EFFECTIVE SOURCE NUMBER ENUMARATION APPROACH UNDER SMALL SNAPSHOT NUMBERS

By

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Direction of Arrival (DOA) estimation of signal sources is one of the research hotspots in the field of array signal processing. However, traditional DOA estimation methods usually require many snapshots, a high Signal-to-Noise Ratio (SNR), and a Gaussian white noise background, which are often difficult to meet in actual environments. To solve this problem, this study proposes a signal source number estimation method based on supplementary empirical mode decomposition (SEMD). The method first uses the SEMD method to decompose the array signal, decomposing the complex signal into several Intrinsic Mode Functions (IMFs), and then extracts features through these IMFs to estimate the number of signal sources. To verify the performance of the proposed SEMD method, this study designs a series of experiments, using theoretical data and measured data from a radio frequency anechoic chamber laboratory as research objects. The experimental conditions cover different snapshot numbers, SNRs, and noise backgrounds, aiming to simulate various complex environments in actual applications. Experimental results show that the SEMD-based method performs significantly better than the traditional signal source number estimation algorithm in these complex environments, especially under a small number of snapshots, the SEMD method can still maintain a high estimation accuracy. This study also makes a significant contribution to data science by providing a comprehensive method for estimating the number of signal sources, which is integrated with a machine learning model. This method overcomes the limitations of traditional methods in complex environments by combining signal processing problems with pattern recognition problems, significantly improves the accuracy of data analysis in complex environments, and provides an innovative solution for signal processing and pattern recognition in data science.

Keywords: DOA Estimation, Signal Source Number Estimation, SEMD

SDG: GOAL 9: Industry, Innovation and Infrastructure

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENDEKATAN NUMERASI NOMBOR SUMBER YANG BERKESAN DI BAWAH NOMBOR GAMBAR KECIL

Oleh

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Anggaran Arah Ketibaan (DOA) sumber isyarat merupakan salah satu titik panas penyelidikan dalam bidang pemprosesan isyarat tatasusunan. Walau bagaimanapun, kaedah anggaran DOA tradisional biasanya memerlukan banyak syot kilat, Nisbah Isyarat-ke-Bunyi (SNR) yang tinggi dan latar belakang hingar putih Gaussian, yang selalunya sukar ditemui dalam persekitaran sebenar. Untuk menyelesaikan masalah ini, kajian ini mencadangkan kaedah anggaran nombor sumber isyarat berdasarkan penguraian mod empirikal tambahan (SEMD). Kaedah ini mula-mula menggunakan kaedah SEMD untuk menguraikan isyarat tatasusunan, menguraikan isyarat kompleks kepada beberapa Fungsi Mod Intrinsik (IMF), dan kemudian mengekstrak ciri melalui IMF ini untuk menganggarkan bilangan sumber isyarat. Untuk mengesahkan prestasi kaedah SEMD yang dicadangkan, tesis ini mereka bentuk satu siri eksperimen, menggunakan data teori dan data diukur dari makmal ruang anechoic frekuensi radio sebagai objek kajian. Keadaan percubaan meliputi nombor syot kilat yang berbeza, SNR dan latar belakang hingar, bertujuan untuk mensimulasikan pelbagai persekitaran kompleks dalam aplikasi sebenar. Keputusan eksperimen menunjukkan bahawa

kaedah berasaskan SEMD menunjukkan prestasi yang lebih baik daripada algoritma anggaran nombor sumber isyarat tradisional dalam persekitaran yang kompleks ini, terutamanya di bawah sebilangan kecil syot kilat, kaedah SEMD masih boleh mengekalkan ketepatan anggaran yang tinggi. Penyelidikan ini juga memberi sumbangan penting kepada sains data dengan menyediakan kaedah komprehensif untuk menganggar bilangan sumber isyarat, yang disepadukan dengan model pembelajaran mesin. Kaedah ini mengatasi batasan kaedah tradisional dalam persekitaran yang kompleks dengan menggabungkan masalah pemprosesan isyarat dengan masalah pengecaman corak, meningkatkan ketepatan analisis data dengan ketara dalam persekitaran yang kompleks, dan menyediakan penyelesaian inovatif untuk pemprosesan isyarat dan pengecaman corak dalam sains data.

