Studies on Novel Anti-jamming Technique of Unmanned Aerial Vehicle Data Link

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Abstract

Based on the M-ary spread spectrum (M-ary-SS), direct sequence spread spectrum (DS-SS), and orthogonal frequency division multiplex (OFDM), a novel anti-jamming scheme, named orthogonal code time division multi-subchannels spread spectrum modulation (OC-TDMSCSSM), is proposed to enhance the anti-jamming ability of the unmanned aerial vehicle (UAV) data link. The anti-jamming system with its mathematical model is presented first, and then the signal formats of transmitter and receiver are derived. The receiver’s bit error rate (BER) is demonstrated and anti-jamming performance analysis is carried out in an additive white Gaussian noise (AWGN) channel. Theoretical research and simulation results show the anti-jamming performance of the proposed scheme better than that of the hybrid direct sequence frequency hopping spread spectrum (DS/FH SS) system. The jamming margin of the OC-TDMSCSSM system is 5 dB higher than that of DS/FH SS system under the condition of Rician channel and full-band jamming, and 6 dB higher under the condition of Rician channel environment and partial-band jamming.

Keywords: UAV data link; OC-TDMSCSSM; systemview simulation; orthogonal code; anti-jamming

1 Introduction

Unmanned aerial vehicle (UAV) has become one component of the prosperous modern aviation weapon system for its outstanding tactical and technical performance. However, in implementing tasks such as reconnaissance, surveillance, airborne warning, communication relay and electronic countermeasures, it is often subjected to interference. As an important part of UAV system, the UAV data link demands the highest reliability in data transmission, and the most powerful ability of anti-jamming and anti-multipath[1]. As an existing UAV data link, the applied simple anti-jamming systems, direct sequence spread spectrum (DS-SS) or M-ary spread spectrum (M-ary-SS), seem to be weak in anti-jamming performance, and unable to satisfy the requirements of UAV data link in unfavorable and complex electromagnetic environments[2-3]. Recent researches introduce the application and performance analysis on frequency hopping spread spectrum (FH-SS), multi-carrier code division multiple access (MC/CDMA)[4-5], and hybrid direct sequence frequency hopping spread spectrum (DS/FH SS) system[6]. They show that the hybrid DS/FH SS system has an anti-jamming performance better than DS-SS, M-ary SS, FH-SS and MC/CD-MA. Thus, to enhance the anti-jamming ability of the UAV data link in various complex environments, the advantages of the traditional spread spectrum system can be utilized and optimized in the development of a new anti-jamming technology to improve the elec-
tronic counter measures of UAV data link.

This paper proposes a novel anti-jamming technique, termed orthogonal code time division multi-subchannels spread spectrum modulation (OC-TDMSCSSM), in which the M-ary is associated with the DS-SS and orthogonal frequency division multiplex (OFDM). Different from the M-ary system, the former spread spectrum is added before serial-parallel converter, and in mapping coding, the draft of orthogonal spread spectrum subchannel is chosen instead of pseudorandom (PN) code. Different from the DS/FH SS system, though the former spread spectrum employs the same theory as DS-SS, in the DS/FH SS system, one hoping frequency transmits multiple bits information, or multiple hoping frequencies transmit one bit information, while in the new scheme associated with M-ary SS, multiple orthogonal spread spectrum subchannels represents one bit information. Different from the OFDM system, a new segment of former spread spectrum is added and orthogonal spread spectrum subchannels are adopted instead of the orthogonal subchannels[7]. The simulation results confirm that the output signals of OC-TDMSCSSM system like the Gaussian white noise signals lead to an anti-jamming performance better than the DS/FH SS system.

2 System Description

2.1 Transmitter model

Fig.1 shows the model of transmitter, in which the input binary data sequence at 1/Ts rate is first encoded and multiplied by a higher rate channel PN sequence. The result is a binary data sequence at Mk/Ts rate. Then these data are grouped according to k bits forming a data symbol with M=2^k symbols. Each data symbol is mapped with one of M orthogonal spread spectrum subchannels which are composed of M orthogonal spread spectrum sequences modulated by binary phase-shift-keying (BPSK) in the orthogonal spread spectrum code set, and each symbol selects respective orthogonal spread spectrum subchannels to transmit according to the mapping coding principle. Then orthogonal spread spectrum subchannels are transmitted timely through a radio frequency (RF) part.

The data source period is denoted by Ts, the amplitude of qth data source by Aq, and the power of data source denoted by Pq equals A_q^2/2. In the orthogonal code set, the code length of each orthogonal sequence equals N, and the period is Tc.

