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Optimization Method for Frequency Offset Estimation based on Pulse Waveform Collision Conditions

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Abstract. This article introduces a frequency offset estimation optimization method based on pulse waveform for high dynamic communication systems under the condition of partial synchronization code loss caused by collision. This method is based on using synchronous codes for correlation calculations to calculate pulse frequency offset, and solves the problem of synchronous code loss and inability to estimate frequency offset under collision conditions, while occupying less receiver system resources. This method greatly improves the anti-interference ability of the system, meets the low latency requirements of networking systems, and meets the needs of modern warfare and electronic technology development.

Keywords: pulse waveform, collision, frequency offset estimation, anti-interference

1. Research background

A major characteristic of high dynamic communication systems is the high dynamics of the transmitter and receiver, which means there may be rapid relative displacement between the transmitter and receiver. When there is relative movement between the source and the sink, there is a Doppler effect, causing changes in the electromagnetic wave length of the transmitted signal, thereby affecting the center frequency of the electromagnetic wave signal in the channel. In order to increase the anti-interference ability of the communication system, pulse division and time-hopping frequency hopping will be designed for the communication system. In high dynamic communication systems, pulse structured waveforms are often used for information transmission. Different pulses are transmitted using different center frequencies, and each pulse at each frequency point is equipped with a set of synchronization codes and data information to form a pulse.

For the receiver, after capturing the signal, in order to address the impact of Doppler frequency offset caused by high dynamic conditions on subsequent demodulation of the received signal, it is first necessary to use synchronous codes to estimate and compensate for the frequency offset of the pulse. However, in non-stationary transmission situations, some frame headers or frame endings may be severely affected by channel noise or other factors, resulting in their own calculation results no longer reflecting the magnitude of frequency and phase offset. The frequency and phase offset estimation results calculated using the frame head and frame tail of this pulse may not only fail to complete the correction of frequency and phase offset, but may have a worse impact on the results.

In order to optimize the estimation and compensation process of frequency offset, this design innovatively proposes an optimization method for frequency offset estimation based on pulse waveform collision conditions.

2. Pulse Waveform Structure Model and Frequency Offset Estimation Algorithm

2.1. Pulse waveform structure

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The waveform structure of the pulse is shown in Fig. 1. For the smallest unit of M-bit data sent in a single transmission, it is evenly divided into N parts, where each data is added with a pre and post synchronization code to form a pulse group of N pulses.

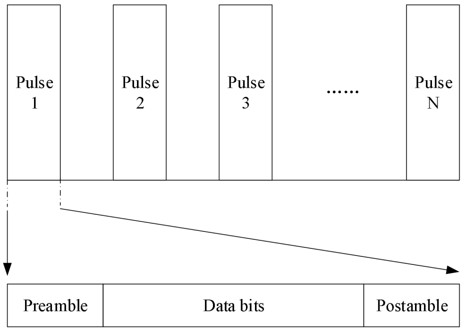

Fig. 1: Schematic diagram of basic structure of pulse waveform.

The frequency of each pulse emission is different, and the time interval between each pulse within a pulse group is also different. From this, time and frequency hopping of data can be achieved. At the receiving end, different receiving frequency points receive pulse signals corresponding to each frequency point.

2.2. Frequency and phase offset estimation algorithm

The basic idea of estimating the frequency offset of the received signal is to use the phase offset generated by two synchronization codes within a single pulse for subtraction. Firstly, calculate the phase offset by calculating the phase difference between the captured frame header signal $s_{head}(n)$ and the local reference signal $h(n)$. It is necessary to conjugate $s_{head}(n)$ and multiply it with $h(n)$ to obtain:

$$P = \sum_{n=0}^{N-1} s_{head}^{*}(n) * h(n) \tag{1}$$

In equation (1), N is the length of the frame header. From this calculation, the phase difference φ between $s_{head}(n)$ and $h(n)$ is:

$$\varphi = \text{angle}(P) \tag{2}$$

In equation (2), 'angle' is the phase calculation, and φ is the phase difference between the pulse frame header and the local reference signal. The frame header is the starting position of the pulse, and φ can be considered as the phase difference between the entire pulse signal and the local reference signal.

Perform a phase rotation of φ angle on each point in the data segment $s_{head}(n)$ to achieve phase offset compensation for the signal, resulting in signal $s_1(n)$:

$$s_1(n) = s_{payload}(n) \cdot e^{j\varphi} \quad n = 0,1,2,\ldots, L-1 \tag{3}$$

In equation (3), L is the length of the data segment $s_{payload}(n)$.