Kata Kunci: Anggaran DOA, Anggaran Nombor Sumber Isyarat, SEMD

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treasure their love and encouragement. I am committed to persevering diligently, continuously striving to improve myself, and contributing meaningfully to society.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AEMD	Augmented Empirical Mode Decomposition
AIC	Akaike Information Ceriterion
BP	Back Propagation
BIC	Bayesian Information Criterion
CBF	Conventional Beam Forming
CSM	Coherent Signal-Subspace Method
D-AIC	Diagonal Akaike Information Ceriterion
D-MDL	Diagonal Minimum Description Length
DOA	Direction of Arrial
DSLC	Data Science Life Cycle
EMD	Empirical Mode Decomposition
ESPRIT	Estimating Signal Parameter via Rotation Invariance Techniques
EQDL	Eigenvalue Quadratic Diagonal Loading
FDC	Frequency Divergence Combination
GDE	Gerschgorin Disk Estimation
GBIC	Generalized Bayesian Information Criterion
HHT	Hilbert-Huang Transform
HT	Hilbert Transform
ICA	Independent Component Analysis
IMFs	Intrinsic Mode Functions
IPCM	Instantaneous Phase Covariance Matrix
ISM	Incoherent Signal-Subspace Method

ITC	Information Theory Criterion
KL	Kullback-Leibler
MDL	Minimum Description Length
MEEMD	Mirror Extension Empirical Mode Decomposition
MEM	Maximum Entropy Method
MFFNet	Multi-path Features Fusion Network
ML	Maximum Likelihood
MSE	Mean Square Error
M-UCA	M-Antenna Uniform Circular Array
MUSIC	Multiple Signal Classification
MVM	Minimum Variance Method
NMF	Non-negative Matrix Factorization
PCA	Principal Component Analysis
PDF	Probability Density Function
RF	Radio Frequency
RMT	Random Matrix Theory
SEMD	Supplementary Empirical Mode Decomposition
SVM	Support Vector Machine
SML	Stochastic Maximum Likelihood
SNR	Signal-to-Noise Ratio
SORTE	Second-order Statistic of Eigenvalues
SSF	Signal Subspace Fitting
TopSVD	Top Singular Value Decomposition
UCA	Uniform Circular Array
ULA	Uniform Linear Array

WSF	Weighted Subspace Fitting

CHAPTER 1

INTRODUCTION

1.1 Research Background

In this chapter, Section 1.1 provides an overview of the research context and establishes the background information necessary to understand the dissertation. Section 1.2 clearly defines the specific problem or research gap that the dissertation aims to address. Section 1.3 outlines the overall goal of the research and presents the specific objectives that the dissertation aims to achieve. Section 1.4 formulates the research questions that guide the investigation and help focus the study. Section 1.5 highlights the original contributions or novel aspects of the research. Section 1.6 emphasizes the broader significance and implications of the research. Section 1.7 provides a reasonable organization and structure for the thesis.

In today's modern warfare, electronic countermeasures have become a key tactical means directly used in offense and defense (Lyu & Zhan, 2022). With the emergence of new aircraft, ships, satellites, and devices specially used for electronic countermeasures, such as anti-radiation missiles (Gupta, Jain, Kothari, & Chakravarthy, 2024), modern warfare has transformed into a multi-dimensional complex form of land, sea, air, space, and electricity (Chuchu, Guo, Chao, Zhengxiang, & Xiangming, 2022). The advent of these new devices expands the battlespace into the electromagnetic realm, allowing military operations to involve the jamming, detection, and protection of electronic signals.

In these new devices, the use of array antennas becomes crucial for receiving, processing and localizing electromagnetic signals in space (Friedlander, 2019). Array antennas can provide wider coverage and higher accuracy, enabling combat units on the battlefield to accurately obtain target information and conduct precise strikes (Reddy, Karthik, Vinyojitha, & Charulatha, 2023). At the same time, the array antenna also has anti-interference and anti-jamming capabilities, and can deal with electronic interference and strikes from the opponent (Yang, Wang, Liu, & Chen, 2022).

