Pilot spacing controller in orthogonal frequency division multiplexing systems

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Abstract. As the backbone of the fifth generation, 5G communications, Orthogonal Frequency Division Multiplexing, OFDM is seen to be reliable in addressing Inter-symbol Interference, ISI issues as well as providing high-speed access to broadband. Channel estimation and tracking are generally carried out by transmitting known pilot symbols in given positions of the frequency-time grid. However, the use of a fixed amount of pilot for all channel circumstances is hugely detrimental. Several methods, especially on block-type and comb-type pilot arrangement, have presented. In this paper, the method of determining the pilot space depends on the current channel quality. The proposed technique focused on improving estimation and bandwidth in time-varying and frequency-selective fading channels without increasing the complexity and sacrifice the bandwidth efficiency of the OFDM system.

1. Introduction
For various types of multiplexing techniques, OFDM has recognized as an efficient spectrum through selective frequency channels. One of the advantages of OFDM is that it can transfer data at high speeds and has high bandwidth efficiency. Besides, it can reduce the effects of Inter Symbol Interference (ISI). As a backbone for 5G systems, OFDM has been extensively applied in mobile communication systems [1]. The example of application is not limited to Extended Reality, XR, Esports, immersive gaming and toys, Ultra high definition TV, UHD TV, multi-person video call, and many more. The key to OFDM advantage is to divide the existing spectrum into several overlapping sub-channels but maintain the orthogonality each sub-channel and then convert it back to frequency selective channels to non-frequency selective channels [2]. High-speed transmission obtained by splitting the frequency-selective-fade signal band into several narrow-fade subchannels. Then level up by applying a compact constellation to each subcarrier. High spectral efficiency obtained by choosing a specific carrier frequency, which is orthogonal, as the spectra of SCs overlap with each other. Inter Symbol Interference, ISI was the main problem for multicarrier methods. However, it can evade the implementation of cyclic prefix, CP by spreading the OFDM symbol to several parts. The extended symbol is known as the head or tail for the symbol. Principally, the OFDM systems performance relied on the channel estimation process. It depends on the capability to estimate the channel behavioral precisely. In OFDM systems, both frequency and time domain represented by wireless channel transfer function existed irregularly. This irregularity happens because of the radio channels in wideband wireless communication systems typically frequency selective and time-variant.
Mostly OFDM-based communication standards offer some arrangements of reference signals individually as pilot signals or preamble. The purpose of the reference signal is to attain accurate channel estimation focus to equalize each subcarrier. Techniques used for channel estimation divided into two. First is decision direct channel estimation and secondly known as pilot-assisted channel estimation. Comparing two techniques, some drawbacks of decision direct channel estimation methods have identified. One of the weaknesses of the decision direct channel estimation method is because of its behavioral to error detection leads to the propagation of error. It is also required a massive amount of data, which can lead the convergence rate to slow down [3].

The ability of reference signals to provide good estimation for the whole frequency and time grid depends on the number of reference signals injected in the pair of the frequency domains and time domains. It comprised of the case of wireless channels, which subjected to time selectivity and high frequency. The receiver estimates the channel in frequency-domain by consuming information about the reference symbols around the location of the reference symbol. Inserting a pilot signal with a specific duration or on each OFDM symbol is known as pilot-assisted channel estimation [4]. The initial channel information then estimated with a certain number of pilots. Between OFDM symbols, interval pilot signals inserted. Using one-dimensional linear interpolation channel estimation results can be obtained [2,6]. The determining factor between the channel estimation accuracy and bandwidth efficiency refers to the number of pilot signals used. Therefore, the optimum quantity of the pilot signal needs to be determined. The challenge in designing the OFDM system is to maintain a low number of pilot signals while maintaining Bit Error Rate, BER under the desired value of Signal to Noise Ratio, SNR. The problem is the same as determining the maximum pilot distance to meet the BER requirement on a given SNR.