For given M modulators, their carriers are in an orthogonal frequency set, \( \{f_1, \ldots, f_M\} \), and then \( T_c = T_s/MN \).

Assume that the chip waveform of the spread spectrum code is a unit-amplitude rectangular pulse with chip duration Tc, and then \( p(t) \) is

\[
p(t) = \begin{cases} 
1, & 0 \leq t \leq T_c \\
0, & \text{Other}
\end{cases}
\]  

In the orthogonal code set, the spread spectrum sequence is expressed by

\[
C_\lambda = \{C(\lambda, i), C(\lambda, i) \in [-1, +1]\}
\]  

where \( \lambda = 1, 2, \ldots, M \), \( i = 1, 2, \ldots, N \).

Hence, the output signal of transmitter is

\[
S(t) = \sum_{q=-\infty}^{+\infty} \sum_{\lambda=1}^{M} \sum_{i=1}^{N} \sqrt{2P_q} \cdot C(\lambda, i) \cdot \cos(2\pi f_\lambda t + \phi_q)
\]  

2.2 Receiver model

The model of a receiver is shown in Fig.2. In the parallel correlated synchronization receiver, M digital matched filters (DMFs) are adopted. One self-correlated peak is an output in each period of
spread spectrum subchannel through the orthogonality of spread spectrum subchannel and the correlation of PN code. Thus, \( M \) self-correlated peaks can be obtained and detected while one bit information is transmitted. After de-mapping \( M \) self-correlated peaks to spread spectrum subchannel coding, the result is sent to the correlator of local DS sequence, and one bit information can be obtained. Without considering the radio frequency part, the receipt signal in AWGN can be denoted by

\[
(\mathbf{r}(t) = \mathbf{S}(t) + \mathbf{n}(t) + \mathbf{J}(t))
\]

where \( \mathbf{S}(t) \) is given by Eq.(3), \( \mathbf{n}(t) \) is an additive white Gaussian noise (AWGN) with single-sided spectral density \( N_0 \), and \( \mathbf{J}(t) \) the jamming signal.

3 Bit Error Rate (BER) Analyses in AWGN Channel

In the case that the receiver has caught synchronization in AWGN, assume the transmitting signal symbol is the \( \lambda \)th in AWGN channel, thus the signal in receiver can be expressed by

\[
\mathbf{r}(t) = \mathbf{S}(V_{\lambda}, t) + \mathbf{n}(t)
\]

where \( \mathbf{n}(t) \) is white Gaussian noise with double-sided spectral density \( N_0/2 \). If coherence reception is adopted, the \( \mu \)th correlator, denoted by \( Z_{\mu} \) is the signal symbol of \( 1/M \) bit defined as

\[
Z_{\mu} = \int_0^{NT} \mathbf{r}(t) \sum_{n=1}^N \mathbf{C}(\mu, n) \cdot p(t - nT_c) \cdot \cos 2\pi f_{\mu} t dt
\]

After substituting Eq.(5) into Eq.(6), \( Z_{\mu} \) can be rewritten into

\[
Z_{\mu} = \begin{cases} 
NT_c \sqrt{2P_q} + Q(\mu, r), & \mu = \lambda \\
\frac{Q(\mu, r)}{Q(\lambda, r)}, & \mu \neq \lambda \text{ or } f_{\mu} \neq f_{\lambda}
\end{cases}
\]

where \( Q(\mu, r) \) is a Gaussian stochastic variable with zero-mean and \( NT_c N_0/4 \) variance.

The false judge probability of the \( j \)th orthogonal code and frequency is

\[
P_c(j) = \left[ 1 - P[Z_j > (Z_{1}, Z_{2}, \cdots Z_{j-1}, Z_{j+1}, \cdots, Z_{M})/f_j] \right] \cdot P(f_j)
\]

where \( P(f_j) \) is the false judge probability of the \( j \)th frequency in orthogonal frequency set as \( 1/(M-1) \).

\[
P[Z_j > (Z_{1}, Z_{2}, \cdots Z_{j-1}, Z_{j+1}, \cdots, Z_{M})/f_j] = \int_{\infty}^{\infty} \cdots \int_{\infty}^{\infty} P(Z/f_j) dZ = [P(Z_j > Z_{\lambda}, x \neq j)]^{M-1}(9)
\]

Then Eq.(8) can be rewritten into

\[
P_c(j) = \frac{1}{M-1} \cdot \left[ 1 - [P(Z_j > Z_{\lambda}, x \neq j)]^{M-1} \right]
\]

