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A Reliable Separation Algorithm of ADS-B Signal Based on Time Domain

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ABSTRACT With the development of Aerospace Science and technology, automatic dependent surveillance-broadcast has become a core technique in the field of air surveillance. Installing ADS-B receiver on LEO satellite can solve the problem of small coverage of ground receiver, to realize global coverage and monitoring. However, the satellite ADS-B system is faced with serious collision and overlap problems, which has a serious impact on the signal decoding, leading to the wrong decoding or even loss of important information. In this paper, a time-domain ADS-B blind signal separation algorithm is proposed. When there is a certain power difference between the two source signals, the overlap signals are offset by the high-power signal and low-power signal to get the corresponding cancellation signals. According to the superposition mode of different pulses, different bit decision results are obtained according to the amplitude, to recover the source signal. Simulations demonstrate that the proposed algorithm is feasible and has a lower bit error rate.

INDEX TERMS Blind source separation, ADS-B, space-based, time domain cancellation.

I. INTRODUCTION

Surveillance technology is a key component of intelligent air traffic, Its safety and reliability are very important. The current monitoring technology can be divided into independent monitoring technology and related monitoring technology [1], [2]. Like Primary Surveillance Radar and Secondary Surveillance Radar, Automatic Dependent Surveillance-Broadcast (ADS-B) system also has the ability of air surveillance [3]–[5]. Automatic dependent surveillance-broadcast (ADS-B) is a core technology in the field of air surveillance. Its principle is that the aircraft sends its altitude, speed, longitude, latitude, and other important information to the outside through a fixed data link. The data links of ADS-B include Universal Access Transceiver(UAT) and 1090 MHz Extended Squitter(1090ES) [6], [7]. After receiving these data, other aircraft can locate the target for information exchange, to achieve airspace monitoring. The current land-based ADS-B system mainly relies on the ground base station to complete airspace monitoring. The monitoring range of a single ground base station is small, the deployment cost is high, and it is difficult to deploy in the ocean and rainforest, and other complex terrain areas.

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On March 8, 2014, the MH370 passenger plane lost connection incident caused countries to attach great importance to the continuous tracking and monitoring technology of aircraft across the globe [8]. Although the land-based ADS-B system has certain advantages in monitoring performance, it is still a traditional monitoring technology. Improving the performance of airspace surveillance systems is a major research goal of the aerospace departments of various countries at this stage The space-based ADS-B system transmits its own important information to the Low Earth Orbit (LEO) satellite with ADS-B receiver, and then the LEO satellite transmits these messages to the ground base station. It has the advantages of wide coverage, low deployment cost, and can also improve the airspace traffic efficiency of line management and launch domain management.

A large number of aircraft are monitored in the coverage area of LEO satellites. Due to historical reasons, the access of the onboard transponder to the channel is random, and ADS-B broadcasts information through open and unencrypted protocols. This means that ADS-B data from the different planes will be transmitted asynchronously, which will lead to serious signal collision in the space-based system and two ADS-B signal overlaps most frequently [9]–[11]. If ignoring the signal overlap problem and discarding the overlap ADS-B signal directly, it will be unable to obtain important information and ensure the safety of the aircraft, which will degrade the airspace surveillance performance. To avoid this situation, it is necessary to separate the overlap signals and decode the separated signals to obtain the correct information and features [12], [13]. Therefore, it is essential to study the separation technology of spaceborne ADS-B overlap signals.

Due to the ADS-B signal is seriously overlap in the frequency domain, it is difficult to process from the frequency domain or time-frequency domain. It is difficult to use the traditional blind source separation method [14], [15]. The existing research results can be divided into time-domain separation methods and spatial domain separation method. The ICAO Document Standard provides the methods for the overlapping messages as following [16]: (1)when the overlapping occurs in the data part, the algorithm only can decode the first arrival message; (2) when the overlapping occurs in the data block, the first arrival message will be decoded and other messages will be given up. Thus only one message will be received correctly under mild conditions and the surveillance capacity will be reduced [17]. Sunquan *et al.* [18] introduced anomaly doubt degree to calculate signal overlap time delay and adopted adaptive threshold technology based on power difference to separate ADS-B signal when the overlap signal is relatively large. Lu and Chen [19] proposed a single antenna overlap signal separation method based on empirical mode decomposition and independent component analysis. Chenchen and Wenyi [20] accumulated the sampling points of the signal and adopted the K-means clustering method to realize the classification. Wu proposed a method to separate the big and small pulses of double overlap ADS-B signals in the time domain and realized the separation and decoding of overlap ADS-B signals [21]. The bit information was judged by the classification results and the separation of the two overlap signals was realized. Among the spatial overlap signal separation algorithms, A. van der veen proposed an algebraic constant modulus algorithm and it is suitable for the situation that the relative delay between overlap signals is small [22]. When the relative delay is large, the separation probability is not ideal. Nicolas Petrohilos proposed Projection Algorithm(PA) and Extended Projection Algorithm (EPA), which results in Gram Schmidt orthogonality [23]–[26]. Wang *et al.* [27] utilized Alternating Direction Method of Multipliers to solve the nonconvex blind adaptive beamforming problem. Experiments results show that even there is only one segment which is non-overlap, the performance of the proposed algorithm is satisfactory. Fast Independent Component Analysis(FastICA) takes negative entropy as the measure of signal Gauss, which does not need array calibration and is insensitive to relative delay when solving the separation problem of overlap signals [28]. According to the characteristics of signal modulation, Cardoso proposed a joint approximate diagonalization of eigenmatrix (JADE) algorithm based on fourth-order cumulants [29]. Zhang used the distribution of measured eigenvalues to determine the number of overlap signals, and then uses the DOA to reconstruct the mixing matrix to realize the signal separation [30]. Li proposed an optimization algorithm which takes the estimated value of PA algorithm as the initial value of FastICA algorithm. The combined optimization algorithm has better iterative convergence efficiency than FastICA algorithm [31]. With the development of deep learning, deep learning has been widely used in anomaly detection, channel estimation, speech recognition and separation [32]–[36]. In recent years, modulation signal classification methods based on deep learning emerge in endlessly [37]–[40]. Chen *et al.* [41] applied deep learning to the classification of ADS-B signal, the simulation results showed that the neural network can identify different types of wireless signals. This paper analyzes and classifies overlap signal pulses, and proposes an overlap ADS-B signal separation method based on time-domain cancellation.

