A Pilot-Based Integration Method of Ranging and LS Channel Estimation for OFDM Systems

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Abstract: In the design of unmanned aerial vehicle (UAV) communication systems, orthogonal frequency division multiplexing (OFDM) is a commonly used communication technology. An efficient channel estimation and equalization algorithm is required to recover the amplitude, phase, and frequency of the signal in OFDM systems. At present, the more precise channel estimation method is based on the pilot. However, its spectrum utilization is relatively low. Therefore, this paper presents the design of a new pilot based on the LS channel estimation, which extends the role of the traditional pilot and improves the utilization of the spectrum. In addition to the channel estimation and equalization, the new pilot can also be utilized for ranging. Simulation results show that the proposed scheme can achieve both channel estimation and communication ranging functions by using the new pilot, and it outperforms the conventional method in channel estimation performance. The proposed method can complete ranging when the bit error rate (BER) is above 0 dB. Moreover, compared with the traditional channel estimation, it reduces the requirement for SNR by about 1 dB under the same BER.

Keywords: unmanned aerial vehicles; OFDM; ranging; LS channel estimation; pilot; pseudorandom code

1. Introduction

Unmanned aerial vehicles (UAV) have been widely utilized in the civilian field owing to their advantages of low cost, flexibility and short mission period [1–4]. To better meet the needs of different scenarios and improve the overall work efficiency and survivability, the main work form of the modern UAV system is multi-UAV cooperation [5,6]. In addition to the ability to detect the target range, UAVs should be able to complete data transmission with cooperative UAVs and networks under the mode of multi-UAV cooperation [7]. Therefore, the integration of ranging and communication is a necessary function of UAV systems.

The design of the integrated waveform is one of the crux elements in the study of communication systems that integrate ranging and communication, which can directly affect the receiving process. At present, the signal forms of integrated waveform design mainly include linear frequency modulation, spread spectrum, orthogonal frequency division multiplexing (OFDM) and other composite forms of one or more waveforms [8–12]. Among them, OFDM technology has received more attention and applications in high-speed communications and the integration of ranging and communications owing to its advantages of high spectrum efficiency, strong anti-interference ability and high data transmission rate [13,14]. However, OFDM signals are susceptible to the channel in the variable and complex transmission environment of UAVs. The main approaches to solve this problem are channel estimation and equalization.
The channel estimation is divided into three types: blind estimation, semi-blind estimation, and estimation based on the reference signal [15,16]. Among them, blind channel estimation is an estimation method that does not require training sequences and utilizes only the statistical properties of the received signal and some properties of the transmitted signal for channel estimation [17–20]. Semi-blind estimation is a channel estimation method based on blind estimation and requires a small number of pilots [21–23]. The channel estimation based on the reference signal is mainly performed by transmitting the pilot or guide signal for channel estimation and equalization [24,25]. A subspace-based blind channel estimation method is proposed in [26], which can be applied to OFDM systems without changing the original transmitter. However, the subspace-based blind estimation method is prone to the problem of phase ambiguity. In [27], a semi-blind channel estimation method based on pseudo-random suffixes is investigated. This method avoids pilot overhead compared to known cyclic prefix pilot symbol-assisted modulation schemes. However, this method may suffer from error propagation problems. In the existing reference signal-based channel estimation methods, the minimum mean squared error (MMSE) and least squares (LS) techniques have attracted more attention [28–31]. Among them, the LS channel estimation algorithm is less complex than the other algorithms. In [32], Spyros Konstantinidis and Steven Freear et al. proposed a solution using low-complexity corrected LS channel estimation. Compared with the traditional LS, this method improves the mean square error performance of the improved LS channel estimation and the performance of the bit error rate (BER) system.

