FPGA Implementation of Rake Receiver in Broadband Micro-power Wireless Communication System

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Abstract. Aiming at the problem that receiver performance is seriously degraded by multipath fading in multipath channel, a three-finger Rake receiver design scheme is proposed, based on Chirp spread spectrum technology for multipath search, delay estimation and phase estimation. Firstly, the windowed algorithm is adopted in multipath search to improve the accuracy of multipath search. Secondly, detecting the spacing between multipath peaks can realize the delay estimation of multipath signals. Finally, the multipath signals are merged to enhance the receiving effect, significantly improving the system's block error rate performance under the multipath channel environment. Matlab simulation shows that adding a Rake receiver in the system can improve performance by about 1.2dB. A multi-switching mechanism is applied in FPGA implementation, in order to reduce the hardware power consumption. FPGA simulation results verify rationality and correctness of the design, indicating that the system meets the requirements of block error rate less than 1% in actual transmission, when the signal-to-noise ratio is -2dB.

1. Introduction
The smart grid[1-2] has gradually become the focus of the development of the entire power industry, and will lead the development trend of the entire power grid. The current smart meter data collection methods mainly include RS485, power line carrier communication technology and narrowband micro-power wireless communication technology[3]. The main working frequency is in the 470~510MHz frequency band. However, with the increasing number of users and the increasing demand for network services, the existing narrowband micro-power wireless communication technologies have disadvantages such as low frequency, small bandwidth, unstable signals, and poor networking performance. It is increasingly unable to meet the development needs of the current smart grid. In this context, there is an urgent need to further study broadband micro-power wireless communication technology to effectively solve this problem. This paper focuses on the use of Rake receiver technology[4] in broadband micro-power wireless communication systems to effectively offset the adverse effects of multipath fading.

Multipath fading in broadband micro-power wireless communication systems is primarily Rayleigh fading. Since the multipath component signals arriving at the receiver with different delays and phases, the signals are superimposed on each other to cause fading[5]. By using the Rake receiver, the multipath component in the received signals can be effectively distinguished, and the resulting multipath signals can be subjected to diversity gain, thereby improving the performance of the entire...
system. In addition, the use of FPGA chips to achieve Rake receiver module has the advantages of small size, fast running speed, good real-time performance and high portability.

2. Broadband micro-power wireless communication system model

The block diagram of the broadband micro-power wireless communication system is shown in Figure 1:

![Block Diagram](image)

Figure 1. Broadband micro-power wireless communication system block diagram

In this system, Chirp spread spectrum technology and binary orthogonal keying (BOK) modulation\cite{6} is adopted. The Chirp signals of positive and negative slopes are used to represent the Up-Chirp signal and the Down-Chirp signal respectively, and represent the modulation method of binary 1 and 0. The modulated Chirp-BOK time domain signal can be expressed as:

$$S(t) = ce^{j2\pi f_c t + \Delta \phi} + (1 - c)e^{j2\pi f_c t - \frac{T}{2}}, \ t < \frac{T}{2}$$

(1)

Where, \( k > 0 \) is the modulation slope, \( f_c \) is the center frequency, and \( c = \{0, 1\} \) is the binary symbol data. It can be seen from equation (1) that the positive frequency slope and the negative frequency slope Chirp signal are conjugated after inversion, and the impulse response of their corresponding matched filters can be obtained. At the receiving end, two corresponding matched filters are used to detect the signal, and the received signal is processed by the Up/Down-Chirp matched filter, and the bit information is restored by put the output result into square detector. This method can be used for signal detection, peak detection, and signal demodulation\cite{7,8}.