Array signal processing is a technique that uses sensor arrays to collect signals and then analyze and process them (Wang, Gao, Jin, & Lin, 2019). This technique makes a difference in time or space when receiving a signal. By analyzing and processing these differences, relevant features of the signal, such as direction (Foutz, Spanias, & Banavar, 2022), frequency (Tan, Wang, & Li, 2020), waveform (Shi, Wang, Salous, Zhou, & Yan, 2021), etc., can be extracted. Therefore, it is widely used in wireless communication (Gao, Tian, Larsson, Pesavento, & Jin, 2019), radar (Xu et al., 2021), acoustics (Liu, Chen, & Wang, 2021), biomedical engineering (Zhengwu Liu et al., 2020), and seismic exploration (Aliyu et al., 2021). The main research directions of array signal processing include beamforming (Feng, Cui, Yu, Zhang, & Kong, 2020), spatial spectrum estimation (Zhang, 2022), signal source separation (Wuth, Mahu, Cohen, Stern, & Yoma, 2024), signal source number estimation (Tian, Zhang, Liu, Chen, & Wang, 2024), array design (Zheng, Wang, Kong, & Zhang, 2019), and array calibration (RaviChandran, Aw, & McDaid, 2023).

One of the areas of research in the field of signal processing that receives a lot of interest is DOA estimation, aims to achieve accurate estimation of specific parameters such as angle, distance, and azimuth of the source signal in space (Wei Wang et al., 2022). The high resolution of this technology enables accurate estimation of key parameters such as the range and azimuth of the source signal (Osman, Moussa, Tamazin, Korenberg, & Noureldin, 2020). In electronic countermeasures, high-precision DOA estimation technology can achieve precise positioning of targets, providing a key basis for effective interception and precise strikes (Wan, Sun, Sun, Ning, & Rodrigues, 2020). High-precision DOA estimation technology can also play a crucial part in unmanned systems, navigation systems, and wireless communication systems (Zhimin Chen, Chen, Guo, Zhang, & Wang, 2023). By accurately estimating the direction and distance of the signal source, the unmanned system can achieve precise positioning and navigation, enhancing the effectiveness and precision of its task execution (Eling, Klingbeil, Wieland, & Kuhlmann, 2013). In wireless communication systems, DOA estimation technology can help to locate the signal source accurately and improve the quality of signal reception and anti-interference ability (Xie, Li, Wu, & Wang, 2021). To achieve high-precision DOA estimation, researchers continue to explore new algorithms and methods. These include techniques such as array signal processing, subspace decomposition, and time-frequency analysis (Kou, 2022). At the same time, many new array antenna designs have emerged, such as a uniform linear array (ULA) (Shi & Li, 2022), uniform circular array (UCA) (Shi & Li, 2022), and adaptive array (Ai & Gan, 2021), to improve the performance and accuracy of DOA estimation.

1.2 Problem Statement

Among these spatial spectrum estimation algorithms, the subspace decomposition algorithm has become the most mainstream high-resolution spatial spectrum estimation algorithm due to its high precision and good robustness. Among them, there are two most representative algorithms: one is the noise subspace algorithm represented by Multiple Signal Classification (MUSIC) (Elbir, 2020), and the second is the signal subspace algorithm, which is represented by Estimating Signal Parameter via Rotation Invariance Techniques (ESPRIT) (Ning, Ma, Meng, & Wu, 2020). However, the prerequisite for the use of the subspace decomposition algorithm is that the number of signal sources has been determined. Although the current subspace decomposition algorithms that do not need the number of sources are also researched by many scholars. However, this type of algorithm either has a large amount of calculation, or requires a high SNR, or is prone to false peaks. Therefore, the prerequisite for good performance of the subspace decomposition algorithm is still that the number of signal sources is known or correctly estimated. The array antenna’s signals must be used to accurately estimate the number of signal sources in various real circumstances where the number of signal sources must frequently be approximated.

