Radar Detection Based on Pilot Signals of LTE Base Stations

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Abstract. This paper presented a new signal design method for target detection. As the development of communication equipment, wireless communication has gradually developed to high frequency band and large bandwidth, which makes communication and radar systems gradually have common characteristics in frequency occupancy, system architecture and antenna composition technology. In the context of the LTE base station signal, the pilot signal is inserted into the frame format of the OFDM signal to enhance the target detection performance of the base station. The signal is affected by Doppler shift and the velocity resolution is degraded. This paper presents a new method to improve the speed resolution of the target. Simulation and experiment proved the method has good effect.

Keywords: OFDM · LTE base station · Target detection · Signal sharing

1 Introduction

1.1 A Subsection Sample

In recent years, research on communication radar integration has been ongoing. With the evolution of 4G and 5G, OFDM technology has become one of the most critical technologies of LTE [1]. At the end of the twentieth century, OFDM technology first appeared in radar systems. Jankiraman found that OFDM radar has good velocity range resolution, low autocorrelation side lobes and high probability of interception [2]. The characteristics of OFDM that exhibits anti-clutter interference and suppression of multipath fading in communication systems are also used in radar systems. Martin Braun and Yves Koch proposed a radar and communication system using 24 GHz OFDM signals [3]. However, the convergence of radar and communication poses some problems. If the OFDM waveform is only used for radar transmission, the detection performance will deteriorate. Therefore, some processing of the OFDM signal is required to ensure the performance of the communication while improving the performance of the radar system. Therefore, the coding of OFDM and the frame structure of OFDM require a reliable design. Ruggiano studies OFDM radar signals from the perspective of waveform design and optimization [4], and analyzes the wide-band ambiguity function (WAF) in radar integrated systems to compare the performance of narrow-band ambiguity functions (NAF). The system combines the possibility of an integrated system, and the radar-communication integrated system combines the

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characteristics of high resolution and large data rate. Extending the radar-communication concept into a multi-path, multi-user environment, faced with the challenge of real multipath scene settings near the radar. Interference signals severely damage the dynamic range of the radar. Some researchers have implemented interference cancellation schemes using the received availability of radar communication signals [5]. The interference cancellation scheme utilizes information extracted from regularly spaced pilot symbols within an OFDM frame. The frequency offset information is extracted from the channel estimation matrix by a frequency offset estimator.

The focus of this paper is to share the target detection using the pilot signal of OFDM, and obtain the distance and speed for the moving target in the cell range. The pilot signal is inserted in the frame format of the OFDM signal for better resolution.

2 Theory Basis and Simulation Configuration

2.1 Shared Signal Form and Transceiver Mode

The OFDM waveform transmitted by the base station is radiated in the cell and reflected by objects in the cell, such as a vehicle, which can be received by the passive detection radar. The detection radar needs to determine which of the received signals is the waveform reflected by the vehicle at that time. A signal having a special form, such as a pilot signal, can be inserted in the frame format of the transmitted signal. Pilot signals have a synchronous effect.

The radar part of the communication radar integrated system is the bistatic radar [6]. The definition of bistatic radar is to use transmitters and receivers separated by a certain distance. The receiver is passive detection, and the transmitter is a civilian base station as a radiation source, as shown in Fig. 1.

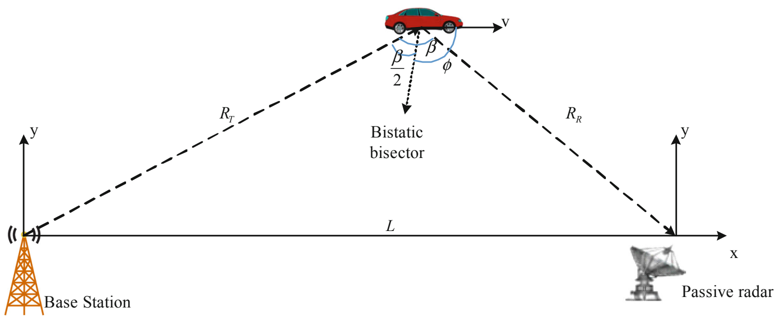


Fig. 1. Shared signal based on bistatic receiving model

In this mode of operation, there is no need to switch the mode of communication or radar, only need to change the format of the transmitted waveform slightly, which can be used for passive detection. The operation not only can synchronize signals, but also improve the performance of target detection. Frame format of the transmitted signal is shown in Fig. 2. The physical layer protocol data unit (PPDU) frame structure is defined in the 802.11a standard, that is, the data structure generated by the baseband transmission processor.