2. **OFDM Systems Description**

A conventional block diagram of the OFDM system with a pilot symbol shown in figure 1. According to the modulation for signal mapping, binary data is first grouped and then mapped. Pilot signals then inserted to each subcarrier regularly or with an exact period between the data sequence. By implementing the Fourier transform, earlier signal converted to multi-carrier modulation. Identically, Inverse Fast Fourier Transform, IFFT, and Fast Fourier Transform, FFT was chosen primarily to reduce the mathematical operations.

![Figure 1. Block diagram of an OFDM system with a pilot symbol.](image-url)
The function of IFFT block in figure 1 is to transform the frequency domain signal into time-domain signal as follow:

\[ x(n) = \text{IFFT}(X(k)), n = 0,1,2, ..., N - 1 \]  
\[ x(n) = \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi kn}{N}} \]  

The guard time mainly to avoid ISI. The parameter for guard time is preferred to be greater than the predictable delay spread. Equation (3) presented the resultant OFDM symbol mathematically:

\[ x_f(n) = \begin{cases} 
  x(N + n), n = -N_g, -N_g + 1, ..., -1 \\
  x(n), n = 0,1, ..., N - 1 
\end{cases} \]  

\( N_g \) represents the length of the guard interval. Noise added to the transmitted signal after passing via the fading channel. The acknowledged signal at the receiver sensed as:

\[ y_f(n) = x_f(n) \ast h(n) + w(n) \]  

Where \( h(n) \) is the channel impulsive response and \( w(n) \) is Additive White Gaussian Noise, AWGN. FFT block then converts back the time domain, \( y_f(n) \) signal toward the frequency domain signal after guard time has removed. Extraction of pilot signal executed at estimation block. This process mainly to obtain the estimation channel \( H_e(k) \), aimed at the respective sub-channels data. Then the estimation of transmitted data presented as:

\[ X_e(k) = \frac{y(k)}{H_e(k)} \quad k = 0,1,2,3 ... N - 1 \]  

At the signal de mapper block, binary information data achieved.

3. Pilot Planning

In this section, the introduction of the famous pilot arrangement preceded. Then followed by channel estimation algorithms. Classification of channel estimation depends on different types of pilot patterns. Dedicated pilot subcarriers interlaced with data subcarriers in OFDM systems. The pilot arrangement relies on the channel state, either flat fading channels or slow fading channels. Therefore, several methods exist and characterized into two types. [7] Describe a pilot pattern base on a 2 x 2 sampling matrix \( Y = [Y_1 \ Y_2] \). As \( y_1 = [y_{11} \ y_{21}]^T \) and \( y_2 = [y_{12} \ y_{22}]^T \) are the two spanning vectors that generated for all pilots in the time-frequency domain. It is also known as a doubly periodic sub-lattice.

The first pilot arrangement is exclusively for slow fading channels. The procedure is by inserting pilot signals with a specific period into all the subcarriers. Known as the block-type pilot, it is insensitive to frequency selectivity with the assumption that the channel is constant. As the pilots set at all carriers, there is also no interpolation error. The second approach for flat fading channels is a comb-type pilot arrangement. Each OFDM symbol inserted with pilot signals and the \( N_p \) pilot signals are constantly presented in \( X(k) \) and shown by the followed equation:

\[ X(k) = X(mL + l) X(k) = \begin{cases} 
  x_p(m), & l = 0 \\
  \text{data}, & l = 1,2,3 ... L - 1 
\end{cases} \]  

Where \( L = \text{number of carrier}/N_p \) and \( x_p(m) \) is the \( m^{th} \) is the value of the pilot carrier. For the comb-type pilot, the interpolation technique is required to estimate channel efficiently at data sub-
carriers. The comb-type pilot and block-type arrangement are the two essential 1D pilot insertion, as shown in Figure 2.

Figure 2: Pilot signal arrangement [4].

