Electrical, Electronics and communications, and Computer Engineering

Pilot Based Channel Estimation and Synchronization in OFDM System

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ABSTRACT

Channel estimation and synchronization are considered the most challenging issues in Orthogonal Frequency Division Multiplexing (OFDM) system. OFDM is highly affected by synchronization errors that cause reduction in subcarriers orthogonality, leading to significant performance degradation. The synchronization errors cause two issues: Symbol Time Offset (STO), which produces inter symbol interference (ISI) and Carrier Frequency Offset (CFO), which results in inter carrier interference (ICI). The aim of the research is to simulate Comb type pilot based channel estimation for OFDM system showing the effect of pilot numbers on the channel estimation performance and propose a modified estimation method for STO with less number of pilot to mitigate ISI effect. Channel estimation is simulated for different pilot number with 16QAM modulation in Ped-A Rayleigh channel. The STO effect assumed less than the cyclic prefix length to minimize ISI and maintain the orthogonality between subcarriers. The simulation results show that the high number of pilots are needed to achieve good channel estimation in case no synchronization used while similar results are achieved with smaller number of pilots if the propose modification on the synchronization method are used aligned with the channel estimation. The proposed system is evaluated in terms of BER and SNR.

Keywords: Channel estimation, pilots, STO.

تخمين ومزامنة القناة بالاعتماد على المسيطرات في نظام OFDM

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الخلاصة

يعتبر تخمين ومزامنه القناة من أكثر المشكلات صعوبة في تنفيذ نظام مضاعفة تقسيم التردد المتعامد (OFDM). تتأثر أنظمة OFDM بدرجة كبيرة بأخطاء المزامنه التي تسبب انخفاضًا في التعامد الفرعي ، مما يؤدي إلى تدهور كبير في الأداء. تسبب

أخطاء المزامنة مسألتين: إزاحة وقت الرمز (STO) ، والتي تنتج تداخل بين الرموز (ISI) وإزاحة تردد الموجة الحاملة (CFO) ، والتي ينتج عنه تداخل بين الناقل (ICI). يهدف البحث إلى محاكاة تخمين القناة القائمة على النوع Comb لنظام OFDM الذي يوضح تأثير عدد المسيطرات على تخمين القناة واقتراح طريقة تخمين معدلة لل STO مع عدد أقل من المسيطرات للتخفيف من تأثير ISI. يتم محاكاة تخمين القناة لعدد مختلف من المسيطرات مع اعتماد تضمين ال QAM16 في نوع قناة Ped-A Rayleigh. تم افتراض تأثير STO أقل من طول البادئة الدورية لتقليل ISI والحفاظ على التعامد بين الموجات الحاملة الفرعية. اظهرت نتائج المحاكاة أن هناك حاجة إلى عدد كبير من المسيطرات لتحقيق تخمين جيد للقناة في حالة عدم استخدام طرق المزامنه في حين يتم تحقيق نتائج مماثلة مع عدد أصغر من المسيطرات إذا تم استخدام التعديل المقترح على طريقة التزامن بالتوافق مع تخمين القناة. تم تقييم النظام المقترح اعتمادا على BER و SNR.

الكلمات الرئيسية: تخمين القناة, المسيطرات, STO.

1. INTRODUCTION

For wireless systems, the transmitted signal is passed through the radio channel and then it reached the receiver side after scattering in frequency and time domains because of the channel characteristics such as path loss, Intersymbol interference (ISI), multipath fading and doppler shift. Hence, these characteristics are considered as critical challenges in the OFDM systems as the channel is changing rapidly depending on the environments (**Nadar, Koti and Jayaswal, 2014**).

Pilot based channel estimation introduced as one of the most efficient methods that utilized by OFDM systems. This method relies on the inserted pilot signals to track the amplitude and the frequency shift errors of the channel and equalize the channel effects on the data signals with the help of interpolation techniques.