The calculation formula for the frequency offset f_d caused by the Doppler effect is:

$$f_d = \frac{\Delta\varphi}{2\pi t_p} \tag{4}$$

Among them, $\Delta\varphi$ is the phase shift caused by the accumulation of Doppler effect within a pulse, and t_p is the duration of the pulse. For each pulse in the pulse group, the phase offset φ_{head} of the pulse frame head and the phase offset φ_{tail} of the frame tail can be estimated using equations (1) and (2). The phase difference $\Delta\varphi$ of the entire pulse head and tail can be obtained by subtracting the difference between the two.

$$\Delta\varphi = \begin{cases} \varphi_{head} - \varphi_{tail} + 2\pi & \varphi_{head} - \varphi_{tail} < -\pi \\ \varphi_{head} - \varphi_{tail} & -\pi \le \varphi_{head} - \varphi_{tail} \le \pi \\ \varphi_{head} - \varphi_{tail} - 2\pi & \varphi_{head} - \varphi_{tail} > \pi \end{cases} \tag{5}$$

The pulse duration t_p can be calculated by dividing the pulse length data by the transmission rate. Since the phase shift algorithm (5) calculates the phase difference between the central part of the frame head or frame tail and the reference signal, the pulse length should be calculated based on half of the length of the two synchronization codes and the sum of the data segment length.

$$t_p = \frac{N+L}{r} \tag{6}$$

In equation (6), N is the length of the synchronization code, L is the length of the data segment, the total pulse length is $N+L$, and r is the data transmission rate.

Using f_d to compensate the signal $s_1(n)$ after phase offset compensation, the data $s_2(n)$ obtained after frequency compensation is:

$$s_2(n) = s_1(n) \cdot e^{-2\pi f_d jn/r} \qquad n = 0,1,2,\ldots,L-1 \tag{7}$$

3. Frequency and Phase Offset Compensation Method Under Collision Conditions

From **2.1**, it can be seen that when there is a collision caused by a transmission and reception conflict, there is a loss of frame head and frame tail. In this case, according to equation (5), as long as the frame head or frame tail is missing, frequency offset calculation cannot be performed normally, and the pulse cannot be demodulated correctly. This article designs an optimization method for frequency offset estimation under collision conditions, in order to obtain approximate frequency offset estimation even when some pulses lose the frame head or frame tail, so as to perform subsequent demodulation.

As shown in Fig. 2, it is a flowchart of the frequency offset estimation and compensation method based on intra group joint.

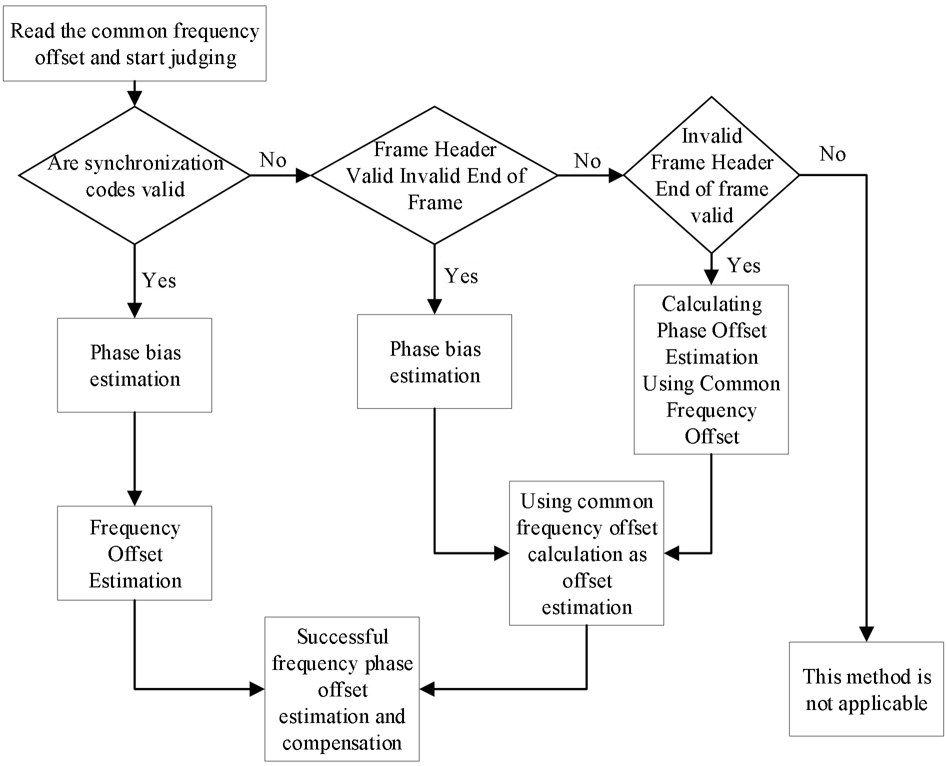

Fig. 2: Flow chart of frequency offset estimation and compensation method based on intra group joint.