The structure of this article is as follows. Section 2 provides additional background knowledge. In Section 3, we propose a two-step algorithm. Based on detecting the time delay, the signal is separated according to the proposed time-domain cancellation criterion. Section 4 provides an evaluation. Finally, conclusions are given in Section 5.

II. ADDITIONAL BACKGROUND KNOWLEDGE

A. SIGNAL STRUCTURE, BRIEF DESCRIPTION

This paper studies ADS-B signal in 1090ES format and the working frequency is 1090MHZ. Generally, the frame length of an ADS-B signal is 120*us* or 60 *us* and this paper studies the long frame length signal, i.e. 120*us*. A long length signal consists of two parts: a preamble with a length of 8 *us* and a data block with a length of 112 *us*. The preamble part contains four pulses with a length of 0.5 *us* at 0*us*, 1*us*, 3.5*us* and 4.5*us*, respectively. The modulation mode if ADS-B signal is Pulse Position Modulation (PPM). The structure of ADS-B signal is shown in Fig.1.

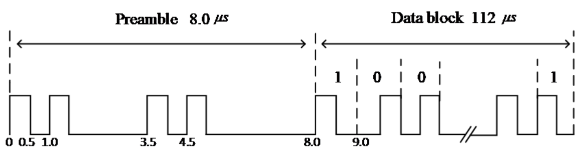

FIGURE 1. ADS-B signal structure.

B. COLLISION PATTERN

ADS-B transmitter sends out messages according to the specified criteria and the status of the aircraft, instead of asking in advance. Generally speaking, aircraft are most often in a stable state in the air. The aircraft is in a stable condition in the air and sends 5.6 messages per second. The ADS-B signal is a bit sequence transmitted by each plane and data from the different plane will be transmitted asynchronously, which means that we have to expect a signal overlap situation to occur, just like the Aloha event. This paper studies the situation of two ADS-B signals overlap because this collision mode accounts for the majority of cases [42].

C. SIGNALS DETECTION AND DECODING

As shown in Fig. 2, the traditional ADS-B signal detection algorithm is divided into two steps: preamble detection and data block decoding [43]. The purpose of preamble detection is to get the arrival time and the power of signal. The purpose of data block decoding is to get the coding information of each bit.

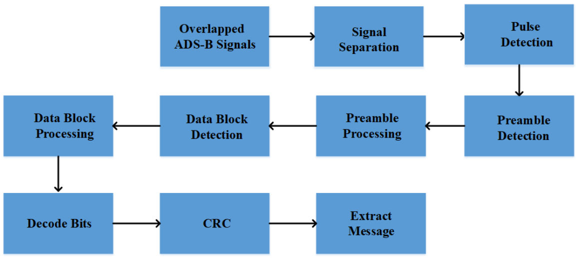

FIGURE 2. ADS-B detection algorithm.

D. SIGNAL MODEL

In the case of single antenna, the signal received at time t can be expressed as:

$$X(t) = \sum_{i=1}^{L} \sqrt{P_i} D_i \left(t - \tau_i\right) e^{j\phi_i + j2\pi f_i t} + e(t)$$

where,L represents the number of source signals,P_i, $D(t)$, f_i, φ_i and τ_i represent the power, baseband signal, carrier frequency, carrier phase and time delay of the i th signal respectively; $e(t)$ represents Gaussian white noise. Without considering the noise, the energy of overlap signals in the time period can be expressed as:

$$\begin{aligned} E(i) &= \int_{\Delta_{i-}}^{\Delta_{i+}} \left| \sum_{i=1}^{L} \sqrt{P_i} D_i \left(t - \tau_i\right) e^{j\phi + j2\pi ft} \right| dt \\ &= \int_{\Delta_{i-}}^{\Delta_{i+}} \left| \sum_{i=1}^{L} \sqrt{P_i} D_i \left(t - \tau_i\right) \right| dt \end{aligned}$$

The signal energy is determined by the signal power and the baseband pulse in Δ_i, that is, by the overlapp signal bits. Therefore, it is very important to distinguish the bits in the overlap signal segment.

