and then it is adjusted continuously along the direction of MMSE until the optimal $w$ is found. Iterative for

$$w(t + 1) = w(t) + \mu L_2(t)e^r(t)$$

(8)

where $\mu$ is the step size factor, the value range is $0 < \mu < 1/\lambda_{\text{max}}$, $\lambda_{\text{max}}$ is the maximum eigenvalue of the autocorrelation matrix of the input signal.

Finally, the error signal $e(t)$ generated by LMS adaptive filtering algorithm is the communication signal $S(t)$ after separation.

4. Simulation results

In this section, the simulation experiments will be performed. The matlab R2018a platform is used. The local carrier frequency in the simulation is 100 kHz. The frequency offset of the communication signal and the masking signal are 2 kHz and 1 kHz, respectively. The rest of the parameters are as follows.

| Parameter     | Value             |
|---------------|-------------------|
| Data length   | 100000bit         |
| Data rate     | 50kbps            |
| Modulation    | BPSK              |
| $E_s/N_0$     | 0~9dB             |
| Power difference | 3dB              |

Table 1. Simulation parameters

![Figure 5. Bit error rate curve under different power difference](image-url)
figure 5 shows the bit error rate curve of communication signal demodulation when the power difference between the masking signal and the communication signal is 0dB, 3dB, 5dB and 10dB, respectively. As can be seen from figure 5, with the increasing of the power difference, the demodulation performance of the communication signal is greatly reduced. Therefore, according to the actual situation, a balance point can be found, which can improve the security of the communication signal and ensure better demodulation performance.

figure 6 is the curve of the simulated bit error rate of the signal separation method based on adaptive cancellation proposed in this paper and the Normalized Complex Least Mean Square (NCLMS) signal separation method proposed in reference [10].

![Bit Error Rate Curve](image)

**Figure 6. Performance comparison of different signal separation algorithms**

figure 6 shows that the bit error rate performance of the algorithm proposed in this paper is better than that of the NCLMS algorithm. Under low SNR conditions, the bit error rate of the two algorithms is almost the same, but under high SNR conditions, the performance of the method proposed in this paper is improved by about 0.5dB. In this paper, we use a combination of the APES spectrum estimation algorithm and Costas loop to greatly improve the accuracy of the estimation. Therefore, compared with the NCLMS algorithm, the adaptive cancellation signal separation method proposed in this paper is more suitable for practical engineering applications.

5. Conclusion
This paper mainly studies and analyzes the problem of large-signal masking technology at the receiving end. Combining the channel transmission characteristics of satellite communication with the correlation between local signal and mixed signal, an adaptive cancellation method is proposed to achieve the separation of continuous signals. The simulation results show that the demodulated signal has good demodulation performance, which proves the feasibility of the proposed method.

Acknowledgments
This work was supported by the National Natural Science Foundation of China under Grant (no.61801445).

References
[1] Yi, K.C., Li, Y., Sun, C.H., Nan, C.G. (2015) Recent development and its prospect of satellite communications. J. Journal of communications, 36 (6) : 157-172.
[2] Sedaghatnejad, S., Farhang, M. (2015) Detectability of Chaotic Direct-Sequence Spread-Spectrum Signals. J. IEEE Wireless Communications Letters, 4(6): 589-592.
[3] Cheng, Y.J., Hong, W., Wu, K. (2007) Half Mode Substrate Integrated Waveguide Directional Filter. J. IEEE Microwave Wireless Component Letters, 17(7):504-506.

[4] Tsoulos, G., Beach, B. (1997) Wireless Personal Communications For 21st Century: European Technological Advances In Adaptive Antennas. J. IEEE Communications magazine, 35(9), 102-109.

[5] Chen, Q., Li, W. (2014) Application of large signal masking technology in information security. J. Telecom Express, 05: 3-5.

[6] Lian, C., Da, X.Y., Zhang, Y.P. (2014) Novel Algorithm of Satellite Covert Communication Based on Chaotic Spread Spectrum Modulation. J. Computer Science, 41(S2): 158-161.

[7] Xie, T.C., Da, X.Y., Chu, Z.Y., Gao, W.G. (2014) Satellite Covert Communication System Based on the Transform Domain Communication System. J. Information and control, 43(05): 524-528.

[8] Xie, A.H., Zhu, L.D., Zhai, J.Q., Li, X.F. (2018) Waveform Design for Satellite Communication Signals with Anti-interception Capability. J. Telecommunications Technology, 58(03): 269-275.

[9] He, Q.H., Zhu, L.D. (2019) Design and Simulation of Satellite Covert Signal Waveform. J. Radio communication technology, 45(01): 24-29.

[10] Huang, B. (2017) Performance Analysis of NCLMS-based PCMA. In: 3rd International Conference on Information Science and Control Engineering. Beijing. pp. 1375-1378.

[11] Xie, A.H, Zhu, L.D., Zhai, J.Q., Li, X.F. (2016) A Method of Designing Covert DSSS-Signal for Anti-blind Detection. J. Acta Electronica Sinica, 46(12): 2817-2823.

[12] Capon J. (1969) High-resolution entropy spectral analysis. J. Proceeding of IEEE, 57(8): 1408-1418.