Demodulation and Recognition of Image Transmission Signals for Small UAV Under Non-Cooperative Conditions

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Abstract. According to the characteristics of CP-OFDM signals, analyzed and studied the subcarrier number estimation, timing synchronization and frequency offset compensation algorithms of CP-OFDM signals under non-cooperative reception conditions, and verified the feasibility of these algorithms based on UAV image transmission signals. As the results show, the algorithm proposed in the article can complete blind demodulation of the CP-OFDM signal and finally complete the sensing and recognition of small UAV signals under the condition of unknown CP-OFDM signal format by means of analysis and estimation algorithms.

Keywords: Non-cooperative; subcarrier number estimation; timing synchronization; frequency offset compensation.

1. Introduction

With the gradual opening of low-altitude airspace control and the widespread use of UAV products, the use of UAV to disrupt normal aviation order, carry out espionage investigation activities and plan terrorist attacks is increasing day by day, which brings increasing risks and threats to national public security. In order to ensure the early warning of military and civilian UAVs and wireless signal emitters around such important facilities as military areas, test sites, command posts and secret areas, it's necessary to carry out real-time monitoring, direction finding, positioning[1-2], early warning, interference and detection of UAVs and radiators within 2 km, and protect normal military training tasks against impacts from civil aerial photography, spy detection and radiation interference, etc., thus it is necessary to study UAV countermeasure technology. The most important and urgent problem of the passive detection technology is to realize UAV signal detection and parameter estimation. The UAV TTC channel includes the uplink and downlink signals, in which the upstream link signal is mainly used for transmitting flight control instruction while the downlink signal is mainly used for transmitting UAV status parameter and video image. All consumer-grade UAVs in the market, for example, Dajiang UAV has chosen 2.4GHz band OFDM (Orthogonal Frequency Division Multiplexing) as its mode of video image transmission. Therefore, from the perspective of military reconnaissance, information security and electronic countermeasures, it is of great significance to study the non-cooperative reception of OFDM signals. At the same time, the CP-OFDM (Cyclic Prefix-OFDM) signal, as the most common and important type of image transmission signals for small
UAVs, uses the form of inserting a cyclic prefix in the guard interval. Against this background, the current patent has developed research on non-cooperative reception of OFDM signals.

2. CP-OFDM Signal Analysis and Demodulation

2.1 Estimation of Subcarrier Number and Subcarrier Symbol Rate of CP-OFDM Signal

The estimation of the number of subcarriers is the primary problem in OFDM signal analysis and demodulation under non-cooperative reception as shown in Fig.1. In Fig.2, the number of subcarriers is the number of FFT points \( N_{FFT} \) in OFDM modulation and demodulation. With the cyclic prefix, the delay autocorrelation of OFDM frames has a peak at \( N_{FFT} \).

![Fig.1 Cyclic prefix inserted in OFDM symbols](image1)

Suppose that \( r_i, i \in [0, N) \) is a certain frame CP-OFDM signal, with \( N \), \( f_i \) and \( f_s \) as the frame length, subcarrier symbol rate and sampling rate respectively. Suppose that \( f_i = f_s \), then each OFDM symbol has \( N_{FFT} \) subcarrier symbols in all. Its delay autocorrelation can be expressed in the formula as follows:

\[
R_k = \sum_{i=0}^{N_{FFT}-1} r_i r^*_i, 0 \leq k \leq K
\]

(1)

Where, \( K \) is the maximum delay \( N_{FFT} \) as estimated, but, in the practical use, the \( N \) value needs to be sufficiently large, that is, only if multiple OFDM symbols participate in the delay autocorrelation operation can we obtain a more obvious peak value.
In practical applications, the symbol rate $f_s$ of subcarriers is unknown; suppose that the rough estimate of the bandwidth is $f_a$, not all subcarriers of OFDM signals send information, so $f_a < f_s$. Take $f_s = P f_a$ as the sampling rate of the signal to be estimated ($P$ is a positive integer greater than 1). If the peak position of delay autocorrelation is $k_p$, then the estimated value $\hat{f}_s$ of the symbol rate for subcarriers of the CP-OFDM signal and the estimated number of subcarriers can be given from the following formula:

$$\hat{N}_{\text{FFT}} = \frac{2\lceil \log_2 k_p \rceil}{P}$$

$$\hat{f}_s = \frac{P \hat{N}_{\text{FFT}}}{k_p}$$

### 2.2 Timing Synchronization of CP-OFDM Signal Symbols

The purpose of symbol timing is to find the initial position of CP-OFDM and thus extract data blocks for demodulation. The CP-OFDM signals copy the tail data of the data frame to the guard interval as a cyclic prefix, forming a unique cyclic structure, which can be used for timing synchronization.

