Deep Learning Network for Frequency Offset Cancellation in OFDM Communication System

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Abstract. A deep learning network for OFDM system is proposed to eliminate the CFO (carrier frequency offset) interference in OFDM system. The CFO greatly reduces the BER performance for the communication system. The frequency offset interference introduced needs to be eliminated before signal demodulation. Therefore, we propose the method to eliminate weights by establishing a deep learning network, and then form the optimization elimination weight matrix through iteration. Among them, the hidden layer and weights are trained and fine-tuned in the forward direction to cancel the interference introduced by CFO. Compared with MMSE and LS algorithm, the proposed deep learning network greatly improves the bit error rate performance. The simulation has proved that the proposed deep learning network algorithm has BER performance in OFDM systems.

Keywords: Deep learning network · Carrier frequency offset · BER

1 Introduction

For multi-user detection of OFDM links communication systems, signal interference is not only due to the frequency selective fading of the multipath channel, but greater interference induced by the carrier frequency offset. When the number of subcarriers in the system is determined, the frequency offset range is larger, and the interference of multi-user access is more serious. Therefore, the access interference introduced by the difference of multi-user CFO is the key to the detection of the uplink user of the low-orbit broadband satellite communication system.

For this kind of problem, many documents have studied the problem of OFDM (Orthogonal Frequency Division Multiple Access) multi-user access interference cancellation. Early literature used traditional single-user detection algorithms to resist multi-user interference. Literature [1] proposed a multi-user interference cancellation algorithm based on the Least Square (LS) criterion and based on the Minimum Mean Square Error (Minimum Mean Square Error, MMSE) criterion of multi-user interference cancellation algorithm, but the algorithm needs to obtain more prior knowledge, and the cancellation accuracy is not high. Literature [2] proposes an iterative way to eliminate

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multi-user access interference, but the algorithm needs to eliminate sub-carrier interference one by one, and the complexity of the algorithm is relatively high. Choi proposed a time-domain multi-user carrier frequency offset compensation algorithm [3], but the accuracy is poor. Pun proposed the iterative detection algorithm [4], which requires larger number of matrix operations after each iteration operation, which is relatively complex. Literature [5] proposed a SIC algorithm to eliminate multi-user access interference. On this basis, the literature [6] proposes to sort the sub-carriers according to the order to improve the elimination accuracy of the SIC algorithm to a certain extent. Literature [7] sorts the sub-carriers according to power, and literature [8] sorts the sub-carriers according to the Signal Interference and Noise Ratio (SINR). Although the ordering of sub-carriers improves the accuracy of SIC algorithm elimination to a certain extent, the elimination of sub-carrier interference increases the signal processing delay of the SIC algorithm, and also affects the achievability of the SIC algorithm, and the SIC algorithm is affected by the initial value of each user's frequency offset estimation. The degree of influence is greater.

Literature [9] analyzes the frequency offset interference of OFDM. Literature [10] uses virtual sub-carriers to eliminate carrier frequency offset interference. This algorithm uses odd-numbered carriers to transmit complete OFDM symbols, and all even-numbered carriers are virtual carriers. Literature [11] uses the Expectation Maximum (EM) algorithm to iterate to eliminate frequency offset interference, and gives the frequency offset elimination range, and also analyzes the characteristics of the frequency domain interference matrix introduced by frequency offset interference. Some documents use Carrier Frequency Offset (CFO) estimation to eliminate frequency offset interference. For CFO estimation, literature [12–14] uses cyclic prefix for CFO estimation, and improves CFO estimation performance by increasing the length of cyclic prefix, but increasing the cyclic prefix length will reduce the system bandwidth utilization. Literature [15] adopts a decision-oriented blind estimation algorithm of carrier frequency offset, which uses the phase of the demodulated signal to estimate the frequency offset. Literature [16] adopts the maximum likelihood criterion (Maximum Likelihood, ML) criterion for joint estimation of carrier frequency offset and channel, but the complexity is relatively high. Literature [17] modifies the cost function to reduce the complexity, but the range of frequency offset estimation is limited. Literature [18] applies phase-locked loop technology (PLL, Phase Locked Loop) to CFO tracking of OFDM system, but the algorithm has a slower convergence speed and a limited tracking range of carrier frequency offset. In order to be suitable for time-varying multipath channels, literature [19] uses training sequences for joint estimation of CFO and channel, but the accuracy is affected by the length and number of training sequences. Many algorithms cannot be directly applied to OFDM communication systems due to the complexity of engineering, or the length of the training sequence is too long, or the convergence speed is slow.