III. PROPOSED ALGORITHM

A. TIME DELAY DETECTION

The first step of the proposed algorithm is to detective the time delay of the overlap signals, so the accurate identification of overlapping time is essential for the effect of signal separation. Singular value decomposition (SVD) is the most widely used algorithm in time detection [44]. The traditional projection algorithm adopts SVD to determine the time delay. Therefore, this paper adopts SVD to detective the time delay. The singular value decomposition of matrix is defined as follows. Let $\mathbf{A} \in R^{m \times n} P$ exist, then there is orthogonal matrix $\mathbf{U} = [u_1, u_2, \ldots, u_m] \in R^{m \times n}$ and orthogonal matrix $\mathbf{V} = [v_1, v_2, \ldots v_n] \in R^{n \times n}$ such that $\mathbf{U}^T \mathbf{A} \mathbf{V} = \mathrm{diag}\left[\sigma_1, \sigma_2, \ldots, \sigma_p\right] = \Sigma$,Then

$$\mathbf{A} = \mathbf{U} \boldsymbol{\Sigma} \mathbf{V}^T$$

is set up. equation is the singular value decomposition of the matrix $\mathbf{A}$. Where,$\sigma_1 \geq \sigma_2 \geq \ldots \sigma_p \geq 0$, $\sigma_i(i = 1, 2, \ldots p)$ is the singular value of $\mathbf{A}$, which is the square root of the eigenvalue of$\mathbf{A}\mathbf{A}^T$ or $\mathbf{A}^T\mathbf{A}$, namely $\sigma_i = \sqrt{\lambda_i}$.

The overlap of ADS-B signal is the overlap of bit pulse, so the separation of overlap ADS-B signals is the separation of signal sub pulse. The pulse overlaps segments have the following forms: bit 0 overlaps with bit 0, which is recorded as 0-0; bit 0 overlaps with bit 1, which is recorded as 0-1; bit 1 overlaps with bit 0, which is recorded as 1-0; bit 1 overlaps with bit 1, which is recorded as 1-1. In the process of processing ADS-B signal, we judge the signal size by the power of the signal, and the unit of signal size is dB. For power characterization

$$\mathrm{dB} = 10 \times \log(A/B)$$

In this paper, we assume that the amplitude of the standard pulse is 1, and the power is proportional to the square of the amplitude when the waveform is unchanged. ADS-B signal is a standard pulse square wave signal, which conforms to this rule. Assuming that the ratio is ($\mathrm{dB} = 10 \times \log(A/B)$, representing high power signal) and the pulse amplitude is m, the relationship between the ratio and the standard pulse is:

$$n(\mathrm{~dB}) = 10 \times \log\left(\frac{k^2 \times m^2}{k^2 \times 1}\right) = 10 \times \log\left(m^2\right)$$

When the data form of overlap segments is the above four overlap forms, each pulse segment can be classified according to the pulse amplitude. Considering the different peak values of high-power signal and low-power signal, there are four possible cases of pulse amplitude in overlap signal: the first is the pulse amplitude of low-power signal, denoted as V_2; the second is the pulse amplitude of high-power signal, denoted asV_1; the third is the superposition of high-power signal and low-power signal, that is, the overlap occurs, denoted as V_{1+2}; the fourth is low-level superposition of large and small power signals, that is, there is no pulse superposition. The schematic diagram of the four peaks is shown in Fig.3. The two source signals have a relative time delay, so there is only one source signal in the initial part and

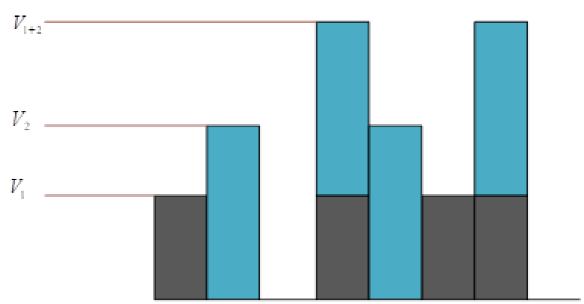

FIGURE 3. Schematic diagram of pulse superposition.

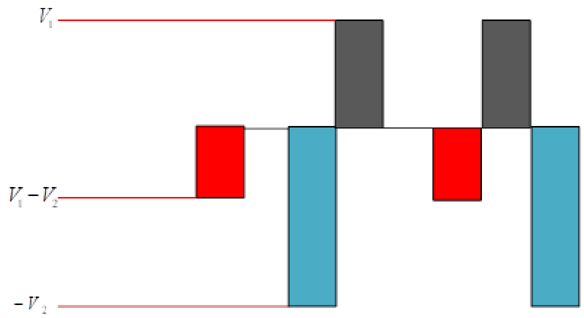

FIGURE 4. Schematic diagram of high-power signal cancellation.

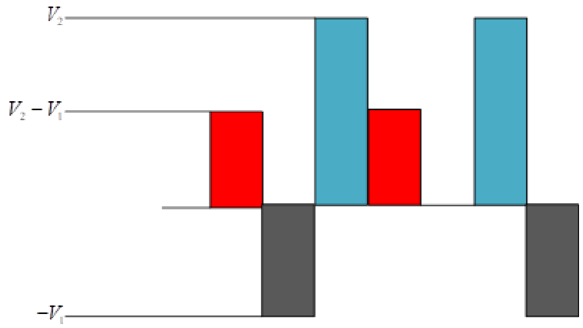

FIGURE 5. Schematic diagram of low-power signal cancellation.