When the signal is correlated to a matched filter, the output signal becomes:

$$S_{\text{match}}(t) = \sqrt{T_sB} \sin(kT_s|t|) e^{j2\pi f_c t + \Delta \phi}$$

(2)

When the signal is not correlated with the matched filter, the output signal becomes:

$$S_{\text{unmatch}}(t) = \left[ C \left( \sqrt{T_sB} - |t| \sqrt{k} \right) \pm jU \left( \sqrt{T_sB} - |t| \sqrt{k} \right) \right] e^{j2\pi f_c t + \frac{\pi}{2} k |t|^2 + \Delta \phi}$$

(3)

Where, \( \Delta \phi \) is the phase difference between the received signal and the corresponding matched filter impulse response, \( C(x) = \int_0^x \cos \frac{\pi y^2}{2} dy \) and \( U(x) = \int_0^x \sin \frac{\pi y^2}{2} dy \) are Fresnel integral terms, when calculating equation (3), if the Up-Chirp signal passes through the Down-Chirp matched filter, “+” is taken, and if the Down-Chirp signal passes the Up-Chirp signal, “-” is taken. It can be seen from equation (2) that when the input signal passes through its corresponding matched filter, the amplitude becomes \( \sqrt{TB} \) times of the input signal at \( t = 0 \), which indicates that the Chirp signal has good pulse compression characteristics after corresponding matching filtering\cite{9}.

Due to the multipath effect, the received signal is superimposed by N signals. The amplitudes of the multipath signals are \( a_i = \{a_1, a_2, \ldots, a_N\} \), the phase deviation are \( \phi_i = \{\phi_1, \phi_2, \ldots, \phi_N\} \), the delay are \( \tau_i = \{\tau_1, \tau_2, \ldots, \tau_N\} \), and the signal at the receiving end can be expressed as:
Where, \( i = 0 \) represents the main path signal, and \( i = 1, 2, \cdots, N \) represents the multipath signals.

The frame structure of the broadband micro-power wireless communication system is shown in Figure 2. Among them, the preamble structure P is composed of 50 Up-Chirp signals, which can be used for time-bias estimation and multipath search, delay estimation and phase estimation in the Rake receiver. The synchronization code M is composed of 5 Down-Chirp signals, which can be used for frequency offset correction. Control bit C carries the attribute information of the frame. The frame interval F consists of 5 Down-Chirp signals, which can be used for frame synchronization. The payload data D carries valid data for different services. This paper mainly introduces the design and implementation of Rake receiver using preamble.

![Figure 2. Frame structure of broadband micro-power wireless communication system](image)

### 3. Rake receiver design

The hardware implementation block diagram of the receiving end is shown in Figure 3. It is mainly composed of data preprocessing module, time offset and frequency offset estimation module, Rake receiver module and channel decoding module. The data preprocessing module includes Automatic Gain Control (AGC), Automatic Frequency Control (AFC), FIR filter and DC cancellation module.

![Figure 3. Hardware implementation diagram of receiver](image)

#### 3.1. Rake receiver principle

Rake receivers use diversity reception technology\[^{[10-16]}\], which is one of the most effective ways to solve multipath fading problems. In the wideband micro-power wireless communication system, according to the good autocorrelation and pulse compression characteristics of the Chirp signal, the multipath component can be regarded as the retransmission of the transmitted signal through different delays, when the delay difference between these multipath components exceeding the length of one chip, the Rake receiver can treat these multipath components as uncorrelated noise.

Since the multipath signals also carry useful information, according to the good autocorrelation property of the Chirp signal, the multipath components of different paths can be detected by the matched filter and distributed to different peaks of the Rake receiver for processing, and the processed multipath signals are effectively combined to improve the signal-to-noise ratio at the receiving end, thereby effectively improving the transmission performance of the system.
3.2. FPGA implementation of Rake receiver

According to the working principle of Rake receiver and the characteristics of physical channel of wideband micro-power wireless communication system, a three-finger Rake receiver design scheme based on Chirp spread spectrum technology for multipath search, delay estimation and phase estimation is proposed, as shown in Figure 4. In the Rake receiver, three-way parallel computing is used, in which the multipath searcher plays a vital role, searching for three effective multipath signals from the received signals and estimating their delays separately, according to the different effective path delay values are assigned to different branches for processing. In the process of phase estimation, there is a switching mechanism. When the switch points to 1, the phase offset value is estimated. When the switch points to 2, the phase compensated is adopted, and the local signal is stored by using a lookup table. It can greatly improve the working efficiency of hardware operation, and finally combine the signals output by the three branches to maximize the ratio.

![Figure 4. Three-finger Rake receiver implementation diagram](image)

Where $r_n$ is the received signal, $\tau_i$ is the estimated delay of each warp, $m(t)$ is the local signal, and $Z_i$ is the phase estimate.

