The modified CP-AFC with Multistage Tracking Mode for WCDMA Reverse Link Receiver

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Abstract: In this paper, we propose a modified CP-AFC(Cross-Product Automatic Frequency Control) algorithm to enhance coherent signal detection for WCDMA reverse link receiver. We introduce a moving average filter at the FDD(Frequency Difference Detector) input to increase the number of cross-products, since pilot symbol in WCDMA is not transmitted continuously. We also add normalization algorithm to overcome the conventional CP-FDD's sensitivity to the variance of input signal amplitude and to increase the linear range of S-curve. For rapid frequency acquisition and tracking, we adopt a multi-stage tracking mode. We applied the proposed algorithm in the implementation of WCDMA base station modem successfully.

1. Introduction

Unlike IS-95, coherent signal detection using pilot symbols is possible in WCDMA. To achieve coherent detection of the received signal, the timing, phase and frequency synchronization should be performed in the reverse link receiver. Out of these synchronization techniques, frequency acquisition and tracking are crucial for accurate decoding of the information transmitted.

The frequency offset is usually caused by two major factors. One is due to the transmitter and receiver oscillator mismatch(residual frequency offset). The other is Doppler shift that occurs when the speed of mobile station is so high and LOS(line of sight) exists between mobile station and base station[2].

AFC scheme is the frequency synchronization technique for compensation of the residual frequency offset and Doppler shift, which is usually not possible by a channel estimator. Various AFC algorithms were developed for frequency acquisition and tracking[1][3]. Generally, CP-FDD is widely used in mobile station modem for implementation simplicity[6]. So, we adopted CP-FDD for WCDMA reverse link receiver design. However, performance improvement is essential for CP-FDD in the frequency selective fading(multi-path propagation) and the time selective fading(Doppler spread) environment, since it's performance is sensitive to variance of input signal amplitude[5]. So, we introduced a normalization algorithm which normalize FDD output with signal amplitude. We proved analytically that this algorithm overcomes the problem of CP-FDD and increases the linear range of frequency acquisition. We applied a multi-stage tracking mode to AFC loop to improve the tracking performance. The performance of these algorithms are validated by extensive computer simulation.

The number of cross-product per slot is restrictive since the transmitted pilot signals are not a channel type but a symbol type. So, we inserted a moving average filter at the input of FDD to enhance the performance of AFC loop. Using a moving average filter can also save the tracking time by increasing the number of cross-product and get the stable FDD output by decreasing the influence of noise.

This paper is organized as follows. In section II, we introduce the receiver model considered in this paper. Section III describes the normalized CP-AFC algorithm modifying the conventional CP-AFC algorithm. In section IV, the output characteristics of the normalized CP-AFC algorithm are derived analytically. The performance results of the proposed algorithms are presented in section V. Finally, we draw conclusions in section VI.

2. Transmitter / Receiver Model

Fig. 1 is the receiver model considered in this paper. The desired signal component is down-converted by carrier frequency f_c generated by the receiver local oscillator. At the same time, the frequency offset f_o takes place by oscillator mismatch and Doppler shift[2]. The average signal level control and the suppression of the dynamic range of the envelope fluctuation are carried out by AGC. The amplitude-controlled received signal is input to AFC after the matched filter. AFC estimates the frequency offset $\hat{f}_o$ from the received signal and compensates it by using the estimated value. The received signal after AFC is compensated for by the complex conjugate of the estimated channel component by the channel estimator[4]. The received signal after the channel estimator is demodulated after decoding. In this procedure, AFC loop works as a very important functional block for signal synchronization.

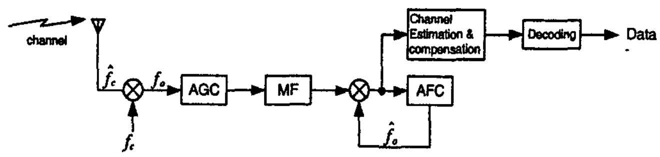

Fig. 1 Receiver model

AFC loop is classified into closed-loop and open loop by the frequency offset estimation method. The closed loop is more appropriate than open loop for base station which should be operated stably, so we chose closed-loop method in this paper[1].