2 System Model

2.1 Signal Processing Model

The following analyzes the performance of OFDM under Doppler frequency shift. Define $x(n)$ is the time-domain signal at the transmitter; $h(n, l)$ is the L-path channel impulse response, and the time-domain signal $r(n)$ at the receiver is,

$$y(n) = \sum_{l=0}^{L-1} x(n)h(n, l) \tag{1}$$

α is the relative FO interference factor, and N is the number of OFDM carriers. After relative motion produces interference, the received signal is expressed as

$$r(n) = \sum_{l=0}^{L-1} x(n)h(n, l)e^{j2\pi n\alpha/N} \tag{2}$$

Perform N-point FFT on the received signal with frequency offset, and after parallel-to-serial conversion, the frequency domain signal $R(k)$ is obtained, which can be expressed as

$$R(k) = X(k)H(k)P(0) + \sum_{\substack{i=0 \\ i\neq k}}^{N-1} X(l)H(l)P(i-k) \tag{3}$$

Among them, $H(k)$ is the frequency domain response of the channel, and $P(k)$ is the frequency domain interference introduced by the frequency offset, which can be expressed by a matrix as

$$P = \begin{bmatrix} p(0) & \cdots & p(N-1) \\ p(N-1) & \ddots & p(N-2) \\ \vdots & p(0) & \vdots \\ p(1) & \cdots & p(0) \end{bmatrix} \tag{4}$$

Equation (4) can obtain the interference matrix P, which is a Toeplitz matrix. The element can be expressed as

$$p(k) = p(k+N) \tag{5}$$

where, $(\cdot)^{-1}$ is the inverse of the matrix, and $(\cdot)^{H}$ is the conjugate transpose of the matrix. It can be expressed as

$$P^{-1} = P^{H} \tag{6}$$

The elements of a matrix can be written in recursive form

$$p(k) = \Gamma \cdot p(k-1) = \Gamma^2 \cdot p(k-2) = \cdots = \Gamma^i \cdot p(0) \tag{7}$$

The first term of Eq. (7) represents the non-carrier interference part.

$$P(i-k)=\frac{\sin(\pi(i+\alpha-k)}{N\sin(\frac{\pi}{N}(i+\alpha-k))}\cdot\exp(j\pi(\frac{N-1}{N})(i+\alpha-k)) \tag{8}$$

The formula (8) also shows that due to the influence of frequency offset, which can be expressed as

$$\left|\alpha_{k,i}\right|^2=\frac{\sin^2(\pi[(i-k)+\alpha])}{N^2\cdot\sin^2(\pi[(i-k)+\alpha]/N)} \tag{9}$$

3 System Model

3.1 Signal Processing Model

The optimization goal is the minimum mean square (MSE) between the received signal and the desired output signal. The equation means that the optimized cost function exhibits a strong nonlinear behavior. Therefore, it is difficult to solve this problem with linear methods and maximum likelihood algorithms.

Therefore, a non-linear weight solution method based on deep learning network is proposed to solve the non-linear problem. The OFDM communication system is seriously affected. Figure 1 shows a typical for signal processing flow. Both the transmitter and the receiver know the training symbols, and they are also considered reference symbols. The deep learning network can iteratively converge through training symbols, and the trained network has the optimal weight and can be used for frequency offset cancellation.