TABLE 1. Bit decision criterion for overlap part of high-power signal cancellation.

first half amplitude	second half amplitude	high-power signal
V_1	$-V_2$	1
0	$V_1 - V_2$	1
$V_1 - V_2$	0	0
$-V_2$	$-V_2$	0

TABLE 2. Bit decision criterion for overlap part of low-power signal cancellation.

first half amplitude	second half amplitude	low-power signal
V_2	$-V_1$	1
$V_2 - V_1$	0	0
0	$V_1 - V_2$	1
$-V_1$	$-V_1$	0

the end part of the overlap signal. The estimated values of (low-power signal) and (high-power signal) are obtained by sampling the initial part and the end part. Then the overlap signals are subtracted by and to get two cancellation signal waveforms. In these two initial waveforms, only the peak value of one signal plays a major role. The cancellation waveforms of high-power signal and low-power signal are shown in Fig.4 and Fig.5, respectively. There are three main peaks in Fig.4:V_1,$V_1 - V_2$and$-V_2$. There are mainly three peaks in Fig.5:V_2,$V_2 - V_1$and$-V_1$. The criteria for determining the bits of high-power signal and low-power signal according to the cancellation signal are shown in Table 1 and table 2. It can be seen from Table 1 that the high-power signal can be determined as bit 1 when the level of the first half of a symbol of the cancellation signal is greater than or equal to 0; and the high-power signal can be determined as bit 0 when the level of the first half of a symbol of the cancellation signal is less than 0. Similarly, it can be seen from Table 2 that when the first half of a symbol of the cancellation signal is greater than or equal to 0, the low- power signal can be determined as bit 1; in other cases, the low-power signal can be determined as bit 0. After determining the bits of the overlap part of the high-power signal and the low-power signal, for the non-overlap part of the signal, because after the overlap signal cancels V_1 and V_2,the original 1-bit code of high-power single signal segment changes from first half V_2 and second half 0 to first half 0 and second half $-V_2$, and the original 0-bit code changes from first half 0 and second half V_2 to first $-V_2$ and second half 0. The original 1-bit code of low-power single signal segment changes from first half and second half 0 to first half 0 and second half$-V_1$, and the original 0-bit code changes from first half 0 and second half V_1 to first $-V_1$ and second half 0. Table 3 and Table 4 show the bit determination criteria of the single signal segment after cancelling.

TABLE 3. Bit decision criterion for single signal part of high-power signal cancellation.

first half amplitude	second half amplitude	high-power signal
0	$-V_2$	1
$-V_2$	0	0

TABLE 4. Bit decision criterion for single signal part of low-power signal cancellation.

first half amplitude	second half amplitude	low-power signal
0	$-V_1$	1
$-V_1$	0	0

It can be seen from Table 3 and Table 4 that when the first half of the symbol is close to 0 and the amplitude of the second half is much larger than the first half, both the high-power signal and the low-power signal are determined as bit 1. Through the analysis of the overlap part, it can be seen that the determining criteria of the single signal segment are consistent with the determined criteria of the overlap signal, so there is no need to do additional processing for the single signal in the subsequent processing.

After obtaining the bit determine criteria of the overlap signal part and the single signal part after the cancellation, the original square wave signal can be recovered through the determined symbols, and the original signal information can be obtained. Therefore, the algorithm steps proposed in this chapter are shown in Table 5.

IV. SIMULATIONS

A. SEPARATION AND PERFORMANCE COMPARISON EXPERIMENT OF ADS-B SIGNAL

Two ADS-B signals are generated randomly, the sampling rate is 10MHz, the power difference between the two signals is 3dB, the relative delay of the overlap signal is 47.5us, the SNR is 20dB, and the preamble of the high-power signal and low-power signal in the overlap signal is not damaged, and the amplitude of the signal is different. The time-domain

TABLE 5. ADS-B overlap signal separation algorithm based on time domain cancellation determine.

Input: overlap signal
1. Signal detection: judge whether there is ADS-B signal through the leading pulse, and detect the starting position of the signal
2. The observed signal is divided into 4 segments and singular value decomposition is used to get the start time and the end time of the overlap.
3. Determine the pulse amplitude of high-power signal and low-power signal.
4. Overlap signal cancellation obtains the high-power cancellation signal, and the bit information of the high-power signal is determined according to Table 1.
5. Overlap signal cancellation obtains the high-power cancellation signal, and the bit information of the low-power signal is determined according to Table 2.
6. The source signal is recovered by the determined bit information to separate the overlap signals
Output: source signal and bit information

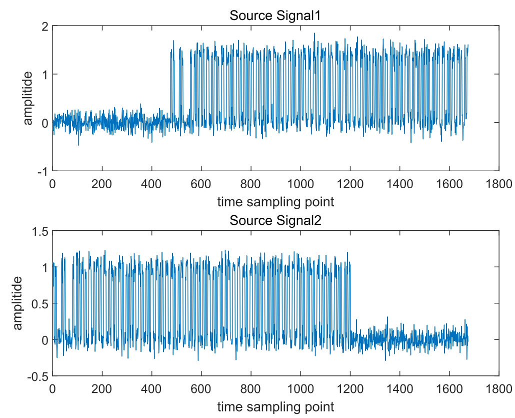

FIGURE 6. Source signal.

