Design of OFDM Joint Synchronization Algorithm Based on Cyclic Prefix

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Abstract: By studying the Maximum Likelihood (ML) algorithm and applying it to Orthogonal Frequency Division Multiplexing (OFDM) system, we analyze its performance. OFDM system has obvious advantages over other wireless communication systems, but it also has disadvantages, such as being sensitive to synchronization errors. The ML algorithm can solve this shortcoming of OFDM system. ML algorithm uses the redundant information carried by the cyclic prefix in OFDM code element. At the same time, ML algorithm calculates its maximum likelihood estimation algorithm to complete the code element timing synchronization and carrier frequency synchronization. Compared with other synchronization algorithms, ML algorithm can complete initial capture and synchronous tracking in one step, so it is widely used in OFDM systems. In this paper, we build a traditional OFDM system and apply the ML algorithm to OFDM synchronization simulation. By changing the design of relevant parameters, we describe the ML algorithm in detail and obtain the same results as the theory.

1. Introduction
Since the beginning of the 21st century, with the gradual improvement of the degree of informatization, information exchange and resource sharing have become extremely convenient. People have put forward higher requirements for the effectiveness and reliability of communication technology. So the fourth generation mobile communication system based on multi-functional integration began to develop gradually[1].

OFDM is a multi-carrier orthogonal modulation technique with high spectrum utilization, strong ability to be undisturbed by other signals and multi-path fading ability caused by multipath propagation. The principle is that the high-speed serial data stream is decomposed and modulated, then sent to several parallel orthogonal sub-channels, so that the code element width of each sub-channel is larger than the channel delay expansion. However, since there are many orthogonal carriers in the orthogonal frequency division multiplexing system, it has higher orthogonality to the system than the traditional single carrier system. When OFDM signals are propagated in the system, they are affected by channel characteristics and other signals, which may result in mismatch between the sender and receiver, destroy the orthogonality between carriers, and cause interference between subcarrier (Inter-carrier interference, ICI). Therefore, a good performance synchronization algorithm is particularly important for OFDM systems.

ML algorithm is a mature algorithm in OFDM synchronization algorithm, which is proposed by Van de Beek. The ML algorithm uses the redundant information carried by the cyclic prefix in the OFDM symbol and performs a maximum likelihood algorithm to calculate the symbol timing
synchronization and the carrier frequency synchronization[2].

2. Fundamentals of OFDM Technology

2.1 OFDM mathematical modulation model

OFDM technology is a kind of multi-carrier modulation technology, and its difference from the general multi-carrier technology is that its carriers are mutually orthogonal.

The multicarrier modulated signal \(s(t)\) can be written as the following plural form:

\[
s(t) = \sum_{n=0}^{N-1} d_n(t) e^{j\omega_nt} \tag{1}
\]

\(\omega_n = \omega_0 + \Delta\omega\) is the carrier frequency of the nth carrier. \(d_n(t)\) is the complex signal above the nth subcarrier. If it remains constant over a code-meta period \(d_n(t)\), \(d_n(t) = d_n\). Set the signal sampling frequency to \(1/T\), so:

\[
s(kT) = \sum_{n=0}^{N-1} d_n e^{j(\omega_0+n\Delta\omega)kT} \tag{2}
\]

There are N sample values in one symbol period: \(\tau = NT\). Without losing generality, set \(\omega_0 = 0\). So

\[
s(kT) = \sum_{n=0}^{N-1} d_n e^{j(n\Delta\omega)kT} \tag{3}
\]

Comparing with Inverse Discrete Fourier Transform (IDFT) form (coefficient neglect), it can be seen that if \(d_n\) is regarded as a frequency domain sampling signal, \(s(kT)\) is its corresponding time domain signal. If the following formula is established

\[
\Delta f = \frac{1}{nT} = \frac{1}{\tau} \tag{4}
\]

Then the above formula is equivalent to the IDFT transformation method.