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission technique which has an efficient spectrum. OFDM gives a chance to minimize the multipath fading effects by converting a frequency selective channel to a flat fading channel which reducing the equalizer complexity at the receiver side (**Frederiksen and Prasad, 2002**).

The multipath channel characteristics result in a delay in the receiving signal depending on the maximum delay speared of the transmitted signal. This delay leads to synchronization errors at the receiver side and impacts the orthogonality between the OFDM subcarriers (**Farhan, 2014**).

The synchronization effect can be divided into two types: Symbol Time Offset (STO) and Carrier Frequency Offset (CFO) (**Cho et al., 2010**). The STO effect represents a delay between the transmitted symbol to the received symbol, while the CFO represents a shift in the frequency domain of the subcarriers.

2. LITERATURE SURVEY

In **2005 Choi and Lee** analytically determined a pilot pattern in order to reduce the mean square error of the channel estimation that found using general interpolators. They determined the spacing of the pilot symbols in terms of Doppler spectrum, pilot density, and power delay profile.

In **2008, Ali Ramadan Ali et al** discussed the BER for OFDM using adaptive pilot distribution in time-varying channels. The simulation results show that the adaptive system resulted in increasing the total capacity of the system with comparable BER performance as compared to the conventional system when selecting appropriate threshold levels.

Peter Fertl and Gerald Matz proposed in **2010** a channel estimation method for a wireless OFDM with irregular pilots' distribution relying on non-uniform sampling techniques. The proposed estimator is implemented with low computational complexity by employing conjugate gradient iterations and FFTs. The proposed method is applied to MIMO-OFDMA (multi users OFDM system with multiple antennas)**.**

In **2011**, **Abdelhakim Khlifi and Ridha Bouallegue,** studied the performance of LS and MMSE channel estimation techniques for the Downlink in LTE system considering the effect the channel length**.**

In **2012, Serkout N. Abdullah and Zainab M.Abid**, studied the effect of adaptive coded modulation for coded OFDM system according to punctured convolutional code, channel estimation, equalization and SNR estimation.

In **2013**, **Michal Simko et al.** addressed the effect of inserting the pilots between data-symbols on the bandwidth. The simulation results show that by significantly increasing the power of the pilots' symbols compared to the power of the data symbols, the number of pilot symbols can be decreased at low SNR.

In **2013, Bashar A.Esttaifan, Oday A.Lateef and Waleed A.Mahmoud**, design and construct an OFDM transmitter with the aid of FPGA in order to simplify FFT calculations by utilizing decoder instead of multipliers.

In **2015**, **Yang Guangxi et al**. proposed a channel estimation technique that applied to slow and fast fading OFDM systems. The proposed technique relied on comb type and comprised of adding a low pass filter in the transform domain to minimize ICI.

A deep learning approach for channel estimation and symbol detection in OFDM systems is proposed by **Ye, Li and Juang, et al**. in **2017**. The proposed deep learning model included two stages: training stage and deployment stage. During the training stage, the characteristics of the wireless channel are learned using data that generated from the simulation process based on channel statistics. While in the deployment stage, the outputs that recover the transmitted data is generated by the model.

Most of the researchers have focused on channel estimation ignoring the synchronization phase. In this research, the channel estimation is carried out by considering the synchronization effect.

3. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)