3.2.1. Multipath search

The multipath searcher plays a key role in the Rake receiver, which is primarily composed of matched filters and multipath selectors\textsuperscript{17-18}. The function of the multipath searcher is to detect multipath components at different delay positions by matching filters. Due to the influence of noise, when the signal-to-noise ratio is low, the searcher may lock the effective path to the wrong peak if the corresponding condition is not judged. To this end, a plurality of windows need to be set in the searcher, and a “correlation peak threshold” (adaptive threshold) is set in the process of searching for the effective path in the search window, and the relevant peak value exceeding the threshold in the search window is referred to as an effective path. The maximum value of the correlation peak is referred to as a quasi-correlation peak. If the quasi-correlation peak appears within the effective range of the search window, the correlation peak detection of the window detection area is successful, and vice versa, the correlation peak in the detection area is determined to be undetectable.

As shown in Figure 5, the range $W$ of multipath search window is set to 57 sample points, and the delay of multipath in a frame remains unchanged by default, where $TC$ is the distance between the
central position of the correlation peak window and the correlation peak of the previous symbol. Here, the width $\tau$ of the correlation peak window is set to 10 samples points. In the noisy environment, the setting of the correlation peak threshold is very important. The key point is that the noise power is effectively estimated, and the correlation value between the current symbol and the previous symbol is accumulated and averaged. The correlation peak threshold can effectively reduce the “missing probability” and the “false detection probability” by setting these effective parameters.

![Diagram](image)

Figure 5. Window Settings for multipath searchers

The multipath selector (Figure 6) selects the three strongest signals from the searched multipath signals and distributes them to the three branches of the Rake receiver for processing. Among them, the main path search is the most important one in the multipath search module, which will determine the accuracy of the delay estimation between multipath signals and whether the Rake receiver can work normally. Within the set effective search range, a sliding window having a width of 10 working clock cycles is generated, wherein a peak larger than the correlation peak threshold is detected as a quasi-main peak, and if a peak larger than the quasi-main peak is detected in the window, the peak is replaced by a quasi-main peak and the sliding window is dynamically extended from the quasi-peak position by 10 working clock cycles, and detection is resumed until the position of the main peak is determined. This can effectively avoid the false main peak and reduce the "missing probability".
Among them, $S$ is the ratio of the peak value of the main path to the average power of one symbol, and the peak-to-average ratio $S$ will function as a switch. When the peak-to-average ratio $S$ is greater than or equal to $V$, the current communication quality is better, and the switch is set to 2, keep the Rake receiver working properly. When the peak-to-average ratio $S$ is less than $V$, it indicates that the current communication quality is very poor. Then the switch is set to 1, the Rake receiver is turned off, the data is not processed until the communication quality is improved. After a large amount of data testing, the peak-to-average ratio threshold $V$ is set to 5, and after finding the main path, the remaining two passes are sequentially searched, and the same method of finding the main path is used. In order to ensure the reliability of the detected multipath position, the function of the peak detection is activated at the detected multipath position. If the multipath searched in the continuous 3 symbols is at the same position, that is, the actual position of the multipath is considered to be found, the leakage peak detection is turned off, otherwise the detection will be restarted.

3.2.2. Phase estimation and multipath merging

Since the multipath effect causes phase rotation of the received signal during transmission, in the process of coherent demodulation, if two phases are reversed, the amplitude of the received signal will be seriously degraded. Therefore, by performing phase estimation and phase correction on the received signal, it plays an important role in improving system performance\textsuperscript{[10]}.

Phase estimation is performed on each path of the multipath signal that has been searched. For the first path, we multiply the received signal by the conjugate of the local signal. To enhance the reliability of the phase estimation result, eight consecutive symbols are used here. To estimate the phase, and the multipath peaks of the 8 symbols are in the same position (the position offset is no more than 1 sample). For the second and third paths, the delayed data is multiplied by the conjugate of the local signal, and the phase estimation is performed using the same estimation method as the first path.

$$\text{phase}_i = \text{angle}(\text{mean}(r_i(t)) \cdot S_{\text{local}}(t - \tau_i))^\ast$$

(5)