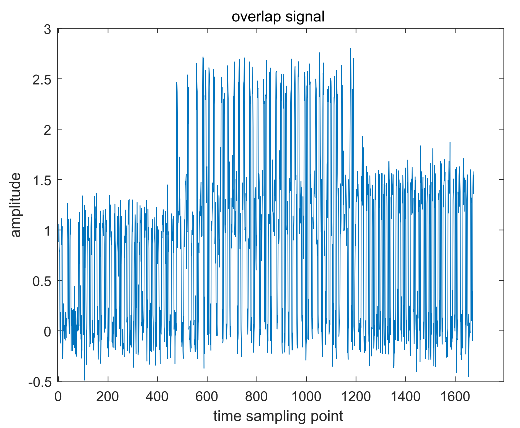

FIGURE 7. Overlap signal.

waveforms of two ADS-B signals and overlap signal are shown in Fig. 6 and Fig. 7 respectively.

It can be seen from Fig.7 that the two ADS-B signals overlap in the time domain after mixing, and the original correct information cannot be obtained from the overlap signal. At the same time, it can be seen that the leading pulse of the signal is complete and undamaged. By detecting the pulse amplitude of high-power signal and low-power signal, we can

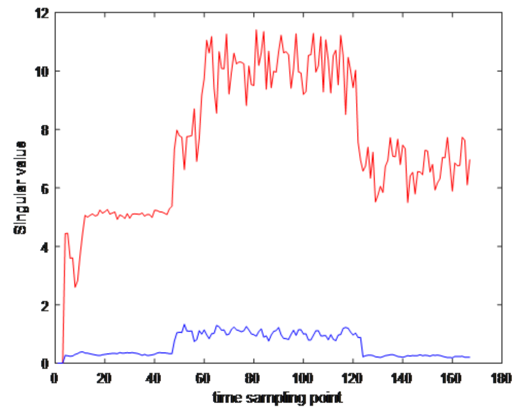

FIGURE 8. Time delay detection.

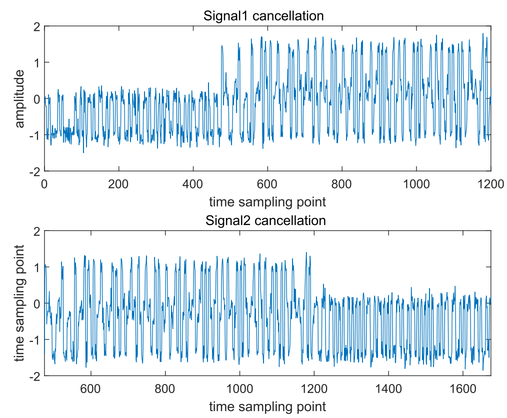

FIGURE 9. Cancellation signals.

get V1 = 1.21dBmW and V2 = 1.50dBmW. Segmented processing and singular value decomposition are performed on the overlap signal. As shown in Fig.8, after the singular value decomposition of the overlap signal, the time delay of the overlap signal can be accurately determined. The two cancellation signals are shown in Fig.9. According to the criteria in Table 1 and Table 2, the bit information of the original information and the waveform of the original signal are obtained. After decoding the determined 88 bit of data block, the recover original signal waveform is shown in Fig. 10. In order to verify the influence of different signal power difference on the algorithm, two independent ADS-B signals are selected, in which the time delay is 30 us, the power difference between high-power and low-power signal is 3dB, and the SNR range is 5dB-25dB. 1000 Monte Carlo experiments are carried out, and the bit error rate is taken as the evaluation criterion. The simulation results are shown in Fig.11. As can be seen from Fig. 10, when the power difference between the two source signals is 3dB and the SNR is 5dB, the bit error rate reaches 10.1%,i.e.1.01×10^{-1}. With the improvement of SNR, the bit error rate of the algorithm proposed in this chapter decreases gradually. When the SNR ratio is 25dB, the bit error rate decreases to 1.3%. The bit error rate obtained by this algorithm is 5.2% and 3.4% lower than that of the traditional PA algorithm and the FastICA algorithm at 5dB,

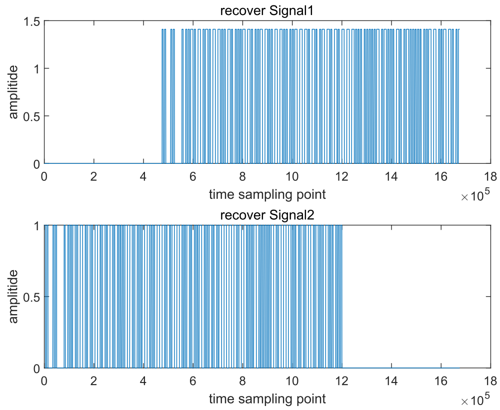

FIGURE 10. Recover signals.

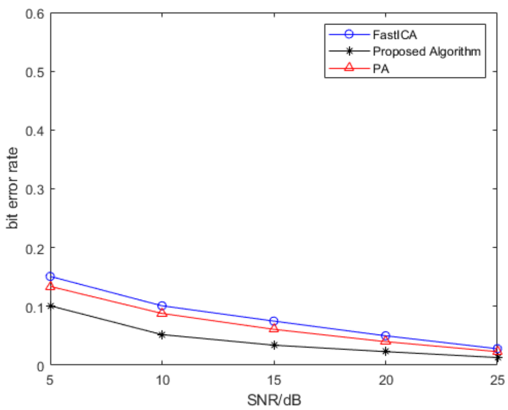

FIGURE 11. Curve of bit error rate with SNR for different algorithms.

respectively, which shows the effectiveness and excellence of the proposed algorithm.