There are two ways to close the frequency tracking loop: short loop or long loop. The long loop connection is not appropriate to use in the reverse link receiver. Because the estimated frequency offset components from every mobile station are different, long loop cannot handle down-conversion properly. Thus, the short loop design which individually compensates for the fingers allocated to each user is selected in this paper.

3. Normalized CP-AFC Analysis

3.1 Definition of Input Signal

The input signal to the AFC module is the pilot signal of DPCCH(Dedicated Physical Control Channel), which is transformed into symbols by summing up 256 chips that is equal to the spreading factor of DPCCH. Let the k-th pilot symbol be

$$S(kN_1) = \frac{1}{N_1} \sum_{m=kN_1}^{(k+1)N_1-1} \alpha_m \sqrt{Ec} \exp(j2\pi f_o T_s m) + w_k \qquad (1)$$

where N_1 is the number of chips per symbol, f_o is the frequency offset, T_s is the sampling time duration, Ec is chip energy and α_m is the random amplitude of a chip. w_k is the noise summed up to 256 chips duration and it's power is N_0 / N_1. Since the chip rate of WCDMA system is so high, most of the fading is slow time-varying. Therefore, α_m has almost the same value in the symbol interval. Consequently, the random amplitude of the k-th symbol is approximated by α_k. Thus, the formula (1) is rewritten as follows.

$$S(kN_1) = \frac{\alpha_k \sqrt{Ec}}{N_1} \sum_{m=kN_1}^{(k+1)N_1-1} \exp(j2\pi f_o T_s m) + w_k \qquad (2)$$

3.2 Moving Average Filter

Use of moving average filter decreases the noise effect on the input signal and increases the number of CP-FDD output. We can consider that the random signal amplitude summed up by moving average filter has the same value as mentioned before. The signal after moving average filter can be described as in (3), where $\hat{w}_k$ is the noise component whose power is $N_0 / N_1 N_2$, and N_2 is moving average period.

$$M(k) = S((k-1)N) + S(kN)$$
$$= \frac{\alpha_k \sqrt{Ec}}{N_1 N_2} \sum_{m=(k-1)N_1}^{(k+1)N_1-1} \exp(j2\pi f_o T_s m) + \hat{w}_k \qquad (3)$$

3.3 CP-FDD

The output of CP-FDD is complex conjugate multiplication of the present input signal and previous input signal. In Fig. 2, the upper branch represents the imaginary part of the CP-FDD output and the lower branch represents the real part of the CP-FDD output. The upper branch corresponds to the conventional CP-FDD[5].

The CP-FDD output is $CP - FDD_{out} = M(k) \times M(k-1)^*$

$$\mathrm{Re}[CP - FDD_{out}]$$
$$= \frac{\alpha_{k-1} \alpha_k Ec}{(N_1 N_2)^2} \frac{1-\cos(4\pi f_o T_s N_1)}{1-\cos(2\pi f_o T_s)} \cos(2\pi f_o T_s N_1) + W_{k,\mathrm{Re}} \qquad (4)$$

$$\mathrm{Im}[CP - FDD_{out}]$$
$$= \frac{\alpha_{k-1} \alpha_k Ec}{(N_1 N_2)^2} \frac{1-\cos(4\pi f_o T_s N_1)}{1-\cos(2\pi f_o T_s)} \sin(2\pi f_o T_s N_1) + W_{k,\mathrm{Im}} \qquad (5)$$

where $W_{k,\mathrm{Re}}$ and $W_{k,\mathrm{Im}}$ are the noise whose power is calculated as $2N_0(Ec + N_0 / N_1 N_2) / N_1 N_2$.