If there are errors in the estimation of the number of signal sources, the performance of the spatial spectrum estimation algorithm will be significantly affected, leading to rapid deterioration or even failure (Zhou, Gao, & Wang, 2012). This is primarily due to the inability to accurately obtain the corresponding noise subspace. Specifically, if the estimated value is smaller than the actual value, certain signal eigenvectors are erroneously classified as part of the noise subspace. Consequently, the dimension of the signal subspace decreases, resulting in the disappearance of certain spectral peaks in the signal space spectrum. Furthermore, the orthogonality between the signal subspace and the noise subspace is compromised, leading to missing alarms and significant deviations in the spatial spectrum estimation when employing the subspace decomposition algorithm. Conversely, if the estimated value exceeds the actual value, the noise component is erroneously included within the signal subspace. Although this causes the subspace decomposition algorithm to generate false alarms, it does not impact the orthogonality between the signal subspace and the noise subspace. Consequently, this effect can be disregarded when the SNR is high.

Therefore, To achieve accurate DOA estimation, it is crucial to accurately estimate the number of signal sources. Empirical mode decomposition (EMD) can decompose non-stationary and nonlinear signals into a series of IMFs. In signal source number estimation, EMD can be used to extract signal features and analyze them. It is more suitable for signal source number estimation problems involving nonlinear interactions. However, EMD has the disadvantage of end effect, that is, there may be overlap between different intrinsic mode functions, making it difficult to clearly separate different frequency components. Therefore, suppressing end effect can effectively improve the performance of the EMD method in source number estimation. Mirror Extension Empirical Mode Decomposition (MEEMD) (Jian Wang, Liu, & Zhang, 2019) and Augmented Empirical Mode Decomposition (AEMD) (Oh, Zhuang, Toh, & Lin, 2019) eliminate the end effect, thus improving the accuracy of signal decomposition.

However, in real-world environments, the estimation algorithm for the number of signal sources is influenced by various factors. These factors include the number of snapshots, the number of signal sources, the number of array elements, and the colored noise background. When these factors become more challenging, the performance of most algorithms tends to degrade or even fail. Hence, the research direction is to develop a high-performance source number estimation algorithm capable of functioning effectively in extreme environments. Existing work has limitations, and many source number estimation algorithms have poor estimation performance:

i. When the signal is decomposed by EMD, there are errors in the signal components, which affects the accuracy of the estimation (Jian Wang et al., 2019; Oh et al., 2019; Pan, Mei, Tian, Ling, & Wang, 2018).
ii. When the noise background is colored noise, it is more difficult to implement the algorithm (Yuan, Zhang, Liu, & Wang, 2020; Zhang, Zhang, & Leung, 2020; Pan, Zhang, Hu, & Zheng, 2019).
iii. When the number of signal sources is close to the number of array elements, the low SNR will decrease the accuracy of the source number estimation algorithm (Yameng, Yue, & Lin, 2021; Pan, Mei, Tian, Ling, & Wang, 2018;).
iv. When the number of signal sources is close to the number of array elements, the small number of snapshots will decrease the accuracy of the source number estimation algorithm (Garg, Santamaria, Ramirez, & Scharf, 2019; Yang, Gao, Qian, & Liao, 2019).

In summary, signal source number estimation is the primary task of most DOA estimation algorithms. However, existing signal source number estimation algorithms have requirements for SNR, number of snapshots, noise background, and number of array elements. Therefore, the purpose of this study is to propose a new high-performance signal source number estimation method that can achieve source number estimation with a low SNR, a small number of snapshots, a colored noise background, and when the number of signal sources is close to the number of array elements.

1.3 Research Questions

This study attempts to use experimental simulations to answer the following questions:

i. How does EMD affect the true decomposition of a signal?

ii. How do different signal noise backgrounds affect the source number estimation algorithm?

iii. How do different SNRs affect the estimation of the number of signal sources?

iv. How do different snapshot numbers affect the estimation of signal source numbers?