In general, for the blind and semi-blind estimation, the final result of the channel estimation based on the reference signal is more closely matched to the actual situation of the channel [33]. However, this method requires the pilot to be inserted into the transmitted effective data in advance, which takes up information bits of the sent data, thus reducing the effectiveness and spectral efficiency of the transmitted data. To solve this problem, this paper innovatively improves the pilot utilization of the traditional LS estimation algorithm and proposes a method using pilot ranging to improve the frequency band utilization of LS channel estimation.

At present, using a single pseudorandom code for ranging is the most common method. The maximum fuzz-free distance measured by this method is proportional to the period of the pseudorandom code. Therefore, the period of the pseudorandom code will be relatively large when measuring distant targets, which means that it is impossible to quickly acquire and track the pseudorandom code [34]. In this paper, different short-period pseudorandom codes are utilized as pilots, and each pseudorandom code is combined into a composite code by using the characteristics of parallel data transmission in the OFDM system. The composite code has a longer period, which can measure a longer fuzz-free distance. Due to each pilot utilizing short-period pseudorandom code, the acquisition and tracking process will cost less time than traditional pseudorandom code. Moreover, the receiver can acquire and track each pilot when using these pilots to estimate the channel. According to the acquisition and tracking results of each pilot, the measured distance of the corresponding composite code can be ranged through the Chinese remainder theorem. In this way, the integration of ranging and communication can be realized under the original OFDM system framework.

In this paper, the communication system paired with this pilot is designed. The paper verifies the feasibility of this design scheme through a simulation and analyzes the channel estimation and ranging performance when using the new pilot. The results show that the OFDM system combined with the ranging code maintains the original good communication performance and achieves the ranging.

The rest of this paper is organized as follows. The system model will be described in Section 2. Section 3 describes the distance solving principles and methods. Section 4 gives the simulation result plots for model verification analysis. Finally, Section 5 concludes the paper.
2. Signal Model

In this paper, we adopt the OFDM system with parallel data transmission. After convolution coding and QPSK modulation, serial baseband transmission data are converted into \( N \) parallel transmission data symbol streams, which are modulated by subcarriers and transmitted [35], where \( N \) is the number of subcarriers.

The basic principle block diagram is shown in Figure 1.

![Figure 1. Principle block diagram of OFDM modulation and demodulation.](image)

Each of the \( N \) symbols that undergo serial-parallel transformation will be modulated by a different subcarrier. Let \( X_l[k] \) denote the \( k \)th transmitted symbol on the \( l \)th subcarrier, where \( l = 0, 1, 2, ..., \infty \) and \( k = 0, 1, 2, ..., N - 1 \). The transmission time of each symbol is \( T_s \).

Then, due to the serial-parallel transformation, the transmission time of \( N \) symbols is extended to \( NT_s \), which is the duration of a single OFDM symbol \( T_{sym} \). The time domain continuous baseband signal can be expressed as

\[
x_l(t) = \sum_{i=0}^{\infty} \sum_{k=0}^{N-1} X_l[k] e^{j2\pi f_k(t-iT_{sym})}
\]

At moments \( t = lT_{sym} + nT_s \), sampling the continuous baseband OFDM signal in Equation (1) yields the corresponding discrete-time OFDM signal:

\[
x_l[n] = \sum_{k=0}^{N-1} X_l[k] e^{j2\pi kn/N}, \quad n = 0, 1, \ldots, N - 1
\]

where \( T_s = T_{sym}/N \), \( f_k = k/T_{sym} \). Equation (2) can be obtained by N-point IDFT of the QPSK modulated signal \( \{X_l[k]\}_{k=0}^{N-1} \), or it can be quickly implemented by IFFT [36].

Without considering the channel and noise effects, the received baseband time domain continuous signal is \( y_l(t) = x_l(t) \). Also the sampled at time \( t = lT_{sym} + nT_s \), the discrete time domain form of the received signal considering the \( l \)th OFDM symbol can be expressed as

\[
Y_l[k] = \sum_{n=0}^{N-1} y_l[n] e^{-j2\pi kn/N}
\]

which is the \( N \)-point DFT of \( \{y_l(n)\}_{n=0}^{N-1} \), i.e., the demodulation of the received signal can also be implemented by the FFT algorithm [36].

