2014 International Symposium on Nonlinear Theory and its Applications
NOLTA2014, Luzern, Switzerland, September 14-18, 2014

An Improved Doppler Frequency Offset Estimation Algorithm in the Indoor OFDM Communication System

Di He
Academy of Information Technology and Electrical Engineering,
School of Electronic Information and Electrical Engineering,
Shanghai Jiao Tong University,
Shanghai, China
Email: dihe@sjtu.edu.cn

Abstract —OFDM(orthogonal frequency division multiplexing) is a multi-carrier digital modulation technique. It's likely to be used in next generation wireless communication and indoor visible light communication (VLC) system. When OFDM is used in these communication systems, Doppler frequency shift will become an important technical barrier because OFDM is sensitive to frequency offset. Especially in the indoor environment, Doppler frequency shift can destroy the orthogonal characteristic between sub-carriers in OFDM system. In this paper, we analyze the performance of OFDM system in the movement environment and propose a new Doppler spread estimation algorithm to improve the BER performance. Theoretical analyses and computer simulations present the advantages of the proposed approach especially under the indoor environment.

Key words — indoor communication environment, OFDM, Doppler frequency shift, frequency offset estimation

I. INTRODUCTION

OFDM(orthogonal frequency division multiplexing)[1] is a multi-carrier digital modulation technique. Its basic idea is to divide a high speed data string to some low speed data strings, and all sub-carriers are orthogonal to each other. It ensures very little interference among the sub-carriers. OFDM is widely used in popular modern communication system like LTE、WLAN, etc. Because of these advantages, OFDM is likely to be used in next generation wireless communication system and indoor visible light communication (VLC) system.

OFDM has a big problem that the system is easy to be affected by frequency shift. Frequency shift occurs when an object is moving, especially in the high speed movement environment. This phenomenon is called Doppler shift. Because of the apparent Doppler shift, it will destroy the orthogonal characteristic between sub-carriers in OFDM system, and it will lead to serious Inter-Carrier Interference (ICI) [2]. Finally, there will be a substantial increase in bit error rate (BER).

Main ideas in literatures to solve this problem are divided into two types. One is the design of the Doppler frequency offset estimation algorithm. The algorithm is based on the received information to obtain the estimated value of Doppler offset. Maximum Likehood Estimation (MLE) and Minimum Estimation (ME) are often used in estimation algorithm [3~5]. But due to the fact that the accuracy or the complexity of calculation is not very perfect, the algorithm sometimes still can't be well used in the OFDM systems.

Another idea is to consider Doppler shift as a resource of diversity. Through designing diversity receivers, it can improve the system's performance. It mainly includes Doppler frequency diversity and joint multi-path Doppler diversity [6]. It was applied in CDMA system, and the further application to OFDM system has not been studied yet.

In this paper, a novel Doppler frequency offset estimation algorithm is proposed, which uses the cyclic cumulative frequency offset estimator to make the estimation more accurate. Section II gives the channel of OFDM system under the indoor OFDM communications environment and discusses the useful S&C algorithm and its disadvantages. Section III presents the novel algorithm based on the improvement of S&C algorithm. Computer simulations are shown in Section IV. And Section V gives the conclusion.

II. OFDM PERFORMANCE IN THE INDOOR COMMUNICATION ENVIRONMENT

The main idea of OFDM is to convert high-speed input data to N road low-speed data, and modulate N low-speed data onto orthogonal sub-carriers. The transmitted signal's baseband expression in a symbol is

$$x(t)=\sum_{k=0}^{N-1} s(k)\cdot e^{j2\pi k(t-t_s)/T},(t_s\le t\le t_s+T) \qquad (1)$$

where N is the number of sub-carrier; $s(k)$ is the transmitted symbol; T is the code period. In every $t=t_s$ or $t=t_s+T$, we have $x(t)=s(k)$. It is obvious that the adjacent sub-carriers of the centre frequency interval is 1/T. Then the orthogonality within sub-carriers can be ensured.