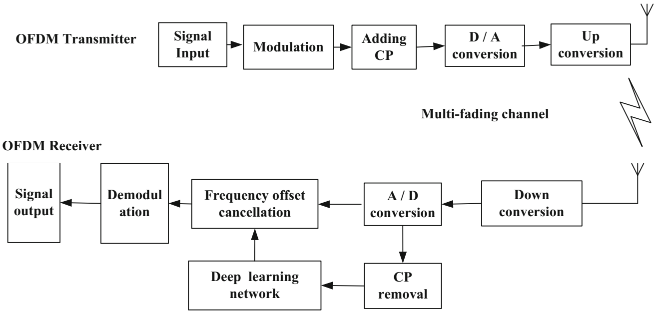

Fig. 1. Signal processing block diagram in OFDM link

3.2 Deep Learning Network Establishment for Carrier Frequency Offset Cancellation

Define the objective function can be expressed as,

$$J(n)=\sum_{n=1}^{N}\|\phi(n)-r(n)\|^2+\tau^n\cdot\|w(n)\|^2 \tag{10}$$

where, τ is exponential weighting factor. $w(n)$ represents the deep learning network weight. $r(n)$ represents the output for the deep learning network

Define,

$$J(n) = \sum_{n=1}^{N} \left\| \phi(n) - w^{*}(n) \cdot r(n) \right\|^{2} + \tau^{n} \cdot \| w(n) \|^{2} \tag{11}$$

Optimization,

$$w^{*} = \underset{w \in C^{nxk}}{\arg\min}\, J(n) \tag{12}$$

$e(n)$ is defined as error.

We obtain,

$$e(n) = \phi(n) - w^{*}(n) r(n) \tag{13}$$

The gradient vector is,

$$\frac{\partial J(n)}{\partial w(n)} = 0 \tag{14}$$

Further, we could obtain,

$$w(n) = \left[\sum_{n=1}^{N} \phi(n)\phi^{*}(n) + \lambda^{n} I \right]^{-1} \cdot \left[\sum_{n=1}^{N} \phi(n)\phi^{*}(n) \right] \tag{15}$$

Define,

$$\Lambda(n) = \sum_{n=1}^{N} \phi(n)\phi^{*}(n) + \lambda^{n} I \tag{16}$$

Further,

$$\Lambda(n) = \left[\sum_{n=1}^{N-1} \phi(n)\phi^{*}(n) + \lambda^{n-1} I \right] + \phi(n)\phi^{*}(n) \tag{17}$$

$$\Lambda(n) = \lambda \Lambda(n-1) + \phi(n)\phi^{*}(n) \tag{18}$$

We could also obtain,

$$w(n) = w(n-1) + \Lambda^{-1}(n-1)\phi(n)e^{*}(n-1) \tag{19}$$

3.3 Proof of Validity

Substituting $e^{j2\pi\xi n/N}$ into (5), we finally get,

$$e(n) = \phi(n) - r(n) = \phi(n) - \phi(n) \cdot e^{j2\pi\alpha n/N} \cdot w(n) = \phi(n) \cdot \left[1 - e^{j2\pi\alpha n/N} \cdot w^*(n)\right] \tag{20}$$

Updating $w(n)$, we could obtain that D is also a constant value.
We obtain as,

$$w(n) = w(n-1) + e^*(n) \cdot \phi(n) = w(n) + D \cdot \left[e^{j2\pi n\alpha/N} - w(n)\right] \tag{21}$$

$$w(n) = (1-D)^n \cdot w(0) + D \cdot (1-D)^{n-1} \cdot \sum_{n=1}^{N-1} (1-D)^{-n} \cdot e^{j2\pi n\alpha/N}, n > 0 \tag{22}$$

Taking the limit, we could obtain,

$$w_\infty = \lim_{n\to\infty} w(n) = \frac{D}{e^{j2\pi\alpha/N} - (1-D)} e^{j2\pi n\alpha/N} \tag{23}$$

After mathematical operation,

$$r(n) = w_\infty^* \cdot w(n) = \frac{D}{e^{-j2\pi\xi/N} - (1-D)} e^{-j2\pi n\alpha/N} \cdot x(n) \cdot e^{j2\pi n\alpha/N} = \frac{D}{e^{-j2\pi\xi/N} - (1-D)} \cdot \phi(n) \tag{24}$$

From Eq. (24), we can obtain that the output can be compensated with weights of deep learning network.