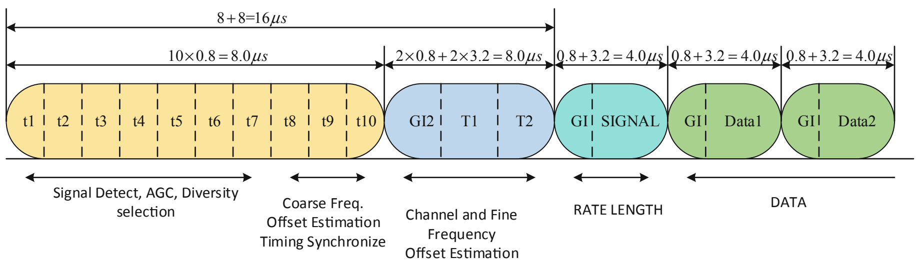


Fig. 2. PPDU frame format

2.2 Signal Model and the Ambiguity Function

An OFDM multi-carrier signal [7] can be considered as a parallel stream carrier waveform with orthogonal multiple carrier signals, each modulated with different transmission information, and the signal can be expressed as

$$x(t) = \sum_{\mu=0}^{N_{sym}-1} \sum_{n=0}^{N_c} a(\mu N_c + n) \exp(j2\pi f_n t) rect(\frac{t - \mu T_{OFDM}}{T_{OFDM}}) \tag{1}$$

with μ representing the sequence number of each OFDM symbol within the total amount of N_{sym}, n being serial number of a single subcarrier within the total amount of N_c subcarriers, a denoting the complex modulation symbols, f_n representing the individual subcarrier frequency, $T_{OFDM} = T + T_G$ being the total duration of an OFDM symbol, consisting of the OFDM symbol duration T and the cyclic prefix time T_G, $rect(t/T_{OFDM})$ denoting a rectangular window time for a duration T_{OFDM}. Time and frequency domain structure of OFDM waveform is shown as Fig. 3 [6].

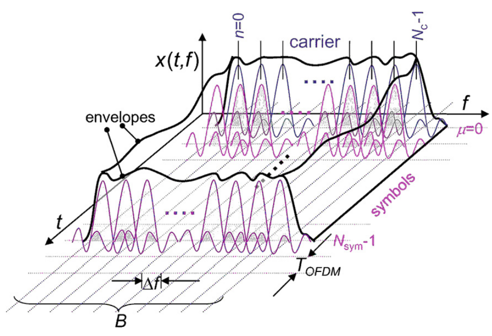


Fig. 3. Time and frequency domain structure of OFDM

During an OFDM symbol time, its frequency domain contains a large number of subcarriers, and the necessary modulation information is carried on these subcarriers, which can achieve a high data transmission rate. The OFDM waveform in the time domain looks like noise which has good transmission performance.

As one of the important indicators of radar signal design, the ambiguity function can analyze whether the OFDM signal can show good detection performance in the radar system.

Taking a single OFDM signal as followed

$$s(t) = \sum_{n=0}^{N-1} a(n) \exp(j2\pi n\Delta f t) \tag{2}$$

The echo signal of a single OFDM signal reflected by a target

$$r(t) = s(t-\tau)e^{j2\pi f_d t} + n(t) \tag{3}$$

with Δf denoting subcarrier spacing, τ being echo delay time, f_d being doppler shift, $n(t)$ representing gaussian white noise.