According to the central limit theorem, when the orthogonal code length \( N \) is big enough, the distribution of \( Z \) can be approximated by the Gaussian process. Because the variance of \( Z_j - Z_{\lambda} \) is \( \sigma^2 = NT_c N_0/4 \), and the mean is \( NT_c (P_q/2)^{1/2} \), the following formula can be obtained:

\[
P(Z_j > Z_{\lambda}, x \neq j) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(y - NT_c (P_q/2)^{1/2})^2}{2\sigma}} dy = \text{erf}(\sqrt{E_b/N_0})
\]

where \( \text{erf}(x) \) denotes the error function. After substituting Eq.(11) into Eq.(10), \( P_c(j) \) can be obtained

\[
P_c(j) = \frac{1}{M-1} \cdot \left[ 1 - [\text{erf}(\sqrt{E_b/N_0})]^{M-1} \right]
\]

Thus in detecting the \( M \)th orthogonal code and orthogonal frequency, the false judge probability is

\[
P_c = \frac{1}{M} \sum_{j=1}^{M} P_c(j) = P_c(j), \ j = 1, 2, \cdots, M
\]

From the transmitter model, when \( M \) orthogonal codes and orthogonal frequencies have been detected correctly, i.e. one bit information has been transmitted, the BER in AWGN is

\[
P_b = P_c = \frac{1}{M-1} \cdot \left[ 1 - [\text{erf}(\sqrt{E_b/N_0})]^{M-1} \right]
\]
4 Anti-jamming Performance Analysis

The current main jamming methods aimed at the UAV data link are of full-band jamming, partial-band jamming, multitone jamming, and pulse jamming[8]. Later, the analysis and simulation of the first two jamming methods are presented.

4.1 Performance in full-band jamming

Assume that the input signal of UAV is

\[ r(t) = S(t) + n(t) \]  \hspace{1cm} (15)

where \( n(t) \) is wide-band noise. Eq.(15) can also be expressed as

\[ r(t) = S(t) + \sqrt{2}n_1(t) \cos 2\pi ft - \sqrt{2}n_0(t) \sin 2\pi ft \]  \hspace{1cm} (16)

where \( n_1(t) \) and \( n_0(t) \) are two mutual independent low-pass Gaussian noises with double-sided power spectral density \( (N_0 + N_{jm})/2 \), where \( N_0 \) denotes single-sided power spectral density of thermal noise, and \( N_{jm} \) single-sided power spectral density of jamming signal. Therefore, the component near the intermediate frequency after correlation is

\[ s(t) = \frac{2}{W_s} \text{Sinc}^2 \left[ \frac{2}{W_s} (f - f_\lambda - f_W) \right] + \frac{2}{W_s} \text{Sinc}^2 \left[ \frac{2}{W_s} (f + f_\lambda + f_W) \right] \]  \hspace{1cm} (17)

where \( H(t) = \sum_{\lambda=1}^{M} \rho_\lambda(t - \lambda T_s / M) \cos[\omega_\lambda t + \theta_\lambda(t)] + \frac{\sqrt{2}n_1(t) \cos \omega_\lambda t - \sqrt{2}n_0(t) \sin \omega_\lambda t}{2 \cos[\omega_\lambda t + \omega_\eta t + \theta_\lambda(t) + \theta_\eta(t)]} \]  \hspace{1cm} (18)

where \( H(t) \) is the self-correlated function for orthogonal code in \( \lambda \)th subchannel, and \( \theta_\lambda(t) \) the random modulation phase. In the receiver, the power spectrum of each subchannel output is

\[ S_R (f) = \frac{N_0 + N_{jm}}{W_s} \int f_{f_W}^{f} \text{Sinc}^2 \left[ \frac{2}{W_s} (f - \lambda - f_\lambda - f_W) \right] d\lambda \]  \hspace{1cm} (19)

With the definition of \( \gamma = f - \lambda - f_\lambda - f_W \), Eq.(19) can be simplified into

\[ N(f) \ast S_R (f) \approx \frac{N_0 + N_{jm}}{2} \int f_{f_W}^{f} \text{Sinc}^2 \left[ \frac{2}{W_s} (f - \lambda + f_\lambda + f_W) \right] d\lambda \]  \hspace{1cm} (20)

and the double-sided spectral density of noise near \( f = \pm f_W \) is

\[ \frac{N_0}{2} + \frac{N_{jm}}{2} \]  \hspace{1cm} (21)

It shows that when the system is subjected to full-band jamming, the noise band is much wider than that of the subchannel, and \( N_0/2 \) approaches \( N_0/2 \) or \( N_{jm}/2 \), meaning that broadband jamming noise possesses features similar to the receiver’s inner noise.