4. Block-type pilot arrangement channel estimation.

Figure 2 shows the pilot symbols are transmitted periodically in a block-type pilot arrangement. Entire subcarriers for dedicated symbols used as pilots, and it is required to estimate channel conditions. Information from the estimated channel condition process by the receiver used to interpret the received data for every block until the next block arrived together with the new pilot symbol. Commonly in the block-type pilot arrangement, MMSE, LMMSE, or LS algorithm is the recognized estimation techniques.

4.1 Minimum Mean Square Error, MMSE.

The channel impulse response, $h$ estimated using the MMSE is given by [2,8–10]:

$$H_{MMSE} = FR_{hy}R_{yy}^{-1}Y$$

(7)

$R_{hy}$ is the cross-covariance matrix between $h$ and $Y$, while $R_{yy}$ is the auto-covariance matrix of $Y$. The $R_{hh}$ represents the auto-covariance matrix of $h$. The time-domain channel vector, $h$ has a Gaussian distribution, and it is uncorrelated with the channel noise, $W$. $\sigma^2$ represents the noise variance of $E[|W(k)|^2]$.

4.2 Linear Minimum Mean Square, LMMSE.

AWGN channel added the noise variance $\sigma^2$ to receive signals. The LMMSE estimation of the channel vector $g$ is given by [11–13]:

$$g = \Gamma_{gy}\Gamma_{yy}^{-1}y$$

(8)

$\Gamma_{gy}$ is the cross-covariance matrix between $g$ and $y$, while $\Gamma_{yy}$ is the auto-covariance matrix of $y$. Covariance matrices should be positive definite to archive a unique minimum MSE.

4.3 Least Square, LS.

[4,14,15] discussed the LS estimation by:

$$H_{LS} = X^{-1}Y$$

(9)
(9) minimizes $(Y - XFh)^H(Y - XFh)$. The channel estimation for each subcarrier inside the block can be updated using the decision feedback equalizer because the effect of fading is slow.

5. Comb-type pilot arrangement channel estimation.

Estimation of pilot subcarriers based on LS is given by [4]:

$$H_e = \frac{Y_p}{X_p}, \quad k = 0, 1, 2, 3 ... N_p - 1$$

(10)

$Y_p(k)$ and $X_p(k)$ are output and input at the $k^{th}$ pilot subcarrier, respectively. Either MMSE and LS estimation techniques have their advantages. For example, MMSE is better to compromise complexity; meanwhile, LS estimation is susceptible to ICI, and noise.

5.1 Interpolation techniques

Subsequently, the pilot signal estimation of the channel transfer functions, the channel response of data signals interpolated concerning the adjacent pilot. The data carrier, $k$, use linear interpolation with the value of $mL < k < m + 1)L$. Higher-order polynomial interpolation performed better in obtaining channel response compared to standard linear interpolation hypothetically.

6. Pilot spacing controller

Better BER performance achieved by applying a dense pilot mode in OFDM systems. Smaller pilot spacing leads to a more substantial complexity burden. However, utilized a sparse pilot-symbol in the OFDM system, reverse the phenomena with the dense pilot. Considered an unknown Doppler environment with the vary channel taps randomly. Standard deviation, $\sigma_p$ of the received pilot signal for every channel tap obtained by equation (11).

$$\sigma_p = \sqrt{\frac{\sum_{i=1}^{k-1} (Y_{p_i} - \overline{Y_{p_i}})^2}{k-1}}$$

(11)

$\overline{Y_{p_i}}$ is, the arithmetic mean of the $Y_{p_i}$ and directly corresponding to the variability of the channel taps. Different channels represented by different standard deviations consequently.

In this paper, the locations of the pilots assumed known at the receiver. Information for pilot locations obtains via the control messages. It is replicated the same pilot structure as that at the transmitter. [16] proposed the number of pilot carriers varied in the OFDM symbol. The aim is to avoid the estimation of the channel on the same pilots' number. It could be unnecessary for high SNR environment. Therefore, the designed pilot controller added to the conventional OFDM systems to control the pilot interval. It is the focus of a higher bandwidth efficiency with tolerable quality channel estimation.