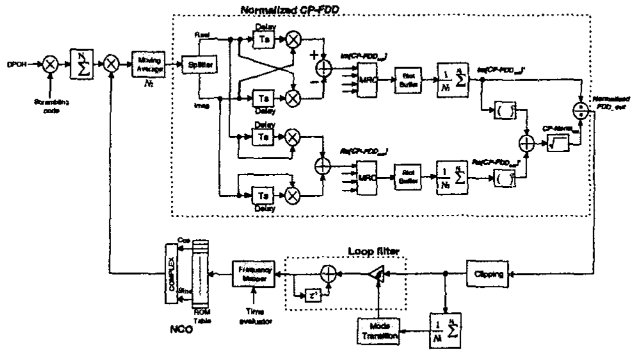

Fig. 2 Structure of normalized CP-FDD

3.4 Normalization Block

As we can see from (5), the output of the conventional CP-FDD is very sensitive to the variance of the input signal This output characteristic decreases the stability of the AFC loop and makes it difficult to perform the accurate and rapid offset frequency tracking. Therefore, we introduce the normalization algorithm to reject the random signal component. To execute the normalization algorithm, the random signal amplitude should be evaluated. The signal amplitude evaluation is carried out by using the real and imaginary part of the CP-FDD output. The calculated signal amplitude is given in (6). The first part of the right side of (6) is the amplitude of the input signal, and the second part is the attenuation factor of the CP-FDD output.
The attenuation factor decreases the linear range of the open loop characteristic.

$$CP - Norm_{out} = \sqrt{\mathrm{Re}[CP - FDD_{out}]^2 + \mathrm{Im}[CP - FDD_{out}]^2}$$
$$= \frac{\alpha_{k-1} \alpha_k Ec}{(N_1 N_2)^2} \frac{1-\cos(4\pi f_o T_s N_1)}{1-\cos(2\pi f_o T_s)} \qquad (6)$$

The enhanced CP-FDD output normalized by the signal amplitude is

$$CP - FDD_{Norm} = \frac{\mathrm{Im}[CP - FDD_{out}]}{\sqrt{\mathrm{Re}[CP - FDD_{out}]^2 + \mathrm{Im}[CP - FDD_{out}]^2}}$$
$$= \sin(2\pi f_o T_s N_1) \qquad (7)$$

From (7), we can see that the random signal amplitude and attenuation factor are cancelled out. Fig. 3 shows the normalized open loop characteristic of the proposed CP-FDD (S-curve).

The noise affects the steady state jitter, which in turn determines the stability of the AFC loop. If we assume that the random amplitude of received signal is 'one', the normalized CP-FDD output is as follows.

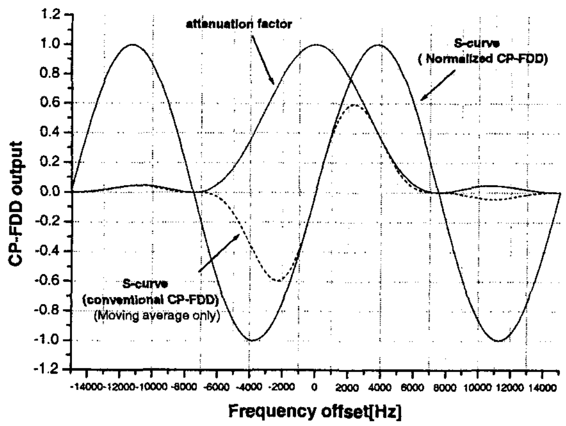

Fig. 3 Open loop characteristic of normalized CP-FDD

$$CP-FDD_{Norm} = \frac{\frac{Ec}{(N_1N_2)^2}\frac{1-\cos(4\pi f_o T_s N_1)}{1-\cos(2\pi f_o T_s)}\sin(2\pi f_o T_s N_1) + W_{k,\mathrm{Im}}}{\sqrt{\left(\frac{Ec}{(N_1N_2)^2}\frac{1-\cos(4\pi f_o T_s N_1)}{1-\cos(2\pi f_o T_s)}\right)^2 + \hat{W}}} \quad (8)$$

In steady state, the frequency offset is nearly zero. Therefore, $\cos(4\pi f_o T_s N_1) = \cos(2\pi f_o T_s)$ and the power is $Ec^2/(N_1N_2)^4 = 0$. The normalized CP-FDD output thus can be approximated as follows.