4.2 Performance in partial-band jamming

Compared with full-band jamming, it is easier to generate partial-band jamming having a higher power spectral density. Assume that \( W \) is the bandwidth of radio frequency, \( W_{jm} \) the jamming bandwidth, \( W_s \) the subchannel bandwidth, \( P_{jm} \) the jamming power, \( \eta \) the rate of \( W \) and \( W_{jm} \), \( N_p \) the spectral density of partial-band jamming, \( N_{jm} \) the spectral density of full-band jamming, and \( N_0 \) single-sided spectral density of thermal noise. Thus the final spectral density of noise is \( N_0 + N_p \), and only \( N_0 \) is the effects in the remaining partial-band. The receiver signal is

\[ r(t) = S(t) + n(t) + n_{jm}(t) \]  \hspace{1cm} (22)

where \( S(t) \) is the useful transmitting signal, \( n(t) \) the thermal noise, and \( n_{jm}(t) \) the partial-band jamming. After correlative calculation, the output of the despectral mixer is

\[ H(t) = \sum_{\lambda=1}^{M} \rho_\lambda(t - \lambda T_s / M) \cos[2\omega_\lambda t + \theta_\lambda(t)] + \frac{N_{jm} + N_0}{W_s} \int f_{f_W}^{f} \text{Sinc}^2 \left[ \frac{2}{W_s} (f - \lambda + f_\lambda + f_W) \right] d\lambda \]
where the second term is the noise caused by co-actions of the thermal noise and the despectral reference waveform, and the bandwidth is much wider than that of the spectral waveform, which has been discussed in Section 4.1. Hereafter, two cases are considered as follows:

**Case one** when \( W_{jm} < W_s \), i.e. one of the sub-channels is jammed, for the single subchannel, the output of despectral mixer is

\[
H_P(t) = \rho \cos(\omega_f t + \theta(t)) + n(t) \left\{ 2c \cdot \cos((\omega_f + \omega_p)t + \theta(t)) \right\} + n_{jm}(t) \left\{ 2c \cdot \cos((\omega_f + \omega_p)t + \theta(t)) \right\}
\]

(24)

where \( \rho \) is the self-correlated function for the orthogonal code of the single subchannel, and \( c \) the orthogonal code of the single subchannel. The power spectral density of the third term, generated by jamming, is the convolution of jamming spectral density and spread spectrum waveform spectral density. Along the similar lines cited in Section 4.1, it can be deducted that the output spectral density in partial-band jamming is determined by

\[
S(\pm f_{IF}) = \frac{N_p}{W_s} \int_{-f_{ps} - W_{ps}/2}^{f_{ps} + W_{ps}/2} \text{Sinc}^2 \left[ \frac{2}{W_s} (f_{IF} - x) \right] dx
\]

(25)

where \( \lambda = 1, 2, \cdots, M \). In such cases, receiver can still obtain a majority of self-correlated peaks and recover the data as long as the number of interferential subchannels is less than half of the number of subchannels.

**5 Simulations and Discussion**

In the simulation, the OC-TDMSCSSM system parameters are assumed as follows: the source rate is 8 Kbps; the former spread spectrum segment adopts BPSK modulation; the length of former spread spectrum code is 64 with a chip rate of 512 kc/s; the number of sub-channels 16 with a chip rate of 2 048 kc/s; the system bandwidth is 32.768 MHz, and the intermediate frequency 85 MHz. The DS/FH SS system parameters are chosen as follows: the source rate is 8 Kbps; the length of DS-SS code 64 with a chip rate of 1 024 kc/s; the number of hopping frequency 16; the FH rate 16 000 hop/s, 1bit per two hoppings; the system bandwidth is 32.768 MHz, and the intermediate frequency 22.36 MHz. The jamming signal parameters are taken as follows: the full-band jamming signal is applied by Gaussian white noise signal with an alterable gain amplifier; the partial-band jamming signal is adopted by DS-SS signal with a bandwidth of 16.384 MHz. In the BER performance analysis, the simulation is based on the MATLAB platform and the Monte Carlo method with a sampling rate of one per chip. In the anti-jamming ability analysis, the simulation is based on the systemview dynamic platform with a sampling rate of 500 MHz and sampling number of 80 000. The Rician channel is chosen with a Rician factor of 11 dB, and the maximum Doppler frequency shift is 500 Hz[9].

The Monte Carlo simulation results of BER in AWGN channel are shown in Fig.3, from which it is clear that the simulation curve accords well with that of the theoretical results, and when \( E_b/N_0 \) is equal to or larger than 9 dB, the two curves are superimposed thus leading to the theoretical credib-
lity of the system BER.