The ambiguity function of a single OFDM signal can be expressed as

$$\chi(\tau, f_d) = \int_{-\infty}^{\infty} r^*(t)s(t)dt$$

$$= \sum_{l=0}^{M-1}\sum_{k=0}^{N-1} \exp(j2\pi l\Delta f\tau)a(k)a^*(l) \int_{-\infty}^{\infty} \exp\{j2\pi(k\Delta f - l\Delta f - f_d)\}dt \tag{4}$$

Extract some integral items

$$\int_{T_{\min}}^{T_{\max}} \exp(-j2\pi f t)dt = T_d \sin c(\pi f T_d) \exp(-j2\pi f T_a) \tag{5}$$

with $T_d = T_{\max} - T_{\min}$, $T_a = (T_{\max} - T_{\min})/2$.

$\chi(\tau, f_d)$ can be expressed as

$$\chi(\tau, f_d) = \sum_{l=0}^{M-1}\sum_{k=0}^{N-1} \exp(j2\pi l\Delta f\tau)a(k)a^*(l)$$

$$\cdot \sin c\{\pi(l\Delta f + f_d - k\Delta f)T_d\} \exp\{j2\pi(k\Delta f - l\Delta f - f_d)T_a\} \tag{6}$$

According to the basic definition of OFDM, the subcarriers in the frequency domain have orthogonality, so only when $k = l$, the value of $\chi(\tau, f_d)$ is the largest, that is, the larger energy is displayed on the ambiguity function. The expression in this case is

$$\chi(\tau, f_d) = \sum_{l=0}^{M-1} \sum_{k=0}^{N-1} \exp(j2\pi l \Delta f \tau) a(k) a^*(l)$$

$$\cdot \sin c\{\pi(f_d - k\Delta f) T_d\} \exp\{j\pi(f_d - k\Delta f) T_a\} \quad (7)$$

When $\tau = 0, f_d \neq 0$, the two-dimensional ambiguity function is transformed into a velocity ambiguity function.

$$\chi(0, f_d) = \sum_{k=0}^{N-1} a(k) a^*(k) \sin c\left\{\pi\left(\frac{f_d}{\Delta f} - k\right)\right\} \exp\{-j\pi(f_d - k\Delta f) T\} \quad (8)$$

with T representing the duration of this OFDM signal, and its speed resolution is determined by the $\sin c$ function with a speed resolution of $1/T$.

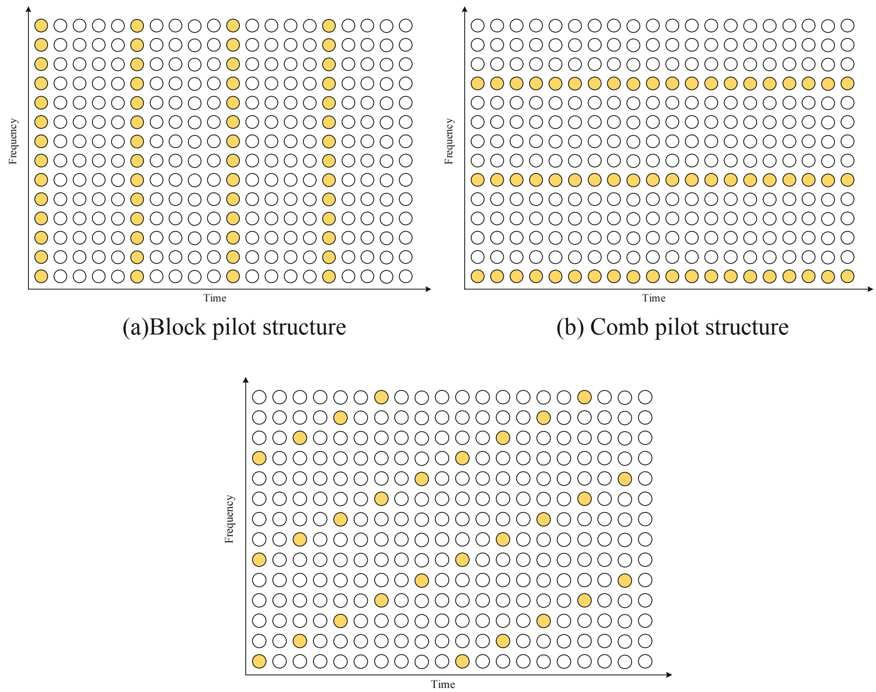
When $\tau \neq 0, f_d = 0$ the two-dimensional ambiguity function is transformed into a distance ambiguity function.

$$\chi(\tau, 0) = \sum_{k=0}^{N-1} a(k) a^*(k) \exp\left(j2\pi \frac{k}{N} B\tau\right) \quad (9)$$

with B represents the subcarrier bandwidth. When $\tau = 1/B$, $\chi(\tau, 0) = 0$. In other words, the distance resolution is $c/2B$.

