Research on four-dimension Bandpass DSSS Modulation

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Abstract. Based on 2-dimension baseband DSSS modulation method and orthogonal frequency conversion theory, a four-dimensional band-pass DSSS modulation and demodulation system model based on a single pseudo-noise code is proposed. Then, the BER performance is analysed, and the hardware experiments based on software defined radio are conducted. Compared with 16QAM and 16PSK, when the BER is 10⁻⁶, the proposed method outperforms 16QAM and 16PSK by 4dB and 8dB respectively, hardware experiments show that the time domain characteristics, power spectrum and power bandwidth of RF signals are consistent with theoretical values. Works in this paper establish the technology foundation for future application.

1. Introduction

As the spectral efficiency of traditional Direct Sequence Spread Spectrum (DSSS) communication system is extremely low, limited by the DSSS modulation and demodulation technologies, it is difficult to effectively improve the transmission rate of DSSS systems, which accounts for a major impediment in the development of spread spectrum communication technology. A modulation method named 2-dimensional baseband DSSS communication based on Hilbert shaped waveform transformation was published in [1]. This method combined the advantages of spread spectrum codes, spread spectrum modulation signals and Hilbert transformation technology [2, 3] to improve the transmission rate of the spread-spectrum system by expanding the spatial dimension of the spread spectrum signals. To be specific, the spatial dimension of signals in the baseband DSSS modulation system based on a single pseudo random (PN) codes was increased from one to two, thus doubling the transmission rate of the baseband DSSS system. This method has multiple advantages: low technical complexity, robust universality, compatible with the traditional DSSS modulation system, so it is applicable to communication and navigation systems that use DSSS technology and enjoys a great prospect.

So far, the DSSS technology [4-9] has seen wide application in communication radio systems, underwater acoustic communication systems and communication navigation systems, but the problem of low transmission rate remains. On the basis of [1] and the orthogonal up-down frequency conversion theory, this paper constructs a four-dimensional band-pass modulation and demodulation model for DSSS systems and analyzes its performance. It is also compared with M-ray QAM and PSK methods under the same transmission bandwidth and transmission rate, and the software radio platform is used to verify the experiment results. The research result confirms the advantage of the proposed method and provides a basis for its further application and development.
2. Four-Dimensional Bandpass DSSS Communication Modulation and Demodulation Scheme

2.1 Four-Dimensional DSSS Modulation Scheme

On the basis of the two-dimensional baseband DSSS transmission system proposed in [1], we adopt the dual-channel characteristics of cosine and sine (I, Q) of bandpass transmission system, uses the cosine carrier and sine carrier to modulate two baseband DSSS modulation signals respectively, and then superposition in time domain is performed, so that the baseband spread spectrum transmission system can be extended to band-pass, and then a four-dimensional band-pass DSSS transmission system is obtained. The structure diagram of the transmitter is shown in Fig. 1.

![Fig. 1 Structure diagram of a four-dimensional band-pass DSSS modulation system](image)

The transmitter of a four-dimensional band-pass DSSS system is mainly composed of two parts: the baseband digital processing part and the dual-channel orthogonal up-conversion part. The baseband digital processing part is used for completing digital modulation of baseband spread spectrum signals and generating baseband digital modulation signals of I and Q, including spread spectrum code generation, parallel serial conversion, data modulation, spread spectrum modulation, baseband shaping, among which the baseband shaping function adopted by the two baseband spread spectrum signals contained in the I and Q channels is in the form of Hilbert transform pairs; the dual-channel quadrature up-conversion module is used for converting the baseband digital modulation signal into an analog signal, up-converting the baseband analog signal to a RF (Radio Frequency) band, and then radiate and output the RF analog signal through an antenna.