4 Experimental Classification Results and Analysis

Assuming that the required signal transmission bit rate of the OFDM link of the system is 40 Mbit/s. At this time, the maximum relative carrier frequency deviation is 0.35. Using BPSK modulation, each sub-carrier in each OFDM symbol can transmit 1 bits, and 240/1 = 240 sub-carriers are required to meet the transmission rate requirements. 4 more zero-padded sub-carriers can be added to facilitate the implementation of 256-point FFT/IFFT. $\alpha_{\max}$ is the maximum Normalized frequency offset, which is defined as the ratio between frequency offset and bandwidth.

We simulate the relationship between BER and SNR through frequency offset cancellation performance. The relationship between the bit error rate (BER) and the average SNR is shown in Fig. 2 and Fig. 3, respectively. The results of the iterative algorithm and the compensation method proposed in the no frequency offset, no cancellation, MMSE algorithm, LS algorithm are given. By investigating these numbers, it can be clearly shown that no cancellation will be affected by ICI and has a high error background. The MMSE algorithm performs well because ICI and MUI can be deleted. The performance of the deep learning network algorithm is better than that of the MMSE algorithm because it can significantly reduce the impact of noise enhancement.

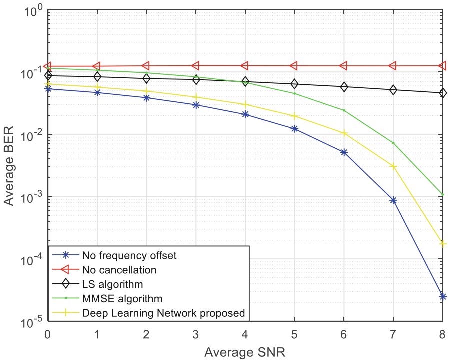

Fig. 2. BER curves under different average SNR, $\alpha_{\max} = 0.05$

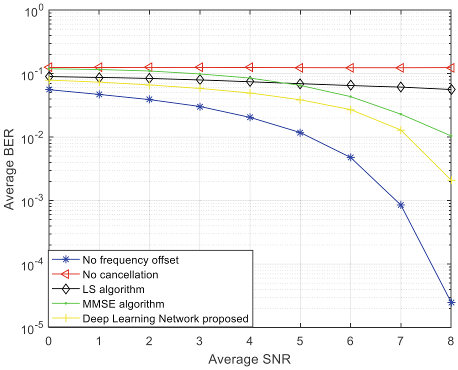

Fig. 3. BER curves under different SNR, $\alpha_{\max} = 0.35$

5 Conclusion

A deep learning network for OFDM system is proposed to eliminate the carrier frequency offset interference of OFDM system. The carrier frequency offset greatly reduces the bit error rate performance of the communication system. The frequency offset interference introduced by the carrier needs to be eliminated before signal demodulation. First, we establish frequency offset cancellation weights through a deep learning network. Therefore, we propose a way to eliminate weights by establishing a deep learning network, and form a system optimization elimination weight matrix through iteration. Secondly, we use positive fine-tuning to train the hidden layer and weights. It has been proved that in the same training sequence, the frequency offset-assisted deep learning network model has higher performance on communication error rate.