To reduce the influence of the channel on the output signal recovery, the OFDM system adopts the means of channel estimation and equalization. In the previous section, we ignored the effect of the channel on the phase, amplitude, and frequency of the signal. However, the effect of the channel and noise is always present in the actual application.
environment. Under the influence of the channel, the received signal is demodulated, and the time domain received signal after discrete sampling is

$$Y[k] = H[k]X[k] + Z[k]$$

(4)

where $X[k]$, $Y[k]$, $H[k]$, and $Z[k]$ denote the transmit symbol, receive symbol, frequency response of the channel, and frequency domain noise on the $k$th subcarrier, respectively. Equation (4) shows that the OFDM system can be regarded as the product of input symbols and channel response in the frequency domain. In the absence of intercarrier interference, the receiver can recover the original signal and remove the channel interference as long as it knows the channel response of each subchannel.

To estimate and compensate for the channel, this paper adopts the LS channel estimation method based on the insertion of a comb pilot in the frequency domain. Moreover, this design utilizes the ranging code instead of the original pilot for ranging to solve the problem of low spectrum utilization of the traditional channel estimation. As shown in Figure 2, the transmitter inserts the pilots in the frequency domain at certain intervals.

![Figure 2. Comb pilot insertion in frequency domain.](image)

Different pseudo-random codes are inserted into OFDM signals in the frequency domain as pilots in Figure 2. After receiving the OFDM signal through the channel, the receiver first converts the serial signal to the parallel. Next, it removes the Cp and performs frequency offset estimation and equalization. Finally, the signal is transformed by FFT, and the result is a series of parallel sub-signals. The receiver will take out the pilots from these parallel sub-signals, which are utilized for channel estimation.

The method of LS channel estimation [37] is:

$$Y[k] = \hat{H}_{LS}[k]X[k], \quad k = 0, 1, 2, \ldots, N - 1$$

(5)

where $\hat{H}_{LS}$ is the vector matrix of LS channel estimates, and $\hat{H}_{LS}[k]$ represents the elements in $\hat{H}_{LS}$ and represents the channel estimates of the $k$th subchannel. $X[k]$ and $Y[k]$ represent the transmitted and received signals on the $k$th subcarrier, respectively. Then, for the inserted ranging subcode, the LS channel estimate value of the corresponding subchannel response is

$$\hat{H}_{LS}[i] = \hat{P}[i] \frac{P[i]}{\hat{P}[i]}$$

(6)

where $P[i]$ is the $i$th ranging code inserted at the transmitter, and $\hat{P}[i]$ is the received ranging code signal after OFDM demodulation. Therefore, the channel response estimate of the sub-channel where the pilot is located can be obtained by Equation (6) at the receiver.

The channel response of other sub-channels can be estimated by the interpolation function. In this paper, a linear interpolation function is utilized, assuming that the chan-
nel response of each sub-channel between adjacent pilots follows a linear variation rule. Therefore, the channel response of each sub-channel between pilots can be estimated by the estimated value of the channel response of adjacent pilots, and then the channel equalization of the transmitted signal will be carried out. Moreover, these extracted pilots have ranging information. In Section 3, these pilots containing ranging information will be utilized to complete the ranging by distance defuzzification algorithm when completing the channel estimation with the guarantee of ranging accuracy. This method innovatively changes the traditional way of using the pilot, which has solved the problem of low spectrum utilization caused by occupying band resources when using pilots for channel estimation.

3. Ranging

The traditional OFDM system will discard these pilots after the receiver utilizes them for channel estimation and equalization and then decode and demodulate the data. However, since these pilots are replaced by ranging codes in this paper, the role of pilots has been expanded in this paper. In addition to the channel estimation and equalization, these pilots can be utilized for ranging. Thus, the receiver will acquire and track these pilots to range the transmission distance of the signal. In this way, the problem of the low spectral efficiency of traditional LS channel estimation is solved.