The baseband DSSS modulated signals of in-phase and orthogonal components can be expressed as

\[ s_i(t) = d_{i1}(i) \cdot c(j) \cdot g[K(t - jT_c)] + d_{i2}(i) \cdot c(j) \cdot \tilde{g}[K(t - jT_c)] \quad 0 \leq t \leq \infty \]  \hspace{1cm} (1)

\[ s_q(t) = d_{q1}(i) \cdot c(j) \cdot g[K(t - jT_c)] + d_{q2}(i) \cdot c(j) \cdot \tilde{g}[K(t - jT_c)] \quad 0 \leq t \leq \infty \]  \hspace{1cm} (2)

Where, \( i = \lfloor t/T_c \rfloor \) (the symbol \( \lfloor \cdot \rfloor \) indicates rounding down) is the serial number of the modulation symbol, \( d_{i1}(i), d_{i2}(i) \) and \( d_{q1}(i), d_{q2}(i) \) are two channels of modulation data in the in-phase and quadrature channels, respectively; \( j = \lfloor (t - iT_c)/T_c \rfloor \) refers to the sequence number of the spread chip, \( c(j) \) \( j = 0, ..., N_c - 1 \) means \( j+1 \)st chip in the spread spectrum modulation symbol; \( g(t) \) refers to the baseband shaping function defined in the time interval \( [0, KT_c] \), where \( K \) is the expansion multiple in time domain caused by the shaping function; \( \tilde{g}(t) \) is the Hilbert transform of the shaping function \( g(t) \), \( T_c \) is the duration of spread spectrum modulated symbol, \( T_s \) is the chip interval, both of which satisfies

\[ T_s = N_c \cdot T_c \]  \hspace{1cm} (3)

\( N_c \) is the length of the PN code.

The RF modulated signal \( s(t) \) can be expressed as:

\[ s(t) = s_i(t) \cdot \cos(2\pi f_s t) - s_q(t) \cdot \sin(2\pi f_s t) \]  \hspace{1cm} (4)

From the RF signal equation (4) and the modulation system flow chart, it can be seen that the RF signal is composed of two channels of in-phase and orthogonal components, and in-phase and
orthogonal components are composed of another two components respectively, with a total of four signal components. While RF signal of the traditional DSSS is composed of in-phase and orthogonal components, with only a total of two signal components.

2.2 Demodulation Scheme
In alignment with the modulation system, the demodulation system also consists of two modules: a quadrature dual-channel down-conversion module and a baseband signal demodulation and detection module. The overall structural structure is shown in Fig. 2.

The down-conversion module converts the received RF signals into baseband signals of I and Q, and performs analog-to-digital conversion; the demodulation and detection module performs matched filtering demodulation and detection on the two baseband signals respectively, four ways demodulated data can be obtained, and then parallel-to-serial conversion convert the four ways parallel data to one-way serial data.

The received signal can be expressed as

$$r(t) = s(t) + n(t)$$  \hspace{1cm} (5)

Where $n(t)$ is band-limited additive white Gaussian noise with mean zero and variance $\sigma^2$.

$r(t)$ can also be expressed by

$$r(t) = r_i(t) \cos 2\pi f_c t - r_q(t) \sin 2\pi f_c t$$  \hspace{1cm} (6)

$r_i(t), r_q(t)$ indicate in-phase and orthogonal components of the received signal

$$r_i(t) = s_i(t) + n_i(t)$$
$$r_q(t) = s_q(t) + n_q(t)$$  \hspace{1cm} (7)

where $n_i(t), n_q(t)$ represent the in-phase and quadrature components of noise $n(t)$, respectively.

According to the nature of the additive white Gaussian noise, $n_i(t), n_q(t)$ are additive white Gaussian noise with zero mean and variance $\sigma^2$.

3. BER Performance Analysis
Since the four components of the RF signal are equivalent, without losing generality, only the signal in the first component of the in-phase channel is analyzed, and the results can be extended to other three components. Let $G(t)$ be the template signal after the pseudo noise code sequence is shaped by the baseband shaping function $g(t)$, and the energy is $E$. $\hat{G}(t)$ is the Hilbert transform of $G(t)$, and $\hat{G}(t)$ is orthogonal to $G(t)$.