7. Simulation specification

A per objective is to determine channel estimation performance, a perfect synchronization assumed between transmitter and receiver. The guard interval is chosen to be large enough compared to the maximum delay spread towards eliminating the ISI. The Rayleigh fading channel is selected as the channel model to assess the fading effect.

Parameters such as channel characteristics, modulation techniques, interpolation methods, and estimation approaches affected the BER performance on channel estimation. Table 1 shows the simulation OFDM system parameters for block-type.
### Table 1. Simulation parameter of block-type.

| Parameter             | Specification   |
|-----------------------|-----------------|
| Bandwidth             | 7.5kHz          |
| Channel model         | Rayleigh fading |
| FFT size              | 128, 256, 1024, 2048 |
| Guard interval        | 256             |
| Guard type            | Cyclic extension|
| Number of active carriers | 256          |
| Pilot Ratio           | 1/8             |

While table 2 shows simulation parameters detail for comb-type pilot technique. At pilot frequencies, the LS channel algorithm applied. Performance observed for corresponding SNR values.

### Table 2. Simulation parameter of comb-type.

| Parameter             | Specification   |
|-----------------------|-----------------|
| Channel model         | Rician K=11dB   |
| Doppler frequency     | 70Hz            |
| Guard Interval        | 1/32 from symbol period |
| IFFT, FFT size        | 512             |
| Modulation type       | Binary PSK      |
| Number of subcarriers | 512             |
| Pilot ratio           | 1/8             |

8. Results

Figure 3 shows the simulation performance of basic OFDM with AWGN and Rayleigh fading.

![Figure 3. BER vs. SNR for AWGN and Rayleigh fading channel.](image)

In the block-type channel estimation algorithm, all blocks contain a fixed number of symbols, and for the first symbol of each block, pilots sent in all subcarriers. Channel estimation is executed by using LS, MMSE, and LMMSE estimation algorithm. Performance analysis of block-type channel estimation shown in figure 4.
It has noted from figure 4 (a) and (b) that for FFT size, less than 1024 LS algorithm performed less as compared to LMMSE for SNR less than $25\, dB$. However, for higher FFT size (1024 and 2048), figure 4 (c) and (d) shown there is no significant difference in terms of their performance up to $40\, dB$ SNR value. Less pilot spacing is used purposely to improve channel estimation. However, it may cause the data rate reduction or bandwidth efficiency. Increasing the SNR will not improving the performance if the number of the pilot signal is comparatively undersized.

Figure 5 (a) shows the performance of the fixed pilot estimation with the number of pilots fixed at 8 and variable pilot estimation ranging from 2 to 8. The variable pilot controlled at the proposed pilot spacing controller block based on performance BER standard deviation. It shows that the improvement of $0.02\, dB$ compared to fixed pilot estimation across 0: $30\, dB$ SNR range. The total average number of pilots for every SNR range for fixed and variable is 80 and 54.59, respectively. It is shown the variable pilot spacing process at the proposed pilot spacing controller able to reduce the number of pilot signals which is known do not bring any data. Although the number of pilots varies according to BER standard deviation, the proposed technique increases the estimation performance.
Figure 5. Performance of estimation and the total number of pilot allocation for fixed pilot and variable pilot.

9. Conclusions
A variable pilot spacing using the proposed pilot spacing controller approach has presented in this paper. In the case of block pilot insertion arrangement, LS, MMSE, and LMMSE used. It shows that the number of pilots decreased with some improvement in BER and bandwidth. This finding can stimulate the environment with high SNR and has a good line of sight between transmitter and receiver. Proposed method tracks channel variations better than the typical case with fixed pilots in terms of channel estimation accuracy also in terms of channel efficiency.

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