2.3 Pilot Signal

The pilot is a channel estimation method based on auxiliary information. If the pilot is periodically allocated to the OFDM block in the time domain, the pilot is suitable for the slow fading wireless channel [8]. The shape structure of the pilot determines the applicable range of the pilot channel estimate. In the mobile communication system, the coherent monitoring and decoding of data requires prior knowledge of the channel information between the transmitting and receiving antennas. In order to obtain the frequency response of the mobile channel, a common method is the pilot assisted channel estimation algorithm, that is, using the pilot signal to the channel. The channel estimation is performed by sampling at different points in the time domain space and then using interpolation filtering to obtain the frequency response value of the entire channel. Three common pilot structures are shown in Fig. 4.



(a)Block pilot structure (b) Comb pilot structure

(c) Discrete pilot structure

Fig. 4. Three common pilot structures

For the signal transmitted by the base station, this paper proposes a new type of discrete pilot structure which is shown as Fig. 5.

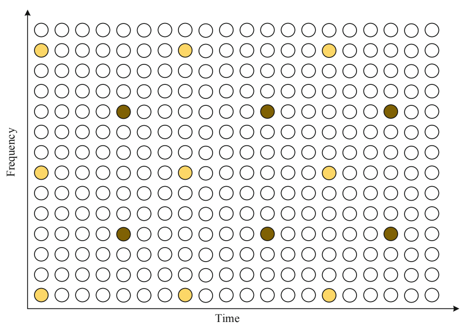


Fig. 5. Pilot structure based on cell-specific reference signal

This kind of structure optimizes moving objects in a cell. The LTE system can operate under high-speed mobile conditions, so the required time interval between reference symbols can be 500 km/h from the maximum Doppler LTE system it supports. The Doppler shift is $f_d = f_c v/c$, with f_c being carrier frequency, v being speed of users, c being Speed of light. Assuming $f_c = 2\,\text{GHz}$, $v = 500\,\text{km/h}$ then the Doppler shift is $f_d \approx 950\,\text{Hz}$. According to the Nyquist sampling theorem, the minimum sampling frequency that can recover the channel is $T_d = 1/(2f_d) \approx 0.5\,\text{ms}$. In other words, two reference symbols are needed for each time slot in the time domain in order to correctly estimate the channel. In the frequency domain, on each OFDM symbol containing reference symbols, there is one reference symbol between every 6 subcarriers. However, reference symbols are staggered, so in each resource block, there is one reference symbol between every three subcarriers.

Table 1. The parameters of the bistatic system

Symbol	Parameter	Value
B	Signal bandwidth	20 MHz
f_c	Carrier frequency	2.6 GHz
N_c	Number of subcarriers	1200
N_{sym}	Number of symbols	120
Δf	Subcarrier spacing	15 kHz
T	OFDM symbol duration	10 ms
F_n	Noise bandwidth	2 dB
$(S/N)_{\min}$	Minimum signal to noise ratio	20 dB
P_T	Transmitter power	20 W
G_T	Transmitter antenna power gain	30
G_R	Receiver antenna power gain	30
σ_B	Cross-sectional area	3–20 m^2

2.4 Detection Performance Analysis

Figure 1 shows the geometric relationship of the bistatic radar. According to this structure, the bistatic radar equation can be obtained.

$$(R_T R_R)_{\max} = \left[\frac{P_T G_T G_R \lambda^2 \sigma_{\mathrm{B}}}{(4\pi)^3 P_{R\min}}\right]^{\frac{1}{2}} \tag{10}$$

with P_T being the transmitter power, G_T being the transmitter antenna power gain, G_R being the receiver antenna power gain, λ being the wavelength of the transmitted signal, σ_B being the cross-sectional area of the target, and $R_T R_R$ being the distance product.