B. EXPERIMENT ON THE EFFECT OF TIME DELAY ON SEPARATION

In order to further verify the performance of the algorithm, the original ADS-B signals with time delay of 4.5us, 30us and 47.5us from two sources are selected in this group of experiments. The relative delay is randomly selected. The sampling rate is 10MHz, the power difference between the two signals is 3dB, the SNR range is 5dB-25dB. 1000 Monte Carlo experiments are carried out. The curves of the BER of the three groups of signals varying with the SNR are shown in Fig.12. As can be seen from Fig.12, with the improvement of SNR, the bit error rates of the three groups of signals are improved. When the time delay of two source ADS-B signals is 4.5us and the SNR is 25dB, the bit error rate is 7.9%. When the time delay of two source ADS-B signals is 47.5$us$and the SNR is 25dB, the bit error rate is reduced to 1.3%. When the time delay of two source ADS-B signals is 20us and 47.5us, the bit error rate is lower than that of 4.5us. The reason is that ADS-B signal has 8us preamble and other parts do not have this coding mode. Therefore, when the leading pulse of the next signal overlaps with the data block of the previous signal in the overlap signal, according to the criterion proposed

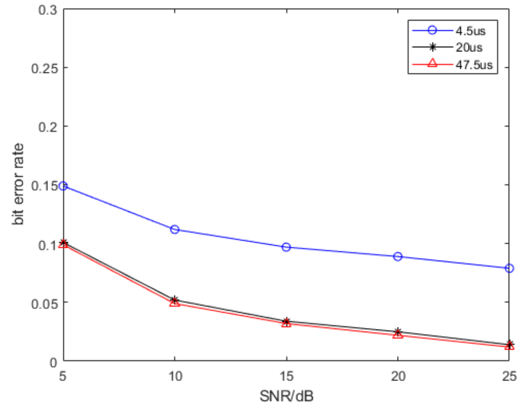

FIGURE 12. Curve of bit error rate with SNR under different delay.

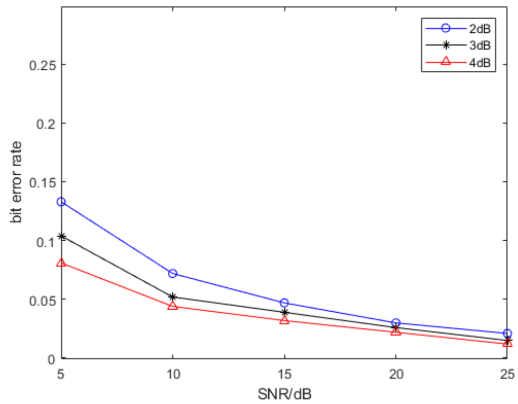

FIGURE 13. Curve of bit error rate with SNR under different power difference.

in this paper there will be an error. When the time delay of the source ADS-B signal is 47.5us, the bit error rate is slightly lower than 20us. The reason is that with the increase of the time delay, the overlap part of the overlap signal will decrease correspondingly, and the part containing only one source signal will increase, which will be more helpful for signal bit determination.

C. EXPERIMENT ON THE INFLUENCE OF SIGNAL POWER DIFFERENCE ON SEPARATION EFFECT

In order to verify the influence of different delay on the algorithm, three groups of original ADS-B signals with power difference of 2dB, 3dB and 4dB between two source signals are selected in this group of experiments. The sampling rate is 10MHz, the relative delay of the two signals is 16us, the SNR is 5dB-25dB. 1000 Monte Carlo experiments are carried out. The curve of bit error rate of three groups of signals with SNR is shown in Figure 13. It can be seen from Fig.13 that the bit error rate of the three groups of signal separation results under different power differences all decrease with the increase of SNR. This is because, with the increase of SNR, the influence of noise on the bit decision of overlap signals becomes smaller. When SNR is low, with the increase of power difference, the bit error rate of the separation result becomes smaller. When the power difference is 4dB, the bit error rate is the lowest and the separation effect is the best. With the increase of SNR, the difference of bit error rate between different power differences decreases gradually, and the separation effect is almost the same when SNR = 25dB. The simulation results show that with the increase of power difference between source signals, the separation effect will gradually improve.

V. CONCLUSION

In this paper, we analyze the time-domain characteristics of two overlap signals and propose an ADS-B separation algorithm based on time-domain cancellation. In the case that the source signal has a certain power difference, this paper starts with the time domain amplitude characteristics of the overlap signal and analyzes four forms of bit overlap. The overlap signal amplitudes are used to cancel the high-power amplitudes and the low-power amplitudes respectively. This paper analyzes the bit overlap of the cancellation signal and gives the corresponding bit decision criteria, to realize the separation of the overlap signal. Simulation results show that the proposed algorithm is feasible and has a lower bit error rate than other traditional methods. The experimental results show that the separation effect is less affected by the time delay of the two source signals. With the improvement of SNR, the separation effect of the proposed algorithm is gradually improved. At the same time, the greater the power difference between the source signals, the better the separation effect.

REFERENCES

[1] E. Agustini, Y. Kareng, and O. A. Victoria, "The role of ICAO (international civil aviation organization) in implementing international flight safety standards," *KnE Social Sci.*, pp. 100–114, Jan. 2021.