OFDM implies sending one data symbol into different linear independent subcarriers that have equal frequency spacing depending on the symbol duration. The orthogonality of OFDM is maintained by using IFFT and FFT due to the simplicity of implementation in the transmitter and receiver. OFDM block diagram is shown in **Fig. 1**.
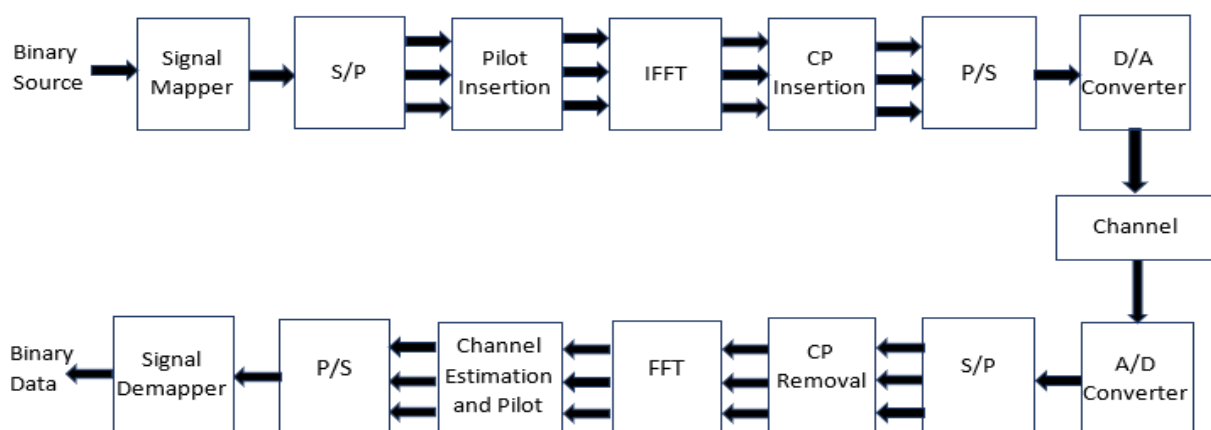

Figure 1. Block diagram for OFDM system **(Liu Kewen and XingKe, 2010)**.

3.1 OFDM Pilot Based Channel estimation

In OFDM system, channel estimation is an essential step to keep orthogonality between the subcarriers to eliminate the channel effect. In pilot based channel estimation, a known data called pilots are inserted during OFDM symbols transmission at specific locations which are known at the receiver. Pilots have an important role in channel estimation, pilots can be allocated in time and frequency domains. Two main kinds of pilot allocations are illustrated in **Fig.2**: Comb and block type. In comb type, pilot data is sent on a specific subcarrier during all time in the OFDM symbols as indicated in **Fig 2.a**. In block type, all the subcarrier frequencies of the OFDM symbol are used as pilots periodically as shown in **Fig 2.b**.
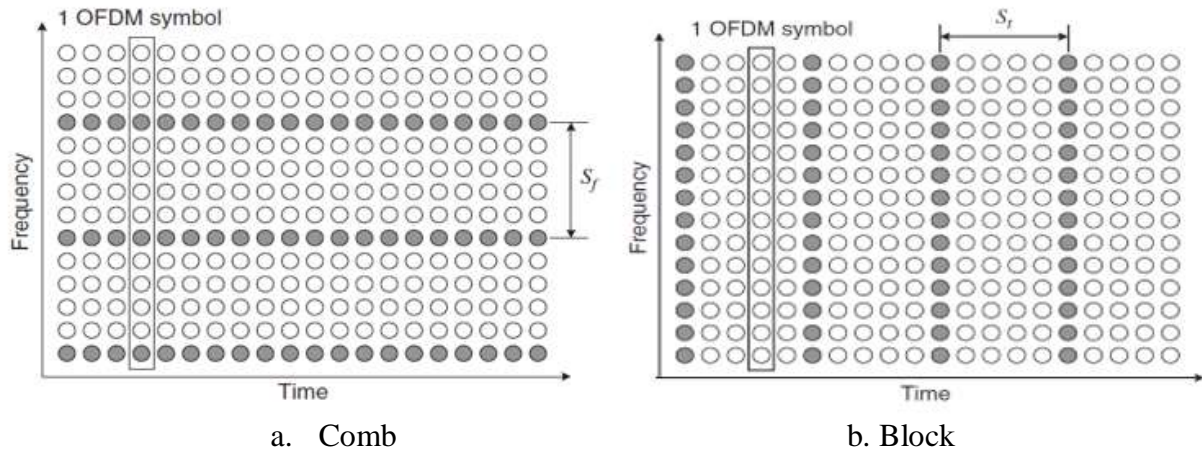

a. Comb   b. Block

Figure 2. Pilot allocation types (**Nadar, Koti and Jayaswal, 2014**).