Set $r_i$ as the signal after sampling rate alignment, apply SAC (Sliding Auto-correlation) to the signal and we can get:

$$R_{\text{SAC,i}} = \sum_{m=0}^{L-1} r_{i+m} f_{i+m}^*$$

When the correlation window slides to the CP initial position, the correlation results will have a peak because the two related data segments are identical. As should be noted, the correlation peak obtained by the above sliding auto-correlation algorithm is a triangular peak, which is greatly affected by noise, interference and other factors, and can not get an accurate timing position. But the CP-OFDM system is insensitive to timing position. If the timing deviates only a few sampling values in the time domain, it will cause a certain phase rotation in the frequency domain, that is, frequency offset, which can be compensated in the frequency domain.

### 2.3 Frequency Domain/Offset Compensation for CP-OFDM signals

The demodulated CP-OFDM signal will have the phase of the frequency domain rotate due to timing error, which is characterized in the star map by the phase rotation caused by frequency offset. Under the condition of cooperative reception, the receiver can compensate the frequency offset by means of the known pilot frequency information.

Assuming that $a_{i,k}$ is the symbol transmitted by the first $k$ subcarrier of the first $i$ OFDM symbol and the modulation symbols of all subcarriers of each OFDM symbol (generally arranged in the order from negative frequency to positive frequency) is connected as a frame after parallel/serial conversion, then the subcarrier symbol modulated by MPSK can be expressed as:

$$a_{i,k} = A_{i,k} \exp(j \theta_{i,k})$$

For MPSK modulation, $A_{i,k}$ is a constant, that is, $A_{i,k} = A$ and $\theta_{i,k} = 2\pi m / M, 0 \leq m \leq M - 1$. The received signal may be expressed as:

$$r_{i,k} = a_{i,k} \exp[j(2\pi f_s k T + \theta_{i,k})] + n_{i,k}$$

Where, $n_{i,k}$ indicates complex Gauss white noise, $\theta_{i,k}$ indicates the unknown initial phase and $f_s$ represents the frequency offset of the signal carrier.
In the document[3], Viterbi have studied the non-linearity method for removing modulation information, namely, Viterbi & Viterbi methods, also known as M-power non-linearity methods. The specific operations are as follows:

\[ z_{i,k} = |r_{i,k}|^\mu \exp\{jM\phi_{i,k}\} \]  

(6)

If there are \( N \) subcarriers in the OFDM signal transmitting modulated MPSK signals, then let:

\[ R_i(k) = \frac{1}{N-k} \sum_{\alpha=1}^{N-1} z_{i,\alpha}^* z_{i,\alpha-k}, 1 \leq k \leq N-1 \]  

(7)

If \( N_i=N-1 \), then the L&R algorithm for finding the frequency offset of the first \( i \) OFDM symbol can be described by the following formula:

\[ \text{Im} \left[ \sum_{k=1}^{N_i} R_i(k) \exp\{-j2\pi fTk\} \right] = 0 \]  

(8)

When the SNR is higher and the frequency offset is smaller, Taylor series can be used to approximate the formula and then obtain the L&R algorithm[4]:

\[ \Delta f = \frac{1}{\pi TM (N_i + 1)} \arg \left\{ \sum_{n=1}^{N_i} R_i(n) \right\} \]  

(9)

The L&R algorithm is approximated under the assumption of higher SNR, but it still has high estimation accuracy at a lower SNR. Moreover, the \( \arg\{\} \) operation requires the principal value interval to be \((-\pi, \pi]\), so the \( \arg\{\} \) operation would lead to phase folding and result in phase calculation errors when \( |2\Delta f T(N_i + 1)| > \pi \). Therefore, in order to avoid phase folding, it requires \( |\Delta f| < \frac{1}{TM (N_i + 1)} \). Thus it can be concluded that the estimation range of the L&R algorithm should be:

\[ |\Delta f| < \frac{1}{TM (N_i + 1)} \]  

(10)

The L&R algorithm[5] has higher estimation accuracy and good noise resistance, but its estimation range is smaller. When the frequency offset is larger, the L&R algorithm, if used directly, will cause algorithm failures and the ideal result can not be obtained[6].