[2] M. Strohmeier, M. Schafer, V. Lenders, and I. Martinovic, "Realities and challenges of nextgen air traffic management: The case of ADS-B," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 111–118, May 2014.

[3] M. S. Farooq, M. Salam, A. Fayolle, N. Jaafar, and K. Ayupp, "Impact of service quality on customer satisfaction in malaysia airlines: A PLS-SEM approach," *J. Air Transp. Manage.*, vol. 67, pp. 169–180, Mar. 2018.

[4] V. K. Gonçalves, "Climate change and international civil aviation negotiations," *Contexto Int.*, vol. 39, no. 2, pp. 443–458, May 2017.

[5] J. Baek, E. Hableel, Y.-J. Byon, D. S. Wong, K. Jang, and H. Yeo, "How to protect ADS-B: Confidentiality framework and efficient realization based on staged identity-based encryption," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 3, pp. 690–700, Mar. 2017.

[6] M. Leonardi, E. Piracci, and G. Galati, "ADS-B jamming mitigation: A solution based on a multichannel receiver," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 32, no. 11, pp. 44–51, Nov. 2017.

[7] L. Xi, Z. Jun, Z. Yanbo, and L. Wei, "Surveillance accuracy analysis of ADS-B supporting the separation service in western China," in *Proc. Integr. Commun., Navigat. Surveill. Conf.*, May 2009, pp. 1–6.

[8] R. Chen, C. Si, H. Yang, and X. Zhang, "ADS-B data authentication based on AH protocol," in *Proc. IEEE 11th Int. Conf. Dependable, Autonomic Secure Comput.*, Dec. 2013, pp. 21–24.

[9] N. Petrochilos and A.-J. van der Veen, "Algebraic algorithms to separate overlapping secondary surveillance radar replies," *IEEE Trans. Signal Process.*, vol. 55, no. 7, pp. 3746–3759, Jul. 2007.

[10] K. Werner, J. Bredemeyer, and T. Delovski, "ADS-B over satellite: Global air traffic surveillance from space," in *Proc. Tyrrhenian Int. Workshop Digit. Commun.-Enhanced Surveill. Aircr. Vehicles (TIWDC/ESAV)*, Feb. 2014, pp. 47–52.

[11] Z. Wu, T. Shang, and A. Guo, "Security issues in automatic dependent Surveillance–Broadcast (ADS-B): A survey," *IEEE Access*, vol. 8, pp. 122147–122167, 2020.

[12] F. Minucci, E. Vinogradov, and S. Pollin, "Avoiding collisions at any (Low) cost: ADS-B like position broadcast for UAVs," *IEEE Access*, vol. 8, pp. 121843–121857, 2020.

[13] H. Blomenhofer, P. Rosenthal, A. Pawlitzki, and L. Escudero, "Space-based automatic dependent surveillance broadcast (ADS-B) payload for in-orbit demonstration," in *Proc. 6th Adv. Satell. Multimedia Syst. Conf. (ASMS)*, Sep. 2012, pp. 160–165.

[14] Y. Li, W. Nie, F. Ye, and Y. Lin, "A mixing matrix estimation algorithm for underdetermined blind source separation," *Circuits, Syst., Signal Process.*, vol. 35, no. 9, pp. 3367–3379, Sep. 2016.

[15] C. Shi, Z. Dou, Y. Lin, and W. Li, "Dynamic threshold-setting for RF-powered cognitive radio networks in non-Gaussian noise," *Phys. Commun.*, vol. 27, pp. 99–105, Apr. 2018.

[16] *Minimum Operational Performance Standards for 1090 MHz Extended Squitter: Automatic Dependent Surveillance-Broadcast (ADSB) and Traffic Information Services-Broadcast (TIS-B)*, document R. SC-186, RTCA, 2006.

[17] *Reception of Automatic Dependent Surveillance Broadcast Via Satellite and Compatibility Studies With Incumbent Systems in the Frequency Band 1 087.7-1 092.3 MHz*, document I. WP5B, 2003.

[18] Y. Sunquan, C. Lihu, L. Songting, and L. Lanmin, "Separation of space-based ADS-B signals with single channel for small satellite," in *Proc. IEEE 3rd Int. Conf. Signal Image Process. (ICSIP)*, Jul. 2018, pp. 315–321.

[19] L. Dan and C. Tao, "Single-antenna overlapped ADS-B signal self-detection and separation algorithm based on EMD," *J. Signal Process.*, vol. 35, no. 10, pp. 1680–1689, 2019.

[20] W. Chenchen and W. Wenyi, "A method of overlap ADS-B signal processing based on accumulation and classification," *J. Signal Process.*, vol. 33, no. 4, pp. 572–576, 2017.

[21] W. Jie, G. Jianhua, J. Kai, and G. Yong, "Time domain separation algorithm for ADS-B double interleaved signals," *J. Commun. Technol.*, vol. 50, no. 10, pp. 2184–2189, 2017.

[22] A.-J. van der Veen and A. Paulraj, "An analytical constant modulus algorithm," *IEEE Trans. Signal Process.*, vol. 44, no. 5, pp. 1136–1155, May 1996.

[23] N. Petrochilos and A.-J. van der Veen, "Algorithms to separate overlapping secondary surveillance radar replies," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, vol. 2, May 2004, pp. 41–49.