Different channel estimation methods are used relying on the pilot symbols, such as Least-Square (LS) and Minimum-Mean-Square-Error (MMSE) (**Cho et al., 2010**).

3.1.1 Least-Square channel estimation (LS)

The main purpose of the LS channel estimator is to minimize the square distance between the received data and the originally transmitted data. The received samples are expressed in Eq. (1).

$$Y(k) = X(k)H(k) + Z(k) \tag{1}$$

Where k is the carrier index, $X(k)$ is the transmitted signal, $H(k)$ channel frequency response, $Z(k)$ is the noise signal and $Y(k)$ is the received signal.
The LS estimation of Eq. (1) is obtained by Eq. (2) depending on pilot subcarriers (**Cho et al., 2010**).

$$H_{LS} = X^{-1}Y \tag{2}$$

The advantages of LS algorithm are simplicity, low complexity and it does not require any previous information about the channel statistics. However, the performance might be affected due to high mean square error (MSE) (**Liu Kewen and XingKe, 2010).**

3.1.2 Minimum-Mean-Square-Error channel estimation (MMSE)

MMSE algorithm is used to overcome the problem of high MSE by using the second order statistics of the channel. However, MMSE suffers from major disadvantage which is high complexity. The MMSE channel estimate $\hat{H}$ in frequency domain is given by **(Cho et al., 2010)**:

$$\hat{H} = R_{HH_{LS}}(E\{HH^H\} + \frac{\sigma_z^2}{\sigma_x^2}I)^{-1}H_{LS} \tag{3}$$

Where $R_{HH_{LS}}$ represents the cross correlation matrix between H and H_{LS}, I is the identity matrix, σ_Z and σ_x represent the standard deviation of the Additive White Gaussian Noise (AWGN) and the transmitted signal.

3.2 OFDM Pilot Based Channel Synchronization

The multipath fading channel causes a delay in the receiving signal depending on the maximum delay speared reflected on the transmitted signal **(Bai and Atiquzzaman, 2003).** This delay can lead to synchronization issues in the OFDM receiver and destroy the orthogonality between the OFDM subcarriers which result in packet error if it is not estimated and corrected. According to the synchronization effect, the receiving symbol at index l is expressed as **(Cho et al., 2010):**

$$\begin{aligned} y_l(n) &= IFFT\{Y_l(k)\} = IFFT\{X_l(k)H_l(k) + Z_l(k)\} \\ &= \frac{1}{N}\sum_{k=0}^{N-1} X_l(k)H_l(k)\, e^{j2\pi(k+\varepsilon)(n+\delta)/N} + z_l(n) \end{aligned} \tag{4}$$

Where N represents the number of samples in OFDM symbol, δ and ε represent the effects of STO and CFO respectively. This research is focusing on the STO effect assuming CFO is neglected.

3.2.1 STO effect

STO represents the delay between the transmitted symbol and the received symbol. From Eq. (4) and assuming ε is zero, the STO delay of δ is determined as the phase offset $2\pi k\delta/N$ in the frequency domain as shown in **Table 1**.

Table 1. The effect of STO on the received signal **(Cho et al., 2010)**.