Fig. 3  BER performance with theoretic and Monte Carlo simulation in AWGN channel.

The output spectrum of OC-TDMSCSSM system and DS/FH SS system are described in Fig.4 and Fig.5, respectively, which show that the transmitted signals of OC-TDMSCSSM system look like the Gaussian white noise signals in line with the theoretical results, while in the DS/FH SS system, there are 16 distinct envelops without the characteristics of Gaussian white noise signals. Fig.6 shows the self-correlated peaks of OC-TDMSCSSM system of the subchannels 1, 4, 7, 11 under the condition of full-band jamming. The program runs two times. The signal-to-noise ratio (SNR) is 0 dB; the jamming to signal ratio (JSR) is 22 dB and 24 dB. In the case of JSR 22 dB, the self-correlated peaks can be extracted completely and the system can recover the data rightly, but this is completely different with 24 dB.

Fig.7 shows the self-correlated peaks of DS/FH SS system under the condition of full-band jamming. The program runs two times. The SNR is 0 dB; the JSR is 17 dB and 19 dB. In the case of JSR 17 dB, the self-correlated peaks can be extracted completely and the data can be recovered rightly, but, for 19 dB, the self-correlated peaks of the 3rd, 4th, 6th, 8th, 12th, 13th hoppings cannot be detected normally leading to the losing of synchronization. Therefore, the jamming margin of the OC-TDMSCSSM system is 5 dB more than that of the DS/FH SS system under the condition of Rician channel and full-band jamming.

Fig. 4  Output signal spectrum of OC-TDMSCSSM system.

Fig. 5  Output signal spectrum of DS/FH system.

Fig. 6  Self-correlated peaks of OC-TDMSCSSM under full-band jamming (1, 4, 7, 11 subchannels).

Fig. 7  Self-correlated peaks of DS/FH under full-band jamming.

Fig. 8  describes the output spectrum of the OC-TDMSCSSM system under the condition of partial-band jamming, which shows that the eight anterior subchannels are covered by the major lobe of jamming signal spectrum, and the eight posterior
subchannels by the side lobe of jamming signal spectrum. Here, SNR is 0 dB and JSR is 25 dB. Fig. 9 shows the self-correlated peaks of OC-TDMS-CSSM system under the condition of partial-band jamming. The program runs two times. The JSR is 25 dB and 27 dB. For JSR 25 dB, the self-correlated peaks can be extracted except those of the 3rd, 4th, 5th subchannels and the right data can be recovered, but, for 27 dB, the self-correlated peaks of the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 10th subchannels cannot be recovered normally leading to the losing of synchronization.

Fig. 9  Self-correlated peaks of OC-TDMS-CSSM under partial-band jamming.

Fig. 8  Output signal spectrum of OC-TDMS-CSSM system under partial-band jamming.

Fig. 10 describes the output signal spectrum of the DS/FH system under the condition of partial-band jamming. It is noted that the eight anterior subchannels are covered by the major lobe of jamming signal spectrum while the eight posterior subchannels by the side lobe of jamming signal spectrum. Here, the SNR is 0 dB and the JSR is 19 dB. Fig. 11 shows the self-correlated peaks of DS/FH system under the condition of partial-band jamming. The program runs two times. JSR is 19 dB and 21 dB. For JSR 19 dB, the self-correlated peaks can be extracted except those of the 4th, 12th subchannels and the right data can be recovered, but, for 21 dB, the self-correlated peaks of the 2nd, 4th, 6th, 11th, 12th, 14th hoppings cannot be detected normally leading to the losing of synchronization. Therefore, the jamming margin of the OC-TDMS-CSSM system is 6 dB more than that of the DS/FH SS system under the condition of Rician channel and partial-band jamming.

Fig. 10  Output signal spectrum of DS/FH system under partial-band jamming.

Fig. 11  Self-correlated peaks of DS/FH under partial-band jamming.

6 Conclusions

The paper proposes the OC-TDMS-CSSM scheme as a novel anti-jamming technique for UAV data link, for which the system and mathematical model are established; the signal format derived; and the BER and anti-jamming performance in AWGN channel analyzed. Theoretical analysis and simulation results demonstrate that the derived system BER formula is correct and the proposed system is technically feasible. The proposed scheme possesses much better anti-jamming capability than the DS/FH system, i.e. the jamming margin of the OC-TDMS-CSSM system is 5 dB more than that of the DS/FH SS system under the condition of Rician channel environment and full-band jamming, and
the jamming margin of the OC-TDMSCSSM system is 6 dB more than that of the DS/FH SS system under the condition of Rician channel environment and partial-band jamming.

References


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