According to the demodulation model, the detection amount of the $i$-th symbol of the first components can be obtained as follows

$$E_{i1}(t) = \int_{t_i}^{t_{i+1}/E} G(t - iT_i) r_i(t) dt$$  \hspace{1cm} (8)
$E_i(i)$ accords with the Gaussian distribution with a mean value of $\varepsilon$ or $-\varepsilon$, variance $\sqrt{\varepsilon^2}$, and a SNR (signal-to-noise ratio) of $\sqrt{\varepsilon^2/\sigma^2}$. Under the condition of uniform distribution of the binary sources, the BER of the first component can be expressed as

$$P_i = Q(\sqrt{\varepsilon^2/\sigma^2})$$

Furthermore, the BER performance of the transmission system is the same as that of the first component, and the BER of the system can be obtained.

$$P_e = P_i = Q(\sqrt{\varepsilon^2/\sigma^2})$$

Under the condition of the same transmission rate and bandwidth, we assume that the traditional modulation method in a certain application scenario requires 16-ary digital modulation (each symbol contains 4 bits, and the typical 16-ary modulation method includes 16QAM and 16PSK) to meet the transmission requirements. While, when 4-dimensional band-pass DSSS modulation is adopted, each component only needs to use BPSK (each symbol contains 4 bits information). The comparison between theoretical BER is shown in Figure 3.

| Table 1 Technical Parameters of Principle Verification System |
|-------------------------------------------------------------|
| **Modulation Method** | **Traditional DSSS (QPSK)** | **Four-dimensional Bandpass DSSS (Binary Modulation)** |
| Symbol rate         | 1kBaud                       | 1kBaud                                      |
| Information rate    | 2kb/s                        | 4kb/s                                      |
| Spread Spectrum Code | m sequence (code length 127) | m sequence (code length 127)               |
| Chip rate           | 127k/s                       | 127k/s                                     |
| Shaping function    | Raised-cosine shaping (roll-off factor: 0.25) | Raised-cosine and Hilbert transform shaping (roll-off factor: 0.25) |
| Main lobe bandwidth | 158.75kHz                   | 158.75kHz                                  |

As Fig.3 shows, the four-dimensional band-pass DSSS modulation method has the least error rate among the three that are compared, followed by the 16QAM method, and the 16PSK method is the worst. When the BER is $10^{-6}$, the four-dimensional band-pass DSSS modulation method outperforms the 16QAM and 16PSK modulation methods by 4dB and 8dB, respectively, which shows the superior performance of the proposed method.

4. Principle Verification System

After construction of the four-dimensional bandpass DSSS modulation and demodulation model. A principle verification system is designed in the 300MHz using a software radio platform, and compared with the traditional DSSS using QPSK. The technical parameters are shown in Table 1.
The generator polynomial of the m sequence is $x^7 + x^5 + 1$, and the transmission environments is a short-distance indoor channel. The principle verification system includes a synchronization tracking module which is used for carrier frequency and phase deviation, symbol synchronization, and frame synchronization. Since synchronization technology is not focus of this paper, and the synchronization technologies adopted are all classical synchronization methods, the technical details of synchronization will not be described here.

Based on the above parameters and the existing hardware and software conditions in the laboratory, a principle verification test system is constructed. Time and frequency characteristics of the RF signals are measured. Meanwhile, the transmission feasibility is preliminarily verified. The design block diagram of the software modulator and receiver based on Matlab/Simulink is shown in Fig. 4, and the test platform is shown in Fig. 5.

![Block diagram of the software modulator](image1.png) ![Block diagram of the software receiver](image2.png)

**Fig. 4 Design block diagram of the software modulator and receiver**

![Test platform](image3.png)

**Fig. 5 Principle experiment verification platform**

Relevant equipment include: two sets of USRP software radio platform (one transmitter and one receiver), vector signal analyzer N9020 and direct radio frequency (RF) sampling oscilloscope MSO7104B.

### 4.1 Measurement of time-frequency Characteristics of RF Modulated Signals

The time domain waveform and power spectrum of traditional DSSS modulation and four-dimensional band-pass DSSS modulation RF signals are observed by using direct RF sampling oscilloscope and a vector signal analyzer respectively.
4.1.1 Measurement of RF Signals in Time Domain

The time domain waveform obtained by direct RF sampling oscilloscope is shown in Fig. 6.