3.1. Coarse Acquisition of Ranging Pilot

In ranging communications, when a single pseudorandom code is utilized for ranging, the period of the pseudorandom code needs to be large enough to achieve the measurement results without ambiguity. However, the acquisition time of traditional code acquisition methods is proportional to the period of the pseudorandom code. Therefore, it is difficult to achieve rapid acquisition of the pseudorandom code when ranging with a single ranging code. To solve this problem, different short-period ranging codes are utilized in this paper instead of the original pilot. This approach utilizes the parallel transmission feature of the OFDM system as a composite method to synthesize different ranging sub-codes into a composite ranging code. The ranging code composed of these sub-codes has greater range ambiguity. Moreover, since there is a smaller period of each sub-code than the traditional method, the receiver can achieve the rapid acquisition and tracking of these sub-codes.

OFDM is a multi-carrier parallel transmission system, and according to (5), we can see that in the absence of inter-carrier interference, each method of parallel transmission can be regarded as a separate way signal. After inserting the pilot in the frequency domain, for the \( k \)th pilot, according to (1), we can observe that the signal of the \( k \)th pilot in the time domain is

\[
p_k(t) = \sum_{l=0}^{\infty} P_l[h] e^{j2\pi f_h(t-lT_{sym})}, \quad (h-1)T_s + lT_{sym} < t < hT_s + lT_{sym} \tag{7}
\]

where \( h \) \((0 < h < N - 1)\) is the subcarrier position where the pilot is located, and \( P_l[h] \) is the \( l \)th pilot symbol on the \( h \)th subcarrier, \( l = 0, 1, 2, \ldots, \infty \).

From Formula (6), we can regard the \( h \)th pilot as an independent subsignal on the \( h \)th subcarrier. The data bit duration of each subsignal has been extended by \( N \) times compared with the original. Thus, the data symbol with the original duration of \( T_s \) has been extended to \( T_{sym} \). Since each subsignal is independent in the absence of inter-carrier interference, the time-domain continuous signal in the corresponding subchannel for the \( h \)th pilot can be equated as

\[
\hat{p}(t) = p_h(t) e^{j2\pi f_h t} \tag{8}
\]

where \( p_h(t) \) is the ranging subcode loaded on the \( h \)th subcarrier.
Under the influence of the channel, the receiver strips the subcarrier of the received ranging signal to obtain

\[ \hat{p}_h(t) = (p_h(t - \tau)e^{j2\pi(f_d-f_d)(t-\tau)} + n_h(t))e^{-j2\pi(f_d-f_d)(t-\tau)} \]

where \( f_d \) is the Doppler shift generated by the signal during propagation, \( \hat{f}_d \) is the frequency offset estimated by the receiver, \( \tau \) is the time delay generated by the signal, and \( \hat{\tau} \) is the time delay compensated after synchronization at the receiver. With perfect frequency offset compensation as well as complete synchronization, i.e., when \( f_d = \hat{f}_d, \tau = \hat{\tau} \), Equation (8) can be expressed as

\[ \hat{p}_h(t) = p_h(t - \tau) + n_h(t)e^{-j2\pi(f_h-f_d)(t-\tau)} \]

Sampling (10) at the sampling frequency \( f_s \geq 2/T_{sym} \), the discrete form of the ranging pilot signal can be obtained as

\[ \hat{p}_h(i) = p_h(i - i_s) + N(i) \]

where \( i_s \) is the phase sampling point of the ranging code corresponding to the time delay offset, and \( N(i) \) is the sampling signal corresponding to the noise. The correlation operation on (11) yields

\[ R = \frac{1}{N_h} \sum_{i=0}^{N_h} \hat{p}_h(i)p_h(i - i_k) \]

where

\[ p_h(i - i_k) \]

is the locally generated \( h \)th ranging subcode, the phase of which is shifted by \( i_k \), and \( N_h \) is the period of the \( h \)th ranging subcode. A peak of \( R \) is obtained by adjusting \( i_k \) cyclically, at which point \( i_k \) is the approximate phase after the offset of the corresponding ranging code.