This method defines an invalid synchronization sequence, that is, when the synchronization sequence at the beginning or end of a pulse is determined to be affected by interference and unable to perform frequency offset correction, the synchronization sequence is determined to be invalid.

This method defines the common frequency offset within the group, which can be regarded as the same frequency offset throughout the entire duration range of the pulse group. The average frequency offset can be calculated as the common frequency offset by using pulses with effective synchronization codes at the beginning and end of the frame.

When the frame head or frame tail of a certain pulse is determined as an invalid synchronization sequence, the effective common frequency offset of other pulses in the same pulse group will be used to estimate the frequency and phase offset of that pulse.

Determine the correlation values obtained from phase bias estimation. Here, a lower limit can be designed. If the value of the frame header or frame tail after relevant calculations is less than this threshold, it can be determined that the frame header or frame tail is invalid as a receiving synchronization sequence.

When the frame head or frame tail of a certain pulse is determined as an invalid synchronization sequence, the effective common frequency offset of other pulses in the same pulse group will be used to estimate the frequency and phase offset of that pulse.

There are two main situations that have an impact on frequency and phase offset estimation during the operation of communication systems. The first type is symbol loss caused by the inability of a single transceiver to transmit and receive simultaneously, and the second type is an increase in error rates caused by a low signal-to-noise ratio. Among them, the inability of a single transceiver to transmit and receive simultaneously can lead to symbol loss, which has three effects on the estimation of frequency and phase offset at the beginning and end of the frame within a single pulse. The first method has no impact on the beginning and end of the frame, and can be considered as a normal situation. The second type is that only one of the frame headers or footers has an impact, while the third type is that both the frame headers and footers have conflicts.

The main purpose of this optimization design is to optimize the second situation caused by transmission and reception conflicts, while taking into account the low signal-to-noise ratio situation and determining a joint and unified decision threshold. For the second scenario of receiving and sending conflicts, due to only one effective synchronization code, frequency offset estimation cannot be performed, and the unified effective frequency offset of the pulse group will be used for frequency offset estimation. If there is a loss of frame end symbols, it has no impact on the phase offset estimation of the pulse. If the frame header symbol is lost, the phase offset estimation of the pulse will use the phase offset at the end of the frame plus the effective frequency offset as the frame header frequency offset estimation.

4. Experimental Results

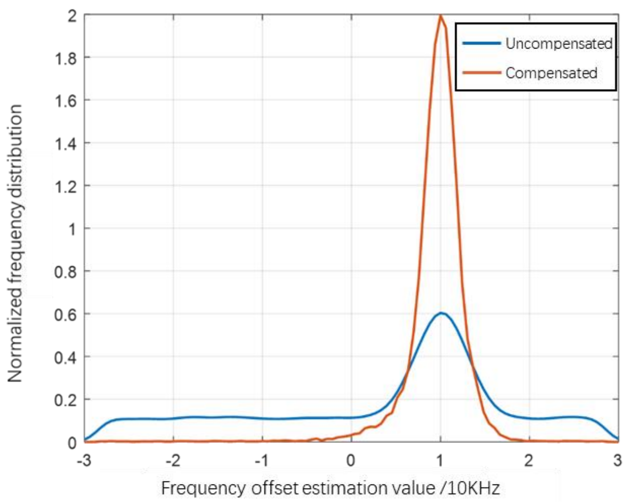

Fig. 3: Comparison of the distribution of frequency offset estimates using this method and not using this method.

Taking the frequency offset size of 10kHz as an example, when the signal-to-noise ratio is 10dB, the receiver estimates the frequency of the received signal. Under collision conditions, the frequency estimation results of the pulse are shown in Fig. 3 when comparing whether the frequency and phase offset compensation method proposed in this article is used.

The horizontal axis represents the distribution range of estimated frequency offset values for each pulse, while the vertical axis represents the magnitude of different estimated values. It is evident that the accuracy of frequency estimation is significantly improved after using the compensation method proposed in this article.

Afterwards, tests are conducted under different signal-to-noise ratios, and the results are shown in the Fig. 4.

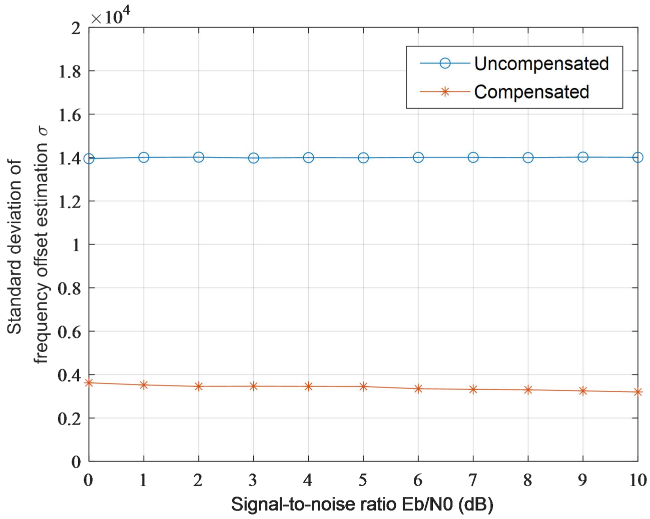

Fig. 4: Comparison diagram of whether to use this method for frequency offset estimation standard deviation under different signal-to-noise ratios.