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References

1. Cao, Z.R., Tureli, U., Yao, Y.D.: Analysis of two receiver schemes for interleaved OFDMA uplink. In: IEEE International Conference on Signals, Systems and Computers, vol. 2, pp. 1818–1821 (2002)
2. Huang, M., Chen, X., Zhou, S., et al.: Iterative ICI cancellation algorithm for uplink OFDMA system with carrier-frequency offset. In: IEEE International Conference on Vehicular Technology, vol. 3, pp. 1613–1617 (2005)
3. Choi, J.H., Lee, C., Jung, H.W., et al.: Carrier frequency offset compensation for uplink of OFDM-FDMA systems. IEEE Trans. Commun. Lett. **4**(12), 414–416 (2000)
4. Pun, M.O., Morelli, M., Kuo, C.J.: Iterative detection and frequency synchronization for OFDMA uplink transmissions. IEEE Trans. Wirel. Commun. **6**(2), 629–639 (2007)
5. Fantacci, R., Marabissi, D., Papini, S.: Multiuser interference cancellation receivers for OFDMA uplink communications with carrier frequency offset. In: IEEE International Conference on Globecom 2004, vol. 5, pp. 2808–2812 (2004)
6. Trajkovic, V.D., Rapajic, P.B., Kennedy, R.A.: Adaptive ordering for imperfect successive decision feedback multiuser detection. IEEE Trans. Commun. **56**(2), 173–176 (2008)
7. Tevfik, Y., Huseyin, A.: Carrier frequency offset compensation with successive cancellation in uplink OFDMA systems. IEEE Trans. Wireless Commun. **6**(10), 3546–3551 (2007)
8. Hou, S.W., Ko, C.: Intercarrier interference suppression for OFDMA uplink in time and frequency selective rayleigh fading channels. In: IEEE International Conference on Vehicular Technology, pp. 1438–1442 (2008)
9. Weeraddana, P., Rajatheva, N., Minn, H.: Probability of error analysis of BPSK OFDM systems with random residual frequency offset. IEEE Trans. Commun. **57**(1), 106–116 (2005)
10. Huang, D., Letaief, K.B.: An interference cancellation scheme for carrier frequency offsets correction in OFDMA systems. IEEE Trans. Wireless Commun. **53**(7), 1155–1165 (2005)
11. Yong, S., Xiong, Z., Wang, X.: EM-based iterative receiver design with carrier-frequency offset estimation for MIMO OFDM systems. IEEE Trans. Commun. **53**(4), 581–586 (2005)
12. Lashkarian, N., Kiaei, S.: Class of cyclic-based estimators for frequency-offset estimation of OFDM systems. IEEE Trans. Commun. **48**(12), 2139–2149 (2000)
13. Krongold, B.S.: Analysis of cyclic-prefix correlation statistics and their use in OFDM timing and frequency synchronization. In: IEEE International Conference on Signals, Systems and Computers, pp. 1466–1470 (2005)
14. Stoica, P., Soderstrom, T.: Statistical analysis of MUSIC and subspace rotation estimates of sinusoidal frequencies. IEEE Trans. Signal Process. **39**(8), 1836–1847 (1991)
15. Visser, M.A., Zong, P.P., Bar-Ness, Y.: A novel method for blind frequency offset correction in an OFDM system. In: IEEE International Conference on Personal, Indoor and Mobile Radio Communications, vol. 2, pp. 816–820 (1998)
16. Chiavaccini, E., Vitetta, G.M.: Maximum-likelihood frequency recovery for OFDM signals transmitted over multipath fading channels. IEEE Trans. Commun. **52**(2), 244–251 (2004)
17. MerliFZ, V.: Blind feedforward frequency estimation for OFDM signals transmitted over multipath fading channels. IEEE Trans. Wireless Commun. **6**(6), 2055–2059 (2007)
18. Kuang, L.L., Ni, Z.Y., Lu, J.H., et al.: A time-frequency decision-feedback loop for carrier frequency offset tracking in OFDM systems. IEEE Trans. Wireless Commun. **4**(2), 367–373 (2005)
19. Ylioinas, J., Juntti, M.: EM based iterative receiver for joint decoding and channel parameter estimation in space-frequency turbo coded OFDM. In: IEEE International Conference on Personal, Indoor and Mobile Radio Communications, pp. 1–5 (2006)