In Section 2, we discussed the modulation and demodulation of OFDM, and the above sampling and demodulation processes can be obtained by fast Fourier transform. Assuming that the maximum period of each ranging subcode inserted as the pilot is \( T_m \), the receiver will extract \( T_m \) seconds of data from the parallel sub-signal with the ranging pilot after stripping the subcarrier. After synchronization, the receiver generates a local corresponding pseudorandom code, which is autocorrelated with the received ranging signal to acquire the phase shift of each ranging pilot. Based on the relatively small \( T_m \), the receiver can perform fast acquisition of each ranging code. To conserve resources, the receiver only acquires the individual ranging signals serially, i.e., it acquires each sub-signal in turn.

3.2. Tracking of Ranging Pilot

The acquisition accuracy is only within ±0.5 code chips after the preliminary acquisition, and a more accurate code chip offset can be obtained by the tracking process.

From the above analysis, it can be seen that each ranging code can be regarded as a single direct sequence spread spectrum signal without carrier interference. Therefore, the paper adopts an equal sampling tracking loop based on the direct spread baseband pseudocode DLL tracking loop. Compared with commonly used tracking loops, it eliminates the complex implementation of the loop numerically controlled oscillator (NCO) and the impact of the uncertainty of the NCO initial phase on the pseudocode tracking accuracy. The structure of the tracking loop is shown in Figure 3, which will track each ranging pilot in parallel. As shown in Figure 3, each loop has the same DLL structure, and \( \hat{p}_i(k) \) is the \( i \)th ranging pilot signal after stripping the sub carrier from the receiving end. In addition, \( i \) is the serial number of the ranging pilot, which indicates that there are \( i \) channels of pilot utilized for ranging. Moreover, \( I - D \) is the integral and accumulated result, \( E \) is the leading correlation result, \( P \) is the current correlation result, and \( L \) is the
lagging correlation result. Furthermore, $E$ and $L$ utilize a pseudo-random code that exceeds or lags behind the current $P$-branch pseudocode by one sample point, respectively. The $E$, $P$, and $L$ of the $i$th pilot can be expressed as

$$
\begin{align*}
E_i &= \sum_{k=0}^{N} \hat{p}_i(k) \cdot PL_i(k + 1) \\
P_i &= \sum_{k=0}^{N} \hat{p}_i(k) \cdot PL_i(k) \\
L_i &= \sum_{k=0}^{N} \hat{p}(k)_i \cdot PL_i(k - 1)
\end{align*}
$$

(13)

where $PL_i(k)$ is the corresponding generated local pseudo-random code signal after acquisition and $k$ represents the current phase.

The phase detector of the loop adopts the normalized point product power phase detection algorithm, and the output error $e(k)$ of the phase detector is

$$
e(k) = \frac{L - E}{P}
$$

(14)

which will control the local regenerative pseudo code generator to update a new set of pseudo code phase output $PL_i(a)$, $a = k + 1, k, k - 1$. The loop filter $F(z)$ can make the local pseudocode phase shift smoothly. This paper adopts an ideal second-order loop, and the digital filter function is

$$
F(z) = C_1 + \frac{C_2}{1 - z^{-1}}
$$

(15)

where $C_1$ and $C_2$ are constant gains.

![Figure 3. Ranging pilot parallel tracking loop.](image_url)

In the simulation analysis of this paper, in order to simplify the complex implementation of a traditional NCO, we adopt a baseband pseudocode digital tracking loop. The phase shift direction of the pseudorandom code is controlled by the new NCO of the tracking loop, and its correlation spacing is the duration of two sampling points. Its specific principle is to set a suitable threshold $\varepsilon$ to compare the output of $F(z)$. When the output of
$F(z)$ is within the range of $(-\varepsilon, \varepsilon)$, the tracking is locked. Otherwise, when the output of $F(z)$ is greater than $\varepsilon$ or less than $-\varepsilon$, the phase of the pseudocode updates the direction to the left or right. The tracking accuracy of this tracking method is related to the sampling frequency of the system. Moreover, the minimum code phase offset that the tracking loop can lock is the offset of the code slice corresponding to one sampling point. Since the receiver has acquired $\pm 0.5$ chips before tracking, the tracking process will be finished after a limited number of shift correlations.