[24] N. Petrochilos, G. Galati, L. Mene, and E. Piracci, "Separation of multiple secondary surveillance radar sources in a real environment by a novel projection algorithm," in *Proc. 5th IEEE Int. Symp. Signal Process. Inf. Technol.*, Apr. 2006, pp. 125–130.

[25] N. Petrochilos, E. Piracci, and G. Galati, "Separation of multiple secondary surveillance radar sources in a real environment for the near-far case," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Oct. 2007, pp. 3988–3991.

[26] N. Petrochilos, G. Galati, and E. Piracci, "Projection techniques for separation of multiple secondary surveillance radar sources in a real environment," in *Proc. 4th IEEE Workshop Sensor Array Multichannel Process.*, Apr. 2006, pp. 344–348.

[27] W. Wang, R. Wu, and J. Liang, "ADS-B signal separation based on blind adaptive beamforming," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 6547–6556, Jul. 2019.

[28] Y. Zhang, W. Li, and Z. Dou, "Performance analysis of overlapping space-based ADS-B signal separation based on fastICA," in *Proc. IEEE Globecom Workshops*, Feb. 2019, pp. 1–6.

[29] Z. Haoran, W. Sen, W. Shihao, and P. Lei, "A method using blind source separation to improve the decoding efficiency of space-based ADS-B receiver," *Int. J. Performability Eng.*, vol. 16, no. 6, p. 950, 2020.

[30] Z. Caisheng, Z. Tao, and Z. Hai, "Overlapping ADS-B signals separation algorithm based on MUSIC," in *Proc. 6th Int. Conf. Inf. Sci. Control Eng. (ICISCE)*, Dec. 2019, pp. 1094–1098.

[31] C. Li, Y. Zhang, and B. Tang, "An improved method for separation of garbled secondary surveillance radar replies," in *Proc. 7th IEEE Int. Conf. Electron. Inf. Emergency Commun. (ICEIEC)*, Jul. 2017, pp. 119–123.

[32] Y. Zhao, H. Jiang, Q. Chen, Y. Qin, H. Xie, Y. Wu, S. Liu, Z. Zhou, J. Xia, and F. Zhou, "Preserving minority structures in graph sampling," *IEEE Trans. Vis. Comput. Graphics*, vol. 27, no. 2, pp. 1698–1708, Feb. 2021.

[33] Y. Lin, Y. Tu, and Z. Dou, "An improved neural network pruning technology for automatic modulation classification in edge devices," *IEEE Trans. Veh. Technol.*, vol. 69, no. 5, pp. 5703–5706, May 2020.

[34] G. Gui, M. Liu, F. Tang, N. Kato, and F. Adachi, "6G: Opening new horizons for integration of comfort, security and intelligence," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 126–132, Oct. 2020.
[35] Z. Zhang, J. Chang, M. Chai, and N. Tang, "Specific emitter identification based on power amplifier," *Int. J. Performability Eng.*, vol. 15, pp. 1005–1013, Mar. 2019.
[36] Y. Lin, Y. Tu, Z. Dou, L. Chen, and S. Mao, "Contour stella image and deep learning for signal recognition in the physical layer," *IEEE Trans. Cognit. Commun. Netw.*, vol. 7, no. 1, pp. 34–46, Mar. 2021.
[37] J. Yu, A. Hu, G. Li, and L. Peng, "A robust RF fingerprinting approach using multi-sampling convolutional neural network," *IEEE Internet Things J.*, vol. 70, no. 1, pp. 389–401, Mar. 2021.
[38] Y. Lin, X. Zhu, Z. Zheng, Z. Dou, and R. Zhou, "The individual identification method of wireless device based on dimensionality reduction and machine learning," *J. Supercomput.*, vol. 75, no. 6, pp. 3010–3027, Jun. 2019.
[39] Y. Lin, H. Zhao, X. Ma, Y. Tu, and M. Wang, "Adversarial attacks in modulation recognition with convolutional neural networks," *IEEE Trans. Rel.*, vol. 70, no. 1, pp. 389–401, Mar. 2021.
[40] Y. Tu, Y. Lin, C. Hou, and S. Mao, "Complex-valued networks for automatic modulation classification," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10085–10089, Sep. 2020.
[41] S. Chen, S. Zheng, L. Yang, and X. Yang, "Deep learning for large-scale real-world ACARS and ADS-B radio signal classification," *IEEE Access*, vol. 7, pp. 89256–89264, 2019.
[42] K. Liu, T. Zhang, and Y. Ding, "Blind signal separation algorithm for space-based ADS-B," in *Proc. Int. Conf. Mechatronics Eng. Inf. Technol.*, 2016, pp. 214–220.
[43] S. Bernhart and E. Leitgeb, "Evaluations of low-cost decoding methods for 1090 MHz SSR signals," in *Proc. Int. Conf. Broadband Commun. for Next Gener. Netw. Multimedia Appl. (CoBCom)*, Jul. 2018, pp. 1–5.
[44] H. Andrews and C. Patterson, "Singular value decomposition (SVD) image coding," *IEEE Trans. Commun.*, vol. COM-24, no. 4, pp. 425–432, Apr. 1976.

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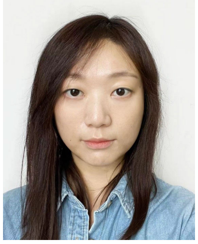

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