In the wireless environment, the frequency offset caused by the movement of objectives is known as Doppler shift, which can be expressed as

$$f_d=\frac{v}{\lambda}\cdot\cos\theta=f_c\cdot\frac{v}{c}\cdot\cos\theta \qquad (2)$$

where c is the speed of light; v is the moving speed of the receiving antenna; f_c is signal's carrier frequency; θ is the angle between the moving directions of receiving antenna and electromagnetic wave. In the indoor OFDM system, we suppose the maximum carrier frequency could reach 2.6G Hz. If the moving directions of the mobile object and the electromagnetic waves are the same, it means that θ may be zero. At this time, the Doppler offset reaches its maximum value, and the maximum Doppler offset may reach more than 200 Hz. The high Doppler shift can destroy the orthogonal characteristic within sub-carriers in OFDM system, and it will certainly lead to serious ICI. Finally, there will be a substantial increase in BER, which is calculated by

$$BER = \frac{bit_{error}}{bit_{transmitted}} \tag{3}$$

where bit_{error} is the number of received error bits; $bit_{transmitted}$ is the total number of transmitted bits.

Generally speaking, talking about the Doppler shift in high mobility environment, the channel fading should be incorporated, and then the Doppler shift expends to a Doppler spectrum. In this paper, we think the mobile object mainly runs on the plains. In this environment, there should be only one strong direct trail and very little (maybe just one or two) reflector trails, so the affect of Doppler shift should be mainly caused by the direct trail. In other words when a lot of reflector trails occurs, the speed of the mobile object shouldn't be too fast. So at most time, there is only one direct trail, and this paper mainly talks about how to detect the direct trail's Doppler shift.

To detect the direct trail's Doppler shift, Schmidl and Cox proposed an important algorithm in 1997 [7]. It's a two-step algorithm and here we name it S&C algorithm for simplicity in the following analyses. It constructs a specific training sequence and it is sent on even sub-carriers. The first half and second half are the same. When the frequency shift occurs, the estimation of the frequency offset can be realized according to the structural change of the received training sequence. A lot of research has been carried out to the further improvement to this algorithm such as [8]. But the algorithm in [8] is much more complicated and it is not suitable for a system which needs a rapid response. In a word, S&C based algorithm is still not good enough for OFDM system under indoor mobile communication system environment.

The analyses details can be obtained from [7], here we just choose to analyze the disadvantages for S&C algorithm applied in the indoor OFDM communication system.

In reference [7], the author failed to give evidence that S&C can be applied in a high mobility environment. That's because the high ICI caused by high speed, can't be easily overcomed by increasing SNR.

There is a formula in reference [7]:

$$S\hat{N}R = \frac{\sqrt{M(d_{opt})}}{1-\sqrt{M(d_{opt})}} \tag{4}$$

In formula (4), M is involved in the received power, d is a time index and d_{opt} is the optimal sampling time. It is obviously that SNR and M are not seriously correlative. It means that increasing SNR will also enhance the ICI, so the system performance will not linearly be improved with the increasing of SNR.

Then we give the performance of OFDM system in the indoor environment. Here we give the BER performance comparison under different SNR environment with the following simulation parameters as shown in Table I.

Table I. Simulation parameters for Fig.1

Center frequency	Sub-carrier bandwidth	Pilot number per symbol
2.6 GHz	15 KHz	10
IFFT number	Symbol length	Modulation mode
256	90 bits	QPSK

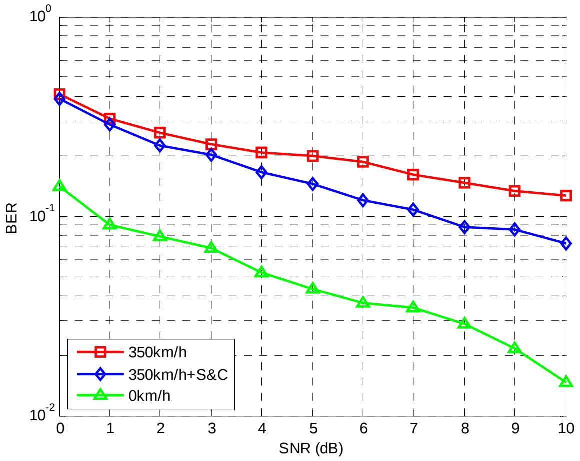

Fig.1. BER performance comparison under different SNR environments

Fig.1 shows that OFDM is not suitable for high mobile environment in above model we proposed. The BER (red line) of the OFDM system increases to the level of 10^{-1} when SNR=10dB, which cannot be acceptable in real applications. This figure also shows that S&C algorithm (blue line) doesn't work well in high mobility environment.

Based on Fig.1, improving SNR will still lead to very high BER without good enough frequency correction algorithms. From above it can be found that S&C algorithm still can't meet the demand under the objective moving environment (frequency offset is more than 200 Hz). In a word, we can't get a big offset estimation range and accuracy at the same time. That's the major contradiction of S&C algorithm under moving objective environment.