3.3. Distance Measurement

After tracking each ranging pilot, the tracking loop will continuously output the phase offset value of the corresponding subcode. Then, according to the Chinese remainder theorem, the receiver can calculate the total phase offset and measure the transmission distance. The ambiguity resolution algorithm based on Chinese remainder is as follows.

1. Assuming that the pilot sub codes utilized for ranging in this design are $p_1$, $p_2$, and $p_3$, respectively, and the periodic coprime of each ranging sub code is $N_1$, $N_2$, and $N_3$, respectively, the maximum unambiguous distance that can be measured by the ranging code is

$$\left( N_1 N_2 N_3 \right) T_{sym} c$$

where $T_{sym}$ is the duration of a single ranging code element, and $c$ is the speed of light.

2. Let the corresponding integer digital slice offsets of the code tracking loop output be $x_1$, $x_2$, and $x_3$, and find $Y_1$, $Y_2$, and $Y_3$ that satisfy the following conditions:

$$\begin{align*}
Y_1 \mod N_1 &= 1 \\
Y_2 \mod N_2 &= 0 \\
Y_3 \mod N_3 &= 0
\end{align*}$$

$$\begin{align*}
Y_1 \mod N_1 &= 0 \\
Y_2 \mod N_2 &= 1 \\
Y_3 \mod N_3 &= 0
\end{align*}$$

$$\begin{align*}
Y_1 \mod N_1 &= 0 \\
Y_2 \mod N_2 &= 0 \\
Y_3 \mod N_3 &= 1
\end{align*}$$

(17)

3. Then the final summed integer offset $Y$ based on the individual subcode integer slice offsets is

$$Y = (x_1 Y_1 + x_2 Y_2 + x_3 Y_3) \mod (N_1 N_2 N_3)$$

The measured transmission distance is

$$(Y + Y_i) T_{sym} c$$

where $Y_i$ is the fractional code piece offset of the tracking code loop output.

The composite code chip offset is sensitive to the chip offset tracked by each ranging code. When the tracking of only one ranging code has errors, the overall calculation result will have multiple errors. However, when multiple ranging codes are used for ranging, the fractional chip offset of different ranging codes is consistent. In addition, when all ranging codes generate the same phase offset, the overall composite code will also generate the same size of phase offset. For example, assuming that the integer digital slice offsets of the code tracking loop output are $x_1 + \varepsilon$, $x_2 + \varepsilon$, and $x_3 + \varepsilon$, the final offset $Y_c$ based on chip offset tracked by each ranging code will be

$$Y_c = Y + Y_i + \varepsilon$$

(20)

Therefore, according to this feature, the receiver can self-correct these tracking results according to the acquisition and tracking results of each ranging code.

Note that the number of pilots will change depending on the number of subcarriers utilized in OFDM. Thus, the number of ranging codes utilized may vary accordingly. In the practical application environment of a UAV, only a few short-period ranging codes are needed to meet the ranging requirements. Therefore, after selecting the required ranging codes, these codes can be reused as pilots. In addition, the number of ranging codes depends on the maximum unambiguous distance of corresponding ranging codes. Table 1
gives the maximum unambiguous distance of different number of periodic coprime ranging
codes when the code rate is 0.6 MHz.

Table 1. Maximum unambiguous distance of coprime ranging codes with different periods.