As Fig. 6 shows, the envelope fluctuation characteristics of the traditional DSSS spread spectrum modulated signal are directly related to chips. While the envelope characteristics of the four-dimensional DSSS RF signal are not directly related to chips. This is because the signal contains the baseband shaping function of the two paths of odd function (Hilbert transform of raised cosine function). The two paths of shaped signals are respectively superposed with the signals after raised cosine shaping, resulting in the envelope profile of the signal becoming unclear.

4.1.2 Power Spectrum and Occupied Bandwidth of RF Modulated Signals

Fig. 7 shows the correlation between the bandwidth of the RF modulated signals and the power spectra observed by the vector signal analyzer.

As Fig. 7 shows, the 99% energy bandwidth of the traditional DSSS RF signal is 136.29kHz, and the 99% energy bandwidth of a four-dimensional DSSS RF signal is 137.01kHz, with an absolute error of 0.72kHz and a relative error of only 0.5%. When the out-of-band attenuation is -26dB, the bandwidth of the traditional DSSS RF signal is 159.5kHz and the bandwidth of the four-dimensional DSSS RF signal is 159.9kHz, with an absolute error of only 0.4kHz, which is basically consistent with the theoretical main lobe bandwidth (158.75kHz).

It should be noted that since the master clock of USRP system is 100MHz, the sampling clock of 1.016MHz cannot be accurately allocated. When we design of sampling clock, the main clock of 100MHz is divided by 98 to obtain a sampling clock of 1.0204MHz. The increase of the actual sampling rate will lead to the bandwidth expansion, about 0.7kHz. The measured RF signal bandwidth needs to
be corrected. The corrected measured -26dB bandwidths of traditional DSSS and four-dimensional DSSS RF signals are 158.8kHz and 159.2kHz respectively. The corrected measured signal bandwidth is closer to the theoretical bandwidth, with absolute errors of 0.05kHz and 0.45kHz respectively and relative errors of 0.031% and 0.28% respectively.

4.2 Transmission Test
Based on the designed software radio transmitting and receiving system, a simple indoor transmission experiment using txt.-format files is carried out. The size of the txt. file is 49.8 KB (398,400 bits). Each data frame is set as 1s duration and contains 1000 symbols, of which the first four symbols are frame synchronization headers and the last 996 symbols are information data. The transmission situations of the two systems are shown in Table 2.

| Information source | 49.8kB txt (398,400bit) |
|--------------------|-------------------------|
| **Modulation Mode** | Traditional DSSS (QPSK) | 4D Bandpass DSSS (Binary Modulation) |
| **Channel rate**    | 2kbit/s                 | 4kbit/s |
| **Information rate**| 1.992kbit/s             | 3.984kbit/s |
| **Transmission duration** | 200s             | 100s |

Because the good indoor channel condition and the distance between the transmitter and receiver is very short, the interference and noise in the 300MHz are very weak, and no artificial noise interference is added, the transmission process of both methods have no errors. The actual measurement shows that it takes 200s to transmit 49.8kB txt by using traditional DSSS method and only 100s by using 4D DSSS method.

5. Conclusion
In this paper, a four-dimensional band-pass DSSS modulation and demodulation system model based on a single pseudo noise code is proposed. The BER performance of the system is analyzed theoretically, and preliminary experimental verification is carried out using a software radio platform. Theoretical analysis shows that the four-dimensional band-pass DSSS modulation and demodulation system can increase the signal space dimension of the traditional band-pass DSSS modulation system from two to four and double the transmission rate on the premise of not expanding the transmission bandwidth, not reducing the bit error code performance and not increasing the transmission power of unit bit information. The proposed method outperforms 16QAM and 16PSK by 4dB and 8dB respectively when the bit error rate is $10^{-6}$; the measured results show that the time domain characteristics, power spectrum and power bandwidth of RF signals are consistent with theoretical values, and the transmission rate is twice as high as that of traditional DSSS systems, which provides a basis for further application of this method.

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