III. CYCLIC CUMULATIVE DOPPLER FREQUENCY OFFSEET ESTIMATION ALGORITHM

From last section, it is found that there is a contradiction between frequency estimation range and accuracy. That's the biggest problem of S&C algorithm in the indoor moving objective applications. Here we try to improve the algorithm combined with the indoor moving objective scene. Generally, suppose the change of the moving objective's velocity is continuous. And the adjoint frames will be sent in several *ms* if their sub-carriers' bandwidth is within several KHz. So we can get the conclusion that the variation of Doppler offset between adjacent symbols will not be over 200 Hz. And within 200 Hz, it is found that the S&C algorithm always performs well.

According to above analyses, we design a cyclic cumulative frequency offset estimation algorithm to solve the problem that S&C algorithm has poor accuracy if the estimation range is beyond 200 Hz. If the accurate value of frequency offset in one symbol period cannot be got, in the next period, add an additional value to the old estimation value to make it nearer to the accurate frequency point.

Then the problem is converted to a "one dimensional search" problem. We suppose the accurate Doppler offset is between 0 and upper bound offset, and we search it from 0 to upper bound offset. We suppose the upper bound offset to be 300 Hz. In one dimensional algorithm, Golden Section proofs to be useful and fast convergence in every one iteration. In the following sections, we choose the golden section method to realize the estimation process. The details of the estimation algorithm are given as follows:

a) When the training sequence A is sent to the estimator, calculate the fractional frequency offset and integer frequency offset with S&C algorithm. Set up a storage S, and put the first estimated offset f_A to this storage S, and it will be used in the next round frequency estimation. Set bound $f_{\min}=0$, $f_{\max}=300$.

b) When the training sequence B is sent to the estimator, use S&C algorithm to get new estimated offset f_b center around f_A. Use golden section method in area [$f_{\min}$, $f_{\max}$]:

1)If $f_b \geq f_A$, set $f_{\min}=f_A$

Else set $f_{\max}=f_A$

2)Let
$$\lambda_1 = f_{\min} + 0.328(f_{\max} - f_{\min}) \qquad (5)$$
$$\lambda_2 = f_{\min} + 0.618(f_{\max} - f_{\min})$$

3)Compare offset λ_1 and λ_2's performance in S&C algorithm

4)If λ_1 performs better, let $f_B=\lambda_1$

else $f_B=\lambda_2$.

c) If $f_{\max} - f_{\min} < \varepsilon$, stop

else go to 2)

As shown in (5), the proposed algorithm uses the golden section method to obtain the linear convergence performance. So after several rounds, we can get a good solution. Besides, as analyzed in above, the Doppler frequency offset between adjacent symbols doesn't have significant changes. So the whole system does not produce obvious oscillations caused by frequency hopping. The structure of the proposed novel estimator is shown in Fig.2.

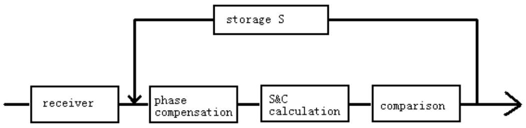

Fig.2. Structure of the proposed novel estimator

Now we discuss the performance of the novel designed algorithm.

The transmitted signal can be expressed in time domain by

$$x(t) = \sum_{k=0}^{N-1} S(k) e^{j2\pi\frac{kt}{T}} \qquad (6)$$

where $T=NT_s$ is the symbol period and T_s is the sampling interval; $S(k)$ is the signal.

Assume Δf_c is the frequency offset, $\Delta\Phi$ is the phase offset. The signal at the receiver can be expressed by

$$y(t) = x(t) \cdot e^{-j2\pi\Delta f_c t + \Delta\Phi} + \eta(t) \qquad (7)$$

where $\eta(t)$ is the additive noise.