<table>
<thead>
<tr>
<th>Number</th>
<th>Period</th>
<th>Maximum Unambiguous Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2, 7</td>
<td>7 km</td>
</tr>
<tr>
<td>3</td>
<td>2, 7, 11</td>
<td>77 km</td>
</tr>
<tr>
<td>4</td>
<td>2, 7, 11, 15</td>
<td>1155 km</td>
</tr>
<tr>
<td>5</td>
<td>2, 7, 11, 15, 19</td>
<td>21,945 km</td>
</tr>
<tr>
<td>6</td>
<td>2, 7, 11, 15, 19, 23</td>
<td>504,735 km</td>
</tr>
</tbody>
</table>

4. Simulation Results

In Sections 2 and 3 of this paper, the general model of this design has been discussed, and in this section, we will simulate and verify the analysis of the proposed algorithm model. The transmission and reception simulation flow are shown in Figure 4.

![Figure 4](image)

**Figure 4.** (a) Block diagram of the OFDM transmitter. (b) Block diagram of the OFDM receiver.

As shown in Figure 4, the transmitter inserts different ranging codes into the transmission signal from the frequency domain as pilots. The receiver utilizes these pilots for LS channel estimation and distance measurement, which improves the spectrum utilization of LS channel estimation. The paper has analyzed the recovery of received signal when using the ranging pilot and traditional pilot through simulation. Moreover, the acquisition and tracking performance of ranging with these pilots under different signal-to-noise ratios (SNRs) is also analyzed. Table 2 shows the parameters adopted in this simulation.
Table 2. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of total subcarriers</td>
<td>$N = 64$</td>
</tr>
<tr>
<td>Length of cyclic prefix</td>
<td>$N_{cp} = 16$</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>QPSK</td>
</tr>
<tr>
<td>Signal frequency $f$</td>
<td>34.8 MHz</td>
</tr>
<tr>
<td>Sampling frequency $f_s$</td>
<td>348 MHz</td>
</tr>
<tr>
<td>Subcarrier frequency $f_{sc}$</td>
<td>0.6 MHz</td>
</tr>
<tr>
<td>Code frequency $f_{code}$</td>
<td>0.6 MHz</td>
</tr>
<tr>
<td>Code sampling frequency $f_{s-code}$</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Channel mode</td>
<td>AWGN</td>
</tr>
<tr>
<td>DLL bandwidth</td>
<td>1 Hz</td>
</tr>
<tr>
<td>DLL correlator spacing</td>
<td>0.25 chip</td>
</tr>
<tr>
<td>Number of pseudo-random codes</td>
<td>3</td>
</tr>
<tr>
<td>The period of pseudo-random codes</td>
<td>15, 19, 23</td>
</tr>
</tbody>
</table>

As shown in Table 2, three different ranging codes are selected as pilots in this simulation, and their cycles are, respectively, 15, 19, and 23 chips. According to (15), the maximum unambiguous distance that the three ranging sub codes can range is 3,277,500 m, which can be completely applied to most UAV working environments. Figure 5 shows the comparison of the BER performance of the ranging pilot and the original pilot.

As shown in Figure 5, compared with the original pilot, the BER performance of the OFDM system has been improved after utilizing ranging pseudocodes as pilots. In the case of the same BER, when utilizing ranging codes as pilots, the requirement for SNR is reduced by about 1 dB. Therefore, this method can well realize the channel estimation function of the original pilot and improve the channel estimation performance.

After channel estimation, the receiver will continue to utilize these range codes for ranging. Since the period of different ranging codes is relatively small, this method consumes less time to acquire and track them. Figure 6 shows the acquisition probability of the receiver for the composite code and each range code under different SNRs.
Figure 5. Performance comparison chart of ranging pilot and original pilot.

Figure 6. Acquisition probability of different ranging codes.