The demodulated \( z_{i,k} \) is a complex single frequency signal, so there is a certain relationship between the maximum position point of its spectrum amplitude and its frequency. Therefore, the signal frequency spectrum can be used to get the frequency offset estimation of the signal and the FFT operation is a commonly used processing method. If the FFT operation is made against \( N \) points of \( z_{i,k} \), let:

\[ k_0 = [\Delta f NT] \]  

(11)

Where, \([x]\) represents the nearest integer to \( x \). Then the DFT amplitude spectrum at \( N \) points of this signal must be maximized at the \( k_0 \) frequency point, marked as \( \hat{f}_{\text{FFT}} \), namely,

\[ \hat{f}_{\text{FFT}} = \arg \max_{f_k} \left\{ \sum_{\alpha=1}^{N} z_{\alpha} \exp\{-j2\pi f_T k\} \right\} \]  

(12)

Let \( f = \Delta f - \hat{f}_{\text{FFT}} \) and \( |f| \leq 1/2N_T \) can be easily obtained, namely, the error will be within \( \pm 1/2N_T \) between the carrier frequency estimation obtained by performing the FFT operation at \( N \) point of \( z_{i,k} \) and the actual \( \Delta f \).
The carrier frequency offset estimation can be carried out in the full frequency band by FFT operation, so the range of coarse frequency offset estimation by FFT should be:

\[ |\Delta f| \leq \frac{1}{2MT} \]  

(13)

By virtue of the FFT operation and the forward carrier synchronization algorithm based on the ML criterion, the following steps can be obtained for frequency difference estimation.

3. Application Examples

This paper has proposed to apply the CP-OFDM analysis and demodulation method to the demodulation of the image transmission signals of small UAVs.

3.1 Estimation of Subcarrier Number and Subcarrier Symbol Rate of Image Transmission Signals

Fig. 3 shows the frequency waveform of the signal, from which the center frequency and bandwidth can be roughly estimated. Suppose the rough estimates of the center frequency and bandwidth are \( \hat{f}_c \) and \( \hat{f}_w \) respectively; Take \( \hat{f}_c \) as the center frequency to downconvert the signal to the baseband and the sampling rate of the baseband signal is \( P \hat{f}_c \), where \( P \) is a positive integer greater than 1 (Let \( P = 4 \) in this paper); as measured, \( \hat{f}_c = 20000000 \text{Hz} \). See Fig. 4 for delay autocorrelation of this baseband signal.

3.2 Symbol Timing Synchronization and Frequency Domain/Offset Compensation of CP-OFDM Symbols for Image Transmission Signals

Apply timing synchronization to the UAV signals with sampling rate alignment completed in the last section, \( N_{FFT} = 2048 \). Assuming that the length of the cyclic prefix is \( L_{CP} \), a moderate value can be taken when the length of the cyclic prefix is unknown, for example, \( L_{CP} = N_{FFT}/8 \) or \( L_{CP} = N_{FFT}/16 \) (\( L_{CP} = N_{FFT}/16 \) in this paper). The error of the cyclic prefix length has little effect on timing errors and the cyclic prefix length can be estimated based on the difference of the starting points of all CP-OFDM symbols obtained by timing synchronization. Fig. 3, Fig. 4 shows the sliding autocorrelation results of timing synchronization. There are five distinct peaks in the figure and the maximum position of each peak is the starting point of an OFDM symbol.

**Fig.3** Frequency Waveform of Image Signals **Fig.4** Delay Autocorrelation of Baseband Signals

The subcarriers of UAV image transmission signals adopt QPSK modulation. See Fig. 5 for the star map with no frequency offset compensation made after OFDM modulation has been removed.
Use the wide-range frequency offset estimation algorithm and see Fig. 6 for the star map for subcarriers of the UAV image transmission signal after OFDM modulation has been removed and the frequency offset has been compensated.

4. Conclusion
This paper has mainly studied the analysis and demodulation of CP-OFDM signals under the condition of non-cooperative reception as well as the algorithm for estimating the number of subcarriers based on delay autocorrelation and the timing synchronization algorithm based on sliding autocorrelation. The L&R frequency offset estimation algorithm features high estimation accuracy and fast processing speed, but its estimation range is small. In order to expand the estimation range, this paper has proposed a two-step processing mode which combines rough estimation with precise synchronization. Therein, the coarse frequency offset estimation based on FFT operation can not only speed up estimation, but also meet the requirements for estimation range of the L&R frequency offset estimation algorithm. In this paper, the UAV image transmission signal is taken as an example to have achieved the algorithm targeting CP-OFDM signals together with the algorithm descriptions. The results show that the algorithm proposed in this paper is effective as a perfect CP-OFDM analysis and demodulation algorithm under non-cooperative conditions.

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