Representation	Received signal	STO δ effect
Time Domain Representation	$y_l(n)$	$x(n+\delta)$
Frequency Domain Representation	$Y_l(k)$	$X_l(k)e^{j2\pi k\delta/N}$

According to the starting point of the received OFDM symbol, four cases of timing offset are shown in **Fig. 3**.
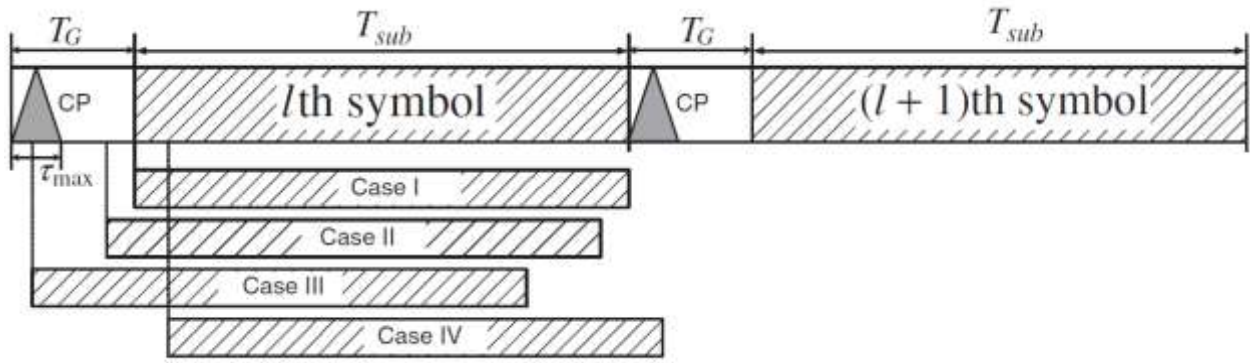
Figure 3. OFDM symbol starting point cases subjected to STO **(Cho et al., 2010).**

- Case I: The starting point of the estimated OFDM symbol is aligned with exact symbol timing preserving the orthogonality between the subcarriers. As a result, it is possible to recover the OFDM symbol correctly.
- Case II: In this case, the estimated OFDM symbol starting point is taken before the exact start point but still lower than the $(T_G - \tau_{max})$ where T_G is the cyclic prefix delay and τ_{max} is the maximum multi-path delay spread. Thus, the lth symbol is not interfered or overlapped with the $(l-1)th$ symbol but still there is a phase rotation in the frequency domain due to the STO effect.
- Case III: In this case, the starting point of the estimated OFDM symbol is taken before the exact start point (similar to case II), but it is higher than
  $(T_G - \tau_{max})$. Therefore, the symbol timing starting point is too early to prevent ISI from the previous symbol.
- Case IV: Assuming that the starting point of the estimated OFDM symbol is a little late after the exact point of the symbol timing which makes the FFT interval have a part of the $(l+1)th$ OFDM symbol in addition to the current lth OFDM symbol.

3.2.2 STO estimation in frequency domain

The STO effect is causing phase rotation depending on the subcarrier frequency index. According to **(Cho et al., 2010),** STO estimation is carried out by finding the difference in phase between adjacent and equal received subcarriers in the frequency domain. When the transmitted samples $X_l(k) = X_l(k-1)$ and channel $H_l(k) \cong H_l(k-1)$ for all k, the received signal $Y_l(k) Y_l^*(k-1) \cong |X_l(k)|^2 e^{j2\pi\delta/N}$. Therefore, the STO parameter δ can be estimated as below **(Cho et al., 2010)**:

$$\hat{\delta} = \frac{N}{2\pi} \arg(\sum_{k=1}^{N-1} Y_l(k) Y_l^*(k-1)) \tag{5}$$

This method is using all samples as pilots to estimate the STO parameter δ. As a result, the data throughput will be low (most of the transmitted samples are used for synchronization). In other words, it is widely used in block type. In this research, a modification on the above technique is suggested to use only two pilots to find the phase difference between the two adjacent LS channel estimation as:

$$\text{phase difference} = \emptyset_{diff} = \arg (H_l(k_2) /H_l(k_1)) \tag{6}$$

where $H_l(k_2)$ and $H_l(k_2)$ are the LS channel estimation at two adjacent pilot on index k_1 and k_2 respectively.