If the carrier time interval is selected as \(1/\tau\), the orthogonality of the signal subcarriers is maintained, and the process can also be defined by DFT. In other words, OFDM system adjustment part can be realized directly by digital signal processing, and doesn’t need to be implemented by using complex algorithms. So the complexity of the system is reduced, and the high computing speed and high computation accuracy can also be satisfied[3-4].

2.2 OFDM Physical Framework

At the transmitting end of the OFDM system, firstly, the data stream to be transmitted is divided into multiple signals by a splitter, and each of them need to be scrambled, and channel forward error correction coding is added. Then, through the symbol interleaver, the multiplexed signals are combined on the same transmission line, and the parallel transmission signals are converted into serial transmission signals. The data signal is then modulated, aimed to form a transmitted frame. And what is embodied here is symbol timing synchronization. Then, the Inverse Fast Fourier Transform Algorithm (IFFT) process is used to calculate the signal in the frequency domain into the time domain. A guard interval is then inserted to accommodate symbol crosstalk. Then, through digital-to-analog conversion, the digital signal is converted into an analog signal, where the signal waveform begins to appear. Then, after quadrature modulation, the signal is amplified, and the transmitted signal power is increased, and then transmitted to the channel.

After the signal reaches the receiving end, it is amplified and then officially enters the demodulation process. In the first step, analog-to-digital conversion is performed, and the analog signal in the channel is converted into a digital signal for subsequent arithmetic processing. Then enter the frequency offset module. Due to the influence of the channel, the received signal at the receiving end is not completely orthogonal to the local carrier, so frequency compensation is needed. Here, three kinds of synchronization occur: symbol synchronization, frequency synchronization, and sampling clock. Synchronize. The sampling clock controls the sampling frequency, and then sends the sampling
frequency value to the crystal oscillator, which controls the frequency of the analog-to-digital
conversion module. Frequency synchronization mainly uses a synchronization algorithm to calculate
the amount of frequency offset. After frequency compensation, a Fast Fourier Transformation (FFT)
operation is performed on the received signal to convert the time domain signal into a frequency
domain signal. The latter phase correction, channel equalization, and demapping are all corresponding
to the corresponding processes at the transmitting end, except that the transmitting end is a modulation
process and the receiving end is a demodulation process. Finally, the corresponding information code
stream is recovered by decoding and descrambling[5].

3. Introduction of ML Algorithm

Due to the limitation of the modulation mode of the OFDM system, the two synchronization processes
need to be completed before the signal is demodulated. The first step is to find the boundary range of
the OFDM signal and the best sampling time point, in order to minimize interference between the
sub-carriers and the inter-symbol interference. The second step needs to be correctly calculated the
frequency offset between carriers, in order to ensure the orthogonality between carriers. The ML
algorithm inserts a cyclic prefix in front of the transmitted OFDM data stream, and calculates the
correlation between cyclic prefixes at the receiving end to calculate the windowing position and
frequency offset[6].

The following is the mathematical principle of OFDM algorithm.

In the OFDM system, the baseband form of the transmitted signal at the transmitting end can be
expressed as

$$s(k) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} c_m e^{j(2\pi/N)km}$$  (5)

Because the actual received signal is affected by delay, frequency offset and gaussian white noise,
the actual received signal should be:

$$r(k) = s(k - \theta) e^{j2\pi \epsilon} + n(k)$$  (6)

In the above formula, s(k) is the transmitter transmitting signal, and n(k) is the channel noise,
and \(\theta\) is the timing offset, and \(\epsilon\) is the normalized carrier frequency deviation.