The minimum detection power of the receiver is

$$P_{R\min} = kF_nT_sB_n\left(\frac{S}{N}\right)_{\min} \tag{11}$$

with k being the Boltzmann constant ($k = 1.38 \times 10^{-23}$ J/K), F_n being receiver detector front noise bandwidth, T_s being the receiver noise temperature, the standard reference temperature being 290 K, B_n being the noise bandwidth before the receiver detector, $(S/N)_{\min}$ being the minimum signal to noise ratio received.

The parameters of the bistatic system are shown in Table 1. From the table can calculate the distance resolution which is

$$\Delta R = \frac{c_0}{2B\cos\left(\frac{\beta}{2}\right)} \tag{12}$$

Speed resolution is expressed as

$$\Delta V = \frac{\lambda}{2T\cos\left(\frac{\beta}{2}\right)} \tag{13}$$

3 Simulation and Results

The regular pilot leads to the appearance of a blur function secondary peak of the OFDM signal, which is a bad influence for target detection. The pilot does not necessarily fill the entire symbol area, but rather exists in a certain interval. Pilot signals have some important characteristics which are shown in the Table 2.

Table 2. The parameters of the pilot signal

Characteristic parameter	Symbol	Comment
Data amplitude	σ_d	Average amplitude of data within the data frame
Pilot amplitude	σ_P	Average amplitude of data within the data frame
Translation distance	m	Translation distance between symbols in a data frame, an integer
Translation distance	p	Translation distance of adjacent symbol pilots in a data frame, integer
Pilot region ratio	α	Proportion of subcarriers containing pilot regions,
Pilot density	k	Proportion of the number of pilots in a data frame, $k \approx \alpha/m$

Assuming $R_T = 2\,\mathrm{km}$, according to the parameters discussed, the minimum detection power of the receiver can be obtained as $P_{R\min} = -84.95\,\mathrm{dbmW}$. The echo power of the target located in the radiation range of the base station base station is shown in Fig. 6.

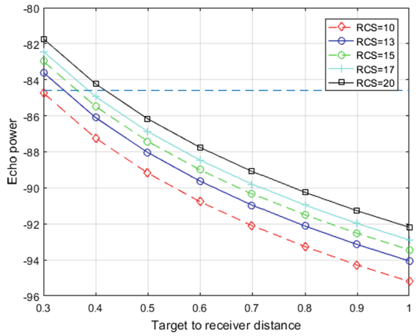


Fig. 6. Echo power for target distance diagram

In the case of a 20M bandwidth communication signal and dual base station target detection, for a target within a cell communication range of the base station (2 km) and its cross-sectional area is relatively large, theoretically the distance from the target antenna to the receiving antenna is 0.45 km. The echo power is greater than the minimum detectable power of the receiver, that is, the target within 0.45 km can be detected. In order to obtain a better detection range, the signal bandwidth can be increased or the transmission power can be increased, and the waveform can be optimized as necessary. With $\beta = 15^{\circ}$, the distance resolution of bistatic radar is $\Delta R = 7.57\,\mathrm{m}$, while the speed resolution is 0.58 m/s.

Change the waveform of the transmitted wave under the model of the dual base station. Figures 7 and 8 shows the ambiguity function of block pilot and comb pilot.

The ambiguity function of the new discrete pilot structure designed in this paper is shown in the Fig. 9. The parameters of the pilot structure are $\sigma_P = 1$, $m = 3$, $P = 6$, $\alpha \approx 0.143$, $k \approx 0.048$.