Assuming the starting point for estimation is similar to case II then the LS channel estimation at pilot location is defined as below:

$$H_l(k_i) = \frac{Y_l(k_i)}{X_l(k_i)} = \left|\frac{Y_l(k_i)}{X_l(k_i)}\right| e^{\frac{j2\pi\delta k_i}{N}} \tag{7}$$

Then the $\emptyset_{diff}$ is expressed as below:

$$\emptyset_{diff} = \arg\left(\left|\frac{H_l(k_{i+1})}{H_l(k_i)}\right| e^{\frac{j2\pi\delta(k_{i+1}-k_i)}{N}}\right) = \frac{2\pi\delta(k_{i+1}-k_i)}{N} \tag{8}$$

where i is the pilot index and by rearranging Eq. (8) the estimated $\hat{\delta}$ is defined as below:

$$\hat{\delta} = \frac{\emptyset_{diff}*N}{2\pi(k_{i+1}-k_i)} \tag{9}$$

After finding estimated $\hat{\delta}$ it is used to synchronize the received signal and keep the new channel estimation for the channel effect only without the STO effect.

3.3 Interpolation
The interpolation can be defined as the estimation of a value or a set of values between two known values. Thus, the channel response of the data subcarriers is estimated by interpolating the estimated channel response from received pilot subcarriers. There are many types for interpolation, linear interpolation is used commonly due to its simplicity. Linear interpolation is used to link two successive pilots by a straight line (**Zhang, Xia and Ching, 2006**).

4. SIMULATION RESULTS
In this research, first LS and MMSE channel estimation techniques are applied to ITU-R Pedestrian-A Model (Ped-A) Rayleigh channel that described in (**Cho et al., 2010**). Then, the STO effect is estimated by frequency domain estimation. Finally, system evaluation is carried out according to different SNR to BER with different pilot numbers. The simulation parameters are shown in **Table 2**.

Table 2. Simulation parameters.

Parameter	Value
Number of Frames	1000
FFT Size	64
Pilot Sub-Carrier Number	4, 8, 16
Pilot Allocation Pattern	Comb Type
Cyclic Prefix Length	16 (25%)
SNR Range	1-40 dB
Interpolation Method	linear
Channel Estimation	LS and MMSE
Synchronization Method	STO Estimation
QAM Modulation	16

• LS and MMSE estimation

Fig. 4 shows the effect of using different pilot numbers on the LS and MMSE estimation performance. In this figure, it can be seen that the channel estimation performance of the LS and MMSE estimators is increased significantly when increasing the number of pilots used in estimation.
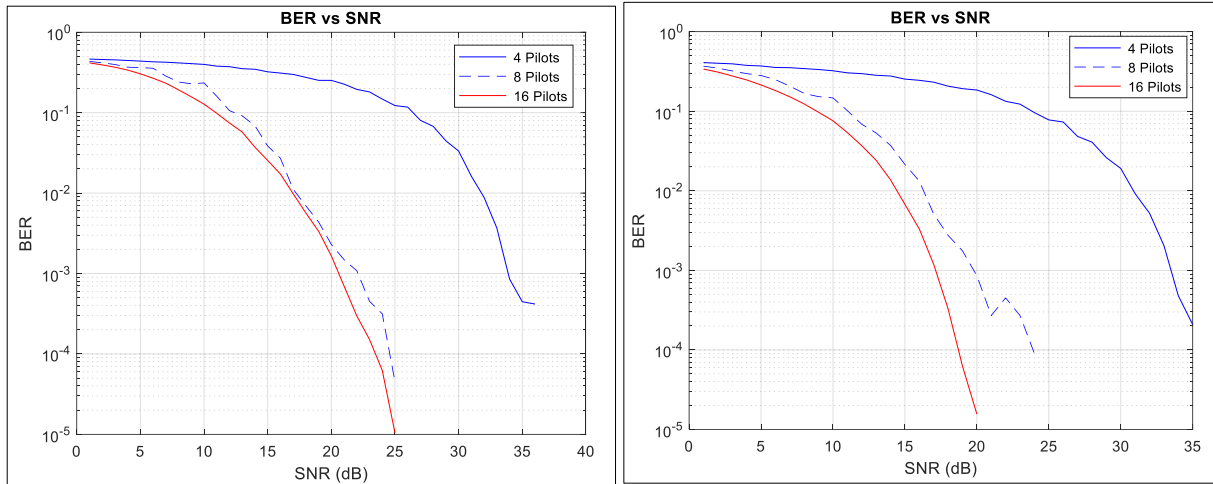
     a.   LS estimation QAM 16   b.   MMSE estimation QAM 16