Remove the CP and after the FFT change, we can get

$$\begin{aligned} R(k) &= \frac{e^{-j\Delta\Phi}}{N} \sum_{m=0}^{N-1} S(m) \cdot \frac{\sin[\pi N(\frac{m-k}{N} - \Delta f_c T_s)]}{\sin[\pi(\frac{m-k}{N} - \Delta f_c T_s)]} \cdot e^{j\pi(N-1)(\frac{m-k}{N}\Delta f_c T_s)} + \eta' \\ &= \frac{e^{-j\Delta\Phi}}{N} \cdot S(k) \cdot \frac{\sin(\pi N \Delta f_c T_s)}{\sin(\pi \Delta f_c T_s)} \cdot e^{j\pi(N-1)\Delta f_c T_s} + \\ &\quad \frac{e^{-j\Delta\Phi}}{N} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} S(m) \cdot \frac{\sin[\pi N(\frac{m-k}{N} - \Delta f_c T_s)]}{\sin[\pi(\frac{m-k}{N} - \Delta f_c T_s)]} \cdot e^{j\pi(N-1)(\frac{m-k}{N} - \Delta f_c T_s)} + \eta' \end{aligned} \qquad (8)$$

To focus on the Doppler frequency offset, simplify the problem by assuming the phase offset caused by the channel can be corrected at the receiver, so we have $\Delta\Phi = 0$. Then the received signal $R(k)$ should be

$$\begin{aligned} R(k) &= \frac{1}{N} \cdot S(k) \cdot \frac{\sin(\pi N \Delta f_c T_s)}{\sin(\pi \Delta f_c T_s)} \cdot e^{j\pi(N-1)\Delta f_c T_s} + \\ &\quad \frac{1}{N} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} S(m) \cdot \frac{\sin[\pi N(\frac{m-k}{N} - \Delta f_c T_s)]}{\sin[\pi(\frac{m-k}{N} - \Delta f_c T_s)]} \cdot e^{j\pi(N-1)(\frac{m-k}{N} - \Delta f_c T_s)} + \eta' \end{aligned} \qquad (9)$$

According to the design, the proposed novel algorithm can improve the estimation of $\hat{g}$. In formula, $\Delta\hat{f} = [\hat{\Phi}/(\pi T)] + (2\hat{g}/T)$. The coefficient of the amplitude $\frac{\sin(\pi N \Delta f_c T_s)}{\sin(\pi \Delta f_c T_s)}$ is $\frac{\sin(\Phi)}{\sin(\Phi/\mathrm{T})}$, so the S&C algorithm and the proposed approach have the same performances.

The same as $e^{j\pi(N-1)\Delta f_c T_s}$, by replacing Δf_c, it is nearly to be $e^{j\Phi}$. And the two algorithms also have the same performances.

The second item in the right side of (9), say $\frac{1}{N} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} S(m) \cdot \frac{\sin[\pi N(\frac{m-k}{N} - \Delta f_c T_s)]}{\sin[\pi(\frac{m-k}{N} - \Delta f_c T_s)]} \cdot e^{j\pi(N-1)(\frac{m-k}{N} - \Delta f_c T_s)}$, will lead to ICI. So, we can get that system performance will not linearly be improved with the increase of SNR. That means this variable will still be the problem by replace Δf_c .

The SNR deterioration caused by the above formula is

$$D_{nf} = 10\log\left\{1+\frac{E_b}{N_0}\left[1-\left|\frac{\sin(\pi N\Delta f_c T_s)}{N\sin(\pi\Delta f_c T_s)}\right|\right]^2\right\} - 10\log\left[\left|\frac{\sin(\pi N\Delta f_c T_s)}{N\sin(\pi\Delta f_c T_s)}\right|^2\right] \quad (10)$$

According to (9), it should be

$$D_{nf}'' = 10\log\left\{1+\frac{E_b}{N_0}\left|\frac{\sin\Phi}{N\sin(\frac{\Phi+2\hat{g}\pi}{N})}\right|^2\right\} - 10\log\left[\left|\frac{\sin\Phi}{N\sin(\frac{\Phi+2\hat{g}\pi}{N})}\right|^2\right] \quad (11)$$

Because the proposed novel algorithm uses golden section method, so after 5 rounds, Δf_c of the integer frequency offset should decrease at least $0.618^4 \approx 85\%$. Considering the oscillation and deviation of calculating integer offset, there is still much possibility to decrease Δf_c to a small range.

At this time, the SNR deterioration should be

$$D_{\mathrm{nf}}' = 10\log\{1+\frac{E_b}{N_0}[1-|\frac{\sin\Phi}{\Phi}|^2]\} - 10\log[|\frac{\sin\Phi}{\Phi}|^2] \quad (12)$$

Compare (12) with (11), it can be found that D_{nf}' in (20) is much better than D_{nf}'' in (11). So the new algorithm can improve the estimation of integer offset, and decrease the SNR deterioration to improve the system performance.