1.4 Research Goal and Objectives

The main goal of this research is to transform the problem of signal source number estimation into pattern recognition based on mathematical modeling, and use neural network to realize the signal source number estimation. The specific goals are as follows:

i. To propose a method to suppress the end effect in EMD and achieve more realistic signal decomposition.

ii. To develop a neural network model for source number estimation, convert complex signal source number estimation into pattern recognition, thereby achieving signal source number estimation more effectively.

iii. To create a high-dimensional data set suitable for source number estimation under low SNR.

iv. To propose an efficient source number estimation algorithm that can estimate signals with a small number of snapshots.

1.5 Research Contributions

The main contribution of this research is to propose a source number enumeration method based on SEMD, so as to realize the estimation of signal source number and provide accurate prior conditions for subsequent DOA estimation algorithms. Several contributions are as follows:

i. The SEMD method is proposed, which solves the problem of end effect in the EMD method.

ii. A high-dimensional dataset is created, suitable for source number estimation under low SNR.

iii. A source enumeration method is proposed to simplify the complex signal processing problem into a pattern recognition problem, thereby realizing the source number estimation when the number of signal sources is close to the number of array elements.

iv. A neural network model suitable for one-dimensional signal data classification was designed, which improved the accuracy of the source number estimation algorithm in the background of colored noise.

1.6 Significance of Research

Most methods used to estimate the angle of arrival for directional signals encounter a significant challenge in accurately determining the number of signal sources. To solve this problem, this research work introduces a high-precision algorithm that can precisely estimate the number of signal sources. This algorithm delivers accurate estimations even in demanding scenarios characterized by low SNR, limited sampling snapshots, and the presence of colored noise. Consequently, it surpasses the limitations faced by traditional algorithms for estimating the number of sources when handling extreme conditions (small snapshot number, low SNR, colored noise background, small number of array elements).

Moreover, this research enhances the EMD method by mitigating the end effect that arise during the mathematical modeling of signal data. This advancement enables us to achieve precise decomposition of non-stationary signals, thereby providing accurate and reliable data for subsequent engineering applications. By improving the EMD method, we enhance its capability to process signal data, subsequently elevating the accuracy and dependability of signal analysis. Consequently, this research provides crucial technical support for signal processing research and applications, offering more reliable solutions for real-world tasks such as signal source localization, communication systems, and radar systems.

Additionally, this research has the potential to expand its application areas further. By combining the proposed algorithm with machine learning techniques, we can estimate the number of signal sources even more precisely in complicated situations.

In conclusion, this research work makes significant strides in addressing the challenges associated with angle-of-arrival estimation for directional signals. By proposing a high-precision signal source number estimation algorithm and an enhanced empirical mode decomposition method, Even under complex and challenging conditions, it can provide accurate and reliable signal analysis results. These accomplishments not only offer technical support for signal processing research but also provide more reliable solutions for practical applications, such as signal source localization, communication systems, and radar systems.

1.7 Thesis Organization

This thesis is divided into six chapters as follows:

i. Introduction: This chapter serves as the foundation for the entire dissertation, introducing key elements such as the research background, problem statement, research aims and objectives, research questions, research contributions, and research significance. Together, these components lay the groundwork for subsequent chapters.

ii. Literature Review: This chapter provides an in-depth analysis of the pertinent literature, including the array signal mathematical model, DOA estimation algorithm, source number estimation algorithm. The literature review critically analyzes existing research, theories, and findings directly relevant to the thesis's topic.

iii. Methodology: This chapter explains the methodology of information source enumeration. This methodology covers the entire process of source number enumeration method research.

iv. Source Number Enumeration Approach: This chapter introduces the source number enumeration method in detail. SEMD is a new signal decomposition method proposed in this thesis. It has been determined that the instantaneous phase can be used for feature extraction. Then the other steps of the source enumeration method are introduced, including obtaining the instantaneous phase, feature extraction, obtaining high-dimensional data sets, and the neural network model for source enumeration.

v. Results and Discussion: In this chapter, both the traditional algorithm and the proposed algorithm are simulated and evaluated. Through analysis, the practicality and superiority of the algorithm proposed in this thesis are demonstrated.

vi. Conclusions and Recommendations for Future Work: This chapter summarizes the source number enumeration method. It points out existing issues related to this method and provides recommendations for potential research directions in the future.

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