Figure 6 shows that the receiver can perform stable acquisition for each ranging code when the SNR is $-5$ dB or more. In the actual OFDM system application, the SNR requirement of OFDM is generally above 10 dB. Therefore, in the OFDM application scenario, the acquisition performance of this system can satisfy the application requirements. From Figure 6, the acquisition probabilities of the three ranging codes are not consistent. However, the receiver needs to successfully acquire each ranging code to correctly range the transmission distance. Therefore, the overall acquisition performance can more directly
reflect the actual SNR requirement of the system. Figure 6 also shows the acquisition probability of the composite code composed of these ranging codes under the same conditions. Compared with the acquisition performance of each sub-ranging code, the overall acquisition performance is much worse under low SNR. With the increase in SNR, the overall acquisition performance is approximately identical to the acquisition of each ranging code. Therefore, when the SNR is above $-5$ dB, the OFDM system designed in this paper can complete the acquisition of the overall composite range code.

After serial acquisition of ranging codes, the receiver will track the three ranging codes in parallel. The tracking loop is shown in Figure 3. Under different SNR, the average tracking accuracy obtained by tracking the three ranging pilots for 1000 ms is shown in Figure 7.

![Figure 7. Tracking accuracy of different ranging codes.](image)

From Figure 7, when the SNR is above 2 dB, the tracking loop enters a stable state. In addition, the tracking accuracy is proportional to the pseudocode period. Therefore, the tracking loop utilized in this paper can perform remarkably under the OFDM system framework. Based on the tracking loop output results, we can range the composite code slice offset and complete ranging by Equations (17)–(19).

In Section 3, we established that the composite code chip offset is sensitive to the chip offset tracked by each ranging code. Moreover, according to the results of acquisition and tracking for each ranging code, the receiver can self-correct these tracking results through Equation (20). Figure 8 shows the average chip offset error calculated according to the tracking and corrected results of each ranging code under different SNRs.
Figure 8. Composite code phase error.

As can be seen from Figure 8, before self-correction, the receiver can only correctly calculate the composite code slice offset when the three ranging codes have been totally tracked. Moreover, the error of the calculated composite code slice offset is larger than the phase error of a single channel ranging code. After the self-correction of the tracking results, the system can correctly range the measured distance when the SNR is above 0 dB. Compared with the SNR requirement for stable tracking of a single channel ranging code, the SNR requirement for correct measurement of transmission distance is reduced by 2 dB. Moreover, the error at low SNR is also greatly reduced.

5. Conclusions

In this paper, a new pilot design scheme is proposed for the LS channel estimation method utilized in OFDM systems. The scheme implements the channel estimation and communication ranging functions on the original OFDM system framework. Moreover, it improves the spectrum utilization of the LS channel estimation. In addition, the paper designs the receiver and transmitter system based on the scheme. The simulation selects three different ranging codes as pilots, and the maximum unambiguous distance is 3,277,500 m. When the code sampling frequency is 6 MHz, the ranging accuracy can reach 50 m. The simulation results show that the system can correctly perform ranging when the SNR is above 0 dB. Moreover, this new pilot design scheme also improves the estimation performance of the LS channel estimation method. With the same BER, the requirement for SNR is reduced by about 1 dB when using the new scheme.

The scheme proposed in this paper can be applied to communication systems based on OFDM technology. Moreover, it provides a new choice regarding how to integrate ranging and communication. However, this study still has some limitations. We preliminarily listed some possible problems and research directions in the follow-up research.

1. In the complex UAV communication environment, the inter-carrier interference is inevitable when OFDM technology is used for transmission. However, this method is sensitive to inter-carrier interference and requires more accurate frequency offset estimation and equalization. In this paper, we mainly conducted research under the
condition of perfect frequency offset equalization. Therefore, research on the way to reduce the inter-carrier interference based on the proposed scheme is needed in the subsequent research.

2. In OFDM systems, there are many pilot-based channel estimation methods. This paper only considers the design scheme based on LS channel estimation. Although LS channel estimation has low complexity and is relatively easy to implement, in different communication environments, it may be necessary to consider using other channel estimation methods. The innovative ideas proposed in this paper can continue to be applied to other pilot-based channel estimation methods for research.

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