Overall, the main idea of the proposed novel algorithm is to use several symbols to improve the accuracy gradually. In case the estimation value is not accurate immediately, the proposed algorithm can still ensure the deviation will gradually reduce.

IV. COMPUTER SIMULATIONS

The computer simulation environment parameters are as follows: OFDM Carrier frequency is 2.6 G Hz. The sub-carrier bandwidth is 15 k Hz. The length of each symbol is 90 bits. The cyclic prefix length is 32. The pilot number in per symbol is 10. The FFT length is 256. The coding mode is interleaved coding and Viterbi coding. The modulation mode is QPSK.

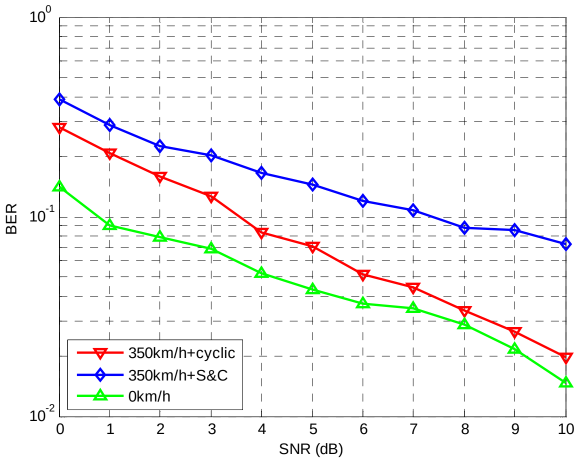

Fig.3. BER comparison of the S&C and proposed algorithms

The indoor communication channel is selected as AWGN flat channel. The moving speed of the objective rise from 60 km/h to 350 km/h gradually. When the speed reaches 350 km/h, keep the estimation offset unchanged, and set the SNR vary from 0dB to +10dB to draw the BER curve.

From the comparison in Fig.3, the performance of the proposed Cyclic Cumulative algorithm (red line) is still worse than curve of 0km/h (green line), but it's very close to it at SNR=10dB. And comparing the red curve and blue curve, our proposed algorithm works much better in the indoor OFDM communication environment than the old S&C algorithm.

V. CONCLUSION

Through the theoretical analyses and computer simulations, it can be found the existing traditional Doppler frequency offset estimation algorithm often doesn't work well in the indoor moving objective environment. In this paper, a novel cyclic cumulative frequency offset estimator is proposed to improve the traditional OFDM system. It not only improves the performance of the traditional S&C algorithm, but also much close to the ideal state.

ACKNOWLEDGMENT

This research work is supported by the National High Technology Research and Development Program of China under Grant No. 2013AA013602, and jointly funded by Beidou Navigation Satellite System Management Office (BDS Office) and the Science and Technology Commission of Shanghai Municipality under Grant No. BDZX005.

REFERENCES

[1] Erik Dahlman. 3G evolution: HSPA and LTE for mobile broadband. Elsevier Ltd., 2008.

[2] R.W. Chang and R.A. Gibby. “A Theoretical Study of Performance of an Orthogonal Multiplexing Data Transmission Scheme”. IEEE Trans. Commu. Technol.1968,15(6):pp.529.

[3] F. Daffara and A. Chouly. “Maximum likelihood frequency detectors for orthogonal multicarrier systems”. In Proc. IEEE Int.Conf. Commun. May 1993,pp.766-771.

[4] J.van de Beek, M. Sandell and P. Borjesson. “ML Estimation of time and frequency offset in OFDM system”. IEEE Trans. Signal Processing, 1997,45:pp.1800-1805.

[5] W.P. Hong. “A Frequency Offset Estimation Architecture of OFDM System in Multipath Doppler Spread Channel”. Conference Record of the Thirty-Third Asilomar Conference on Signals Systems, and Computers,1999, pp.1071-1075.

[6] A.M. Sayeed and B. Aazhang. “Joint multipath-Doppler diversity in mobile wireless communications”. IEEE Trans. Commun., 1999, 47(1): pp.123-132.

[7] T.M. Schmidl and D.C. Cox. “Robust frequency and timing synchronization for OFDM”. IEEE Trans. Commun., 1997, 45(12): pp.1621-1623.

[8] P. Byungjoon, C. Hyunsoo, K. Changeon and H. Daesk. “A novel timing estimation method for OFDM systems”. IEEE Globecom’2002, vol.1: pp.17-21.