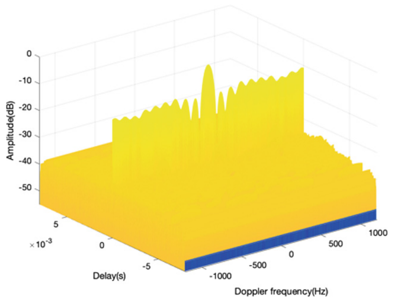


Fig. 7. The ambiguity function of block pilot

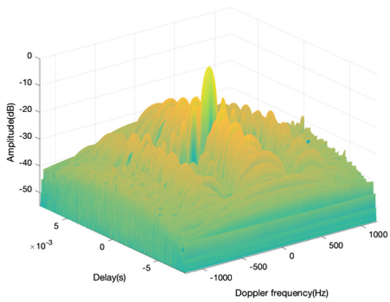


Fig. 8. The ambiguity function of comb pilot

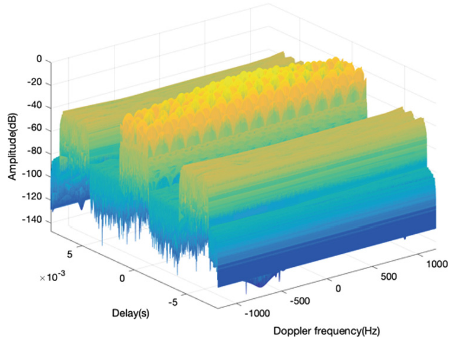
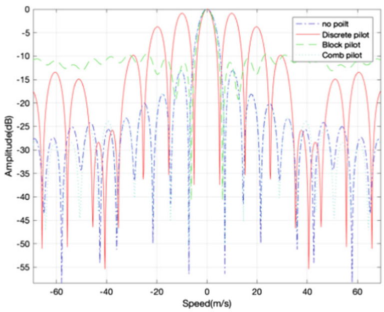
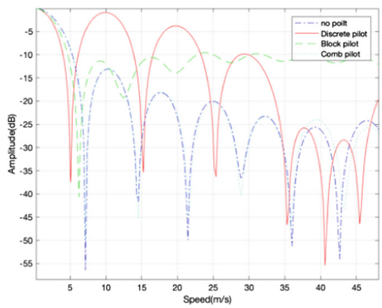


Fig. 9. The ambiguity function of the new pilot discrete

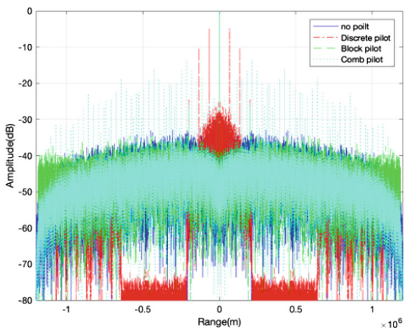
The regular pilot does not contribute to the distance resolution and speed resolution of the downlink OFDM signal. In the actual LTE system, the regular pilot is applied in the uplink, and the scattered pilot is applied in the downlink, the pilot not only enables synchronization and channel estimation, but also improves the speed resolution without affecting the distance resolution. The effect of the scattered pilot on the range resolution is unfavorable, and a higher amplitude side lobe are generated around the main lobe of the origin.



(a) Speed resolution result



(b) Speed resolution result magnified view



(c) Distance resolution result

Fig. 10. Different pilot structure resolution comparison results

Specifically observe the impact of various pilot structures on resolution which is shown as Fig. 10.

From the comparison of the velocity ambiguity function, the main lobes of the velocity ambiguity function inserted into the discrete pilot and the inserted block pilot are narrower than the main lobes without the pilot signal inserted, indicating that the velocity resolution is better, and the insertion is better. The speed resolution of the comb pilot is almost unchanged from that of the unplugged pilot. From the distance ambiguity function, it can be seen that the autocorrelation is reflected in the frequency domain position of the inserted pilot, but around the very narrow main lobe. A narrow side lobe closer to the main lobe are generated, but because the peak ratio of the main lobe and the side lobe main lobe are within an acceptable range, the detection performance of the pilot signal is better to traditional method.

4 Conclusion

This paper proposes a radar communication shared signal waveform, which can achieve higher resolution while using OFDM signals for target detection. Firstly, the ambiguity function of OFDM signal is derived, and then the ambiguity function of OFDM signal in various pilot forms is analyzed. The simulation results show that the proposed discrete pilot form has higher speed resolution than other forms. Therefore, the proposed method can effectively solve the Doppler ambiguity problem and improve the target detection ability.

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