The ML algorithm considers both the symbol timing synchronization position and the carrier
frequency deviation, so the maximization of the log likelihood function is completed in two steps:

$$\max_{(\theta, \epsilon)} \Lambda(\theta, \epsilon) = \max_\theta \max_\epsilon \Lambda(\theta, \epsilon) = \max_\theta \Lambda(\theta, \hat{\epsilon}_{ML})$$  (3)

The maximum carrier offset can be based by the expression of \(\Lambda(\theta, \epsilon)\), which can set to \(0\).
When the cosine value is 1, the maximum carrier frequency offset of \(\Lambda(\theta, \epsilon)\) can be obtained. So the ML of
\(\epsilon\) is estimated as:

$$\hat{\epsilon}_{ML}(\theta) = -\frac{1}{2\pi} \angle \gamma(\theta) + n$$  (7)

In the above formula, n is an integer, taking into account that the general carrier frequency
deviation should be in a relatively small range, so as to take the n=0. At this point, the logarithmic
likelihood function is

$$\Lambda(\theta, \hat{\epsilon}_{ML}(\theta)) = |\gamma(\theta)| - \rho(\theta)$$  (8)

So, \(\theta, \epsilon\)’s combined ML is estimated to be
4. Simulation Results and analysis

Figure 4.1 shows the number of subcarrier \( N = 1024 \), cyclic prefix length \( L = 128 \), signal-to-noise ratio \( SNR = 70 \), frequency deviation \( \varepsilon = 0.25 \), channel situation is the experimental results of additive gaussian white noise.

\[
\hat{\theta}_{ML} = \arg \max \{ |\gamma(\theta)| - \rho(\theta) \} \tag{9}
\]

\[
\hat{\varepsilon}_{ML} = -\frac{1}{2\pi} \angle \gamma(\hat{\theta}_{ML}) \tag{10}
\]
When we use MATLAB for simulation, because the ML algorithm performs a correlation operation on each function value of the cyclic prefix, the calculation amount is extremely large, and it takes a long time to obtain the experimental result. In actual operation, the amount of data of the signal will be larger, and the waiting time needs to be longer, so the ML algorithm is not suitable for the transmission of the burst signal.

According to graph a, it can be seen that the maximum value of the likelihood function is probably the position of the N=120, and according to the setting of the experimental data, the best window opening position is N=128. From this, it can be seen that the ML algorithm for the best window opening position calculation is still more accurate. Moreover, the peak of function value image is prominent, and it is easy to get the best window opening position, which reduces the difficulty of physical level realization. From the a diagram can also be found that the waveform has a periodic, every 1300 points on the peak, but also to meet the composition of the signal is the cycle prefix + useful signal.

The data set by the experiment is that the simulation offset value obtained by the frequency offset e=0.25, b graph’s result is between -0.5-0.5, and it can be found that the frequency offset is the most similar to the setting value when the optimal window opening position can be obtained: the correct optimal window opening position affects the accuracy of the frequency offset value. Therefore, for the ML algorithm, it is very important to get the accurate window opening position.

In practical applications, adding a cyclic prefix in front of the signal reduces the effectiveness of the system, while the ML algorithm relies on the length of the cyclic prefix. When the length of the cyclic prefix is low, the calculation of the window opening position of the system is not very accurate, which affects the calculation of the frequency offset value, resulting in ICI and ISI, which greatly affects the reliability of the system.

During the simulation process, we change the value of the cyclic prefix while keeping other conditions unchanged. When the value of cyclic prefix is L=16, get the following two result graphs:
From the comparison of the above four figures, the ML algorithm requires a very high length of the
cyclic prefix. In this way, the effectiveness of the system will be reduced in practical applications.

5. Conclusion
The application of ML algorithm in OFDM synchronization algorithm is described in this summary. OFDM technology is a kind of more efficient parallel multi-carrier data transmission technology. The main advantages are: High spectrum utilization, anti-multipath fading ability is strong. However, because OFDM system is very sensitive to synchronization error, this has become the main threshold to limit the development of OFDM technology. Therefore, it is very important to study the symbolic timing estimation and carrier frequency offset estimation of OFDM system.

ML algorithm is an algorithm based on cyclic prefix and using maximum likelihood function. Its advantage is that it can get the more accurate window opening position, reduce the interference between symbols, and can also synchronize the frequency offset value of the system. In practical application, the complexity of the algorithm and the maneuverability of physics are reduced. However, because the ML algorithm depends on the length of the loop prefix, this is where it will need to be addressed in the future.

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