Figure 4. BER performance in Ped-A Rayleigh channel with 4, 8 and 16 pilots.

• STO synchronization estimation

Fig. 5 illustrates the synchronization effect on the received signal in time domain representation by using the modified method. In this figure, it is observed that the received symbol is shifted and restored to its original position after synchronization.
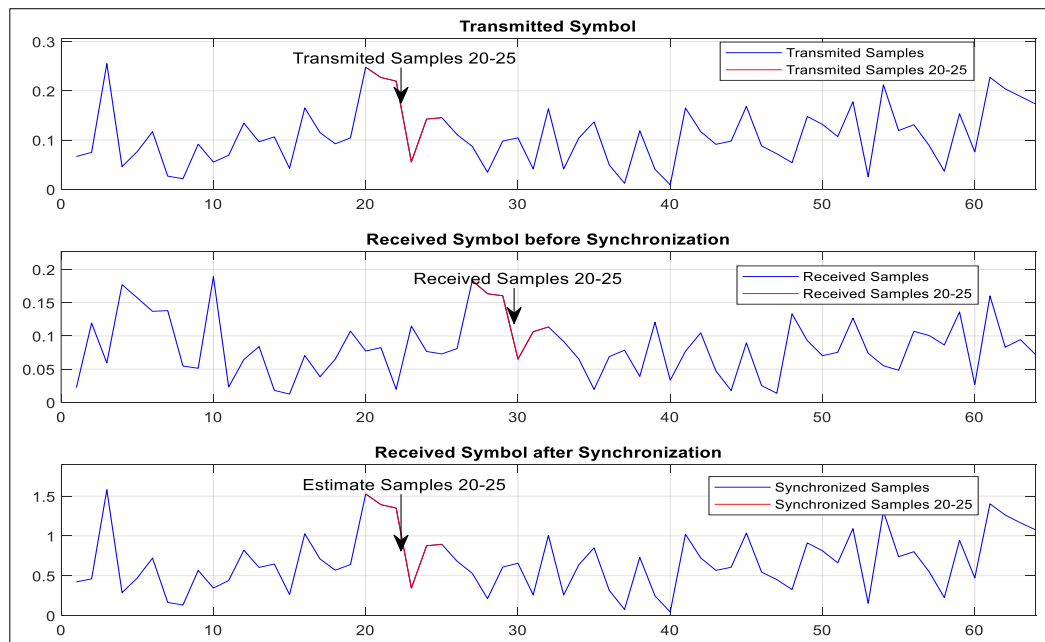

Figure 5. Synchronization effect on the received symbol when $\delta = 7$ using two pilots only.

5. CONCLUSION

This research focuses on the effect of pilots in channel estimation and synchronization by considering the STO effect. The OFDM system is modeled and the BER performance is evaluated for a different number of pilots using 16QAM modulation in the Ped-A Rayleigh channel type. The STO effect is estimated by using the modified method. The simulation results show that the modified STO estimation method which used only two adjacent pilot samples still gives good synchronization performance even with low BER which is depending on channel estimation accuracy according to the number of pilots used.