From Fig. 4, it can be seen that in the range of 0-10dB, the standard deviation of frequency offset estimation after compensation using this method is much smaller than that of traditional frequency offset estimation algorithms without this method. This indicates that after using this method, the accuracy of frequency offset estimation can be effectively improved under various signal-to-noise ratios.

Afterwards, under the condition of collision loss of 35% information, the relationship between the error rate and signal-to-noise ratio after demodulation was tested, and the results are shown in Fig. 5.

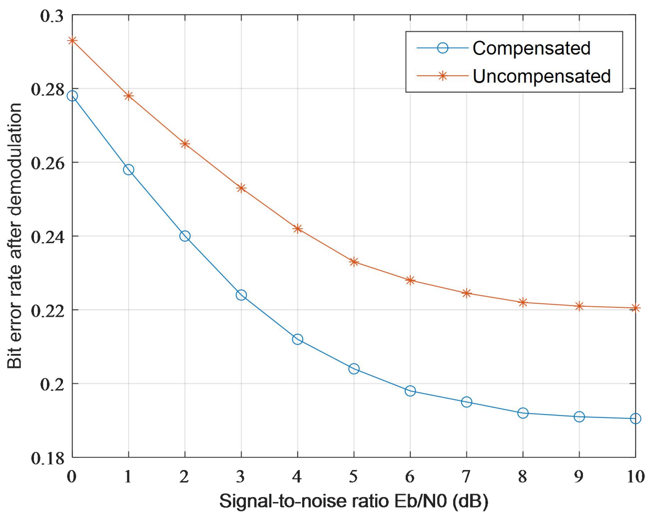

Fig. 5: Comparison diagram of error rate and signal-to-noise ratio after compensation demodulation under collision conditions.

It can be seen that the demodulated signal compensated by this method can achieve a reduction in bit error rate within a large signal-to-noise ratio range.

In general communication systems, the decoding process of error correction encoding is also required after demodulation. Using the commonly used 1/3Turbo encoding as error correction encoding, test whether this method has an impact on the final packet error rate in collision situations.

Through practical testing, it has been found that in a pulse group with a signal duty cycle of 35% and a frequency offset of 8kHz, there is a conflict between transmission and reception. The results of optimizing the system using the compensation method proposed in this article are shown in Fig. 6.

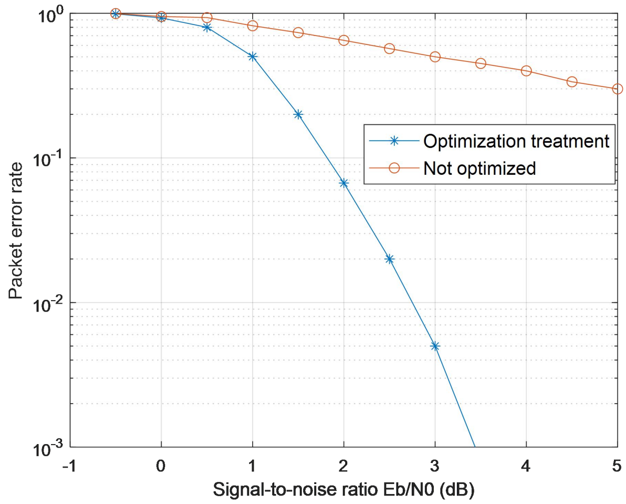

Fig. 6: Schematic diagram of packet error rate and signal-to-noise ratio after optimization under frequency offset of 8kHz.

From Fig. 6, it can be seen that the system with frequency offset optimization can achieve a packet error rate of less than one thousandth under high signal-to-noise ratio conditions, while without optimization, even under high signal-to-noise ratio conditions, the packet error rate is very high. It can be seen that frequency offset optimization and compensation greatly improve the anti-interference ability of the system.

5. Conclusion

This article was based on traditional pulse waveform high dynamic communication systems, and proposed an optimization algorithm for frequency offset estimation to address the phenomenon of synchronization code loss under collision conditions that cannot be accurately estimated. It solved the problem that the frequency offset estimation algorithm fails due to the loss of synchronization code in the presence of collisions, and the receiver cannot demodulate the received information correctly. This method was computationally simple, occupied less resources, and can greatly improve the anti-interference ability of the system. It had very practical significance in engineering applications.

6. References

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