Where $\text{phase}_i$ represents the phase of the $i$th path, $\tau_i$ represents the time delay of the $i$th path, and $r_i(t)$ represents the received data of the Nth path.
4. Rake receiver engineering implementation and performance

The Rake receiver module is added to the broadband micro-power wireless communication system and the Matlab performance simulation is performed. In the simulation, the parameters such as frequency offset, phase offset and time delay of the transmitted signal are modified to simulate multipath phenomenon, and the fading model adopts Rayleigh fading. The Rake receiver is added and not added are simulated in the same environment. The simulation results are shown in Figure 7.

| Parameter               | Parameter content                  |
|-------------------------|------------------------------------|
| channel                 | Using Band-Limited AWGN Channel    |
| Coding method           | 1/2Turbochannel coding             |
| Sampling rate           | 78MHz                              |
| modulation mode         | Chirp-Bok                          |
| Preamble rate           | 37.5Kbps                           |
| bandwidth               | 3.6MHz                             |
| preamble size           | 50                                 |
| Payload rate            | 600Kbps                            |
| Number of test frames   | 2000                               |

Table 1. Simulation parameter

In the hardware simulation, XILINX's ISE 14.7 logic synthesis software was used for design synthesis. The timing simulation was performed by Mentor's ModelSim SE-64 10.4 simulation software. Figure 8 is the timing simulation waveform of Rake receiver.
In the hardware simulation process, as shown in Figure 9, the ROHDE & SCHWARZ SMW200A vector signal generator is used to generate multipath signals for simulating the transmitter and the Rake receiver is implemented on the 5791 board of National Instruments (NI) to simulate the receiver. The frequency offset of the set transmission signal is set to 1.6 kHz, the transmission power is set to -60 dBm, and the second and third paths are attenuated by 3 dB, and the delays are set to 200 ns and 500 ns, respectively, and at different signal to noise ratios. In the case of testing, Table 2 is a performance comparison block diagram of the Rake receiver.
Table 2. Rake receiving performance comparison chart

| Frequency offset /KHz | Transmit power /dBm | With or without Rake | SNR/dB | Block error rate |
|-----------------------|---------------------|----------------------|--------|------------------|
| +1.6                  | -60                 | no                   | +2.4   | 3.2%             |
| +1.6                  | -60                 | no                   | +2.6   | 1.5%             |
| +1.6                  | -60                 | no                   | +2.8   | 0.54%            |
| +1.6                  | -60                 | no                   | +3     | 0.27%            |
| +1.6                  | -60                 | no                   | +4     | 0.02%            |
| +1.6                  | -60                 | have                 | -3     | 4.2%             |
| +1.6                  | -60                 | have                 | -2.8   | 0.97%            |
| +1.6                  | -60                 | have                 | -2.6   | 0.34%            |
| +1.6                  | -60                 | have                 | -2.4   | 0.07%            |
| +1.6                  | -60                 | have                 | -2.0   | 0.01%            |

The experimental results show that in the broadband micro-power wireless communication system, the performance of the multi-path condition is improved by about 1.2 dB compared with the case where the Rake receiver is not added, and the Rake receiver can effectively resist the multipath effects to improve the transmission performance of the broadband micro-power wireless communication system. Then we implemented the hardware on the NI hardware simulation platform. The analog data is transmitted in the real air interface, which further verifies the correctness and feasibility of the solution. And when the signal-to-noise ratio is -2dB, the actual transmission requirement that the block error rate is less than 1% is satisfied.

5. Conclusion
Aiming at the influence of multipath interference on the system in wideband micro-power wireless communication system, Rake receiver technology is used to suppress multipath interference in the system. By simulation with Matlab, the performance of the proposed scheme is improved about 1.2dB with that without Rake receiver, indicating that adding Rake receiver to the system can effectively resist multipath interference. Finally, the proposed scheme is tested on NI's 5791 board. In actual board test, FPGA circuit runs stably and has good real-time performance, further verified the effectiveness and feasibility of Rake receivers in multi-band interference in wideband micro-power wireless communication systems. However, due to the low signal-to-noise ratio, there will be some errors in multipath search. In the following work, it is necessary to further explore new methods with low complexity and excellent performance to reduce the impact of noise on the operation.

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