REFERNCES

• Abdelhakim Khlifi and Ridha Bouallegue (2011) 'Performance Analysis of LS and LMMSE Channel Estimation Techniques for LTE Downlink Systems', International Journal of Wireless & Mobile Networks, 3(5), pp. 141–149.

• Ali Ramadan Ali, Atallah Balalem, Tariq Khanzada, Jan Machac, and Abbas Omar. (2008) 'Adaptive pilot distribution for OFDM systems in time-variant channels', in 2008 Asia-Pacific Microwave Conference. IEEE, pp. 1–4.

• Bashar Adel Esttaifan, Oday AbdulLateef, Waleed Ameen Mahmoud, 2013, '*Design and Implementation of a Multiplier free FPGA based OFDM Transmitter', Journal of Engineering*, Vol.19, No.8, PP. 1056-1072.

• Farhan Farhan. (2014) 'Study of Timing Synchronization in MIMO-OFDM Systems Using DVB-T', International Journal on Information Theory, 3(2), pp. 1–10.

• Fleming Bjerge Frederiksen and Ramjee Prasad (2002) 'An overview of OFDM and related techniques towards development of future wireless multimedia communications', in Proceedings RAWCON 2002. 2002 IEEE Radio and Wireless Conference (Cat. No.02EX573). IEEE, pp. 19–22.

• Haowei Bai and Mohammed Atiquzzaman. (2003) 'Error modeling schemes for fading channels in wireless communications: A survey', IEEE Communications Surveys & Tutorials, 5(2), pp. 2–9.

• Hao Ye, Geoffrey Ye Li and Biing-Hwang Fred Juang (2018) 'Power of Deep Learning for Channel Estimation and Signal Detection in OFDM Systems', IEEE Wireless Communications Letters, 7(1), pp. 114–117.

• Jeba Inbaraj Nadar, Jayasudha Koti and Deepak Jayaswal (2014) 'OFDM pilot based channel estimation', in 2014 International Conference on Advances in Engineering & Technology Research (ICAETR - 2014). IEEE, pp. 1–5.

• Ji-Woong Choi and Yong-Hwan Lee (2005) 'Optimum pilot pattern for channel estimation in OFDM systems', IEEE Transactions on Wireless Communications, 4(5), pp. 2083–2088.

• Liu Kewen and XingKe (2010) 'Research of MMSE and LS channel estimation in OFDM systems', in The 2nd International Conference on Information Science and Engineering. IEEE, pp. 2308–2311.

• Michal Simko, Paulo S. R. Diniz, Qi Wang and Markus Rupp (2013) 'New insights in optimal pilot symbol patterns for OFDM systems', in 2013 IEEE Wireless Communications and Networking Conference (WCNC). IEEE, pp. 3737–3741.

• Peter Fertl, and Gerald Matz. (2010) 'Channel Estimation in Wireless OFDM Systems With Irregular Pilot Distribution', IEEE Transactions on Signal Processing, 58(6), pp. 3180–3194.

• Serkout N. Abdullah and Zainab M.Abid, 2012, 'Adaptive Coded Modulation for OFDM System', *Journal of Engineering*, Vol.18, No.2, PP. 148-162.

• Wei Zhang, Xiang-Gen Xia and P. C. Ching (2006) 'Optimal training and pilot pattern design for OFDM systems in Rayleigh fading', IEEE Transactions on Broadcasting, 52(4), pp. 505–514.

• Yang Guangxi, Deng Lunhui and Chen Xiang (2015) 'An efficient channel estimation method for OFDM systems based on comb pilots', in 2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC). IEEE, pp. 1029–1033.

• Yong Soo Cho, Jaekwon Kim, Won Young Yang and Chung G. Kang. (2010) MIMO-OFDM Wireless Communications with MATLAB, MIMO-OFDM Wireless Communications with MATLAB. Chichester, UK: John Wiley & Sons, Ltd.