$$CP-FDD_{Norm} = \frac{W_{k,\mathrm{Im}}}{\sqrt{\hat{W}}} \quad (9)$$

where $W_{k,\mathrm{Im}}$ is a Gaussian random variable having zero mean and variance of $2N_0(Ec + N_0/N_1N_2)/N_1N_2$, and $\hat{W}$ is the sum of two noise components. One is a central chi-square distributed random variable and the other is non-central chi-square distributed random variable. Because of the dependence between referenced two random variables($W_{k,\mathrm{Im}}$, $\hat{W}$), the pdf calculation of normalized CP-FDD output is too difficult. So we carry out curve fitting to the pdf of the normalized CP-FDD output. Fig. 4 shows the pdf of the normalized CP-FDD output by curve fitting, which is similar to obtaining pdf by computer simulation.

The pdf of $CP-FDD_{Norm}$ modeled as the Truncated Gaussian distribution[7] is as follows.

$$p(x) = \left[\frac{2}{\sqrt{2\pi}\sigma} e^{\frac{x^2}{2\sigma^2}} \left| erf\left(\frac{L_1}{\sqrt{2}\sigma}\right) - erf\left(\frac{L_2}{\sqrt{2}\sigma}\right) \right| \right]^2 \cdot \frac{e^{(\alpha x)^2}}{\sqrt{1-x^4}} \beta$$

$$\alpha = \frac{2e^{-\left(\frac{1}{2}m_{norm}^4 + 1.55\sigma\right)}}{\sqrt{3\sigma}} - \sqrt{0.7(m_{norm} - \sigma)} + 1.5$$

$$\beta = -\frac{2e^{\sqrt{0.6\sigma} - m_{norm}^4}}{\sqrt{5\sigma}} + 0.75e^{-(2m_{norm} - \sigma)} + 1.27 \quad (10)$$

where σ is the standard deviation of conventional CP-FDD's output, m_{norm} is the mean of $CP-Norm_{out}$, L_1 and L_2 are upper and lower boundary of the output of the FDD. Fig 5 shows the comparison between the result of the computer simulation and mathematical analysis.

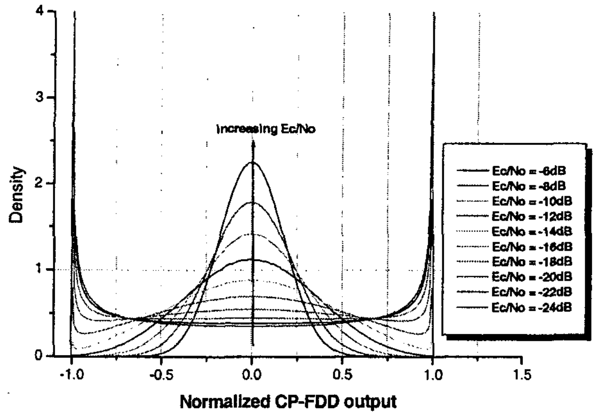

Fig. 4 pdf of the normalized CP-FDD output

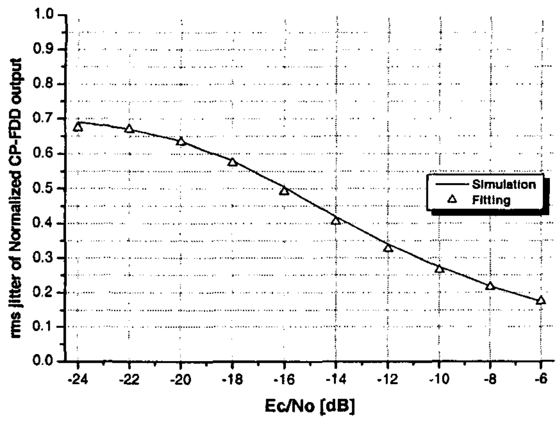

Fig. 5 Steady state jitter of normalized CP-FDD output (Simulation vs. analysis)

3.5 Loop Filter / NCO

The operation of the loop filter is an infinite accumulation of the normalized FDD output with the loop filter gain, and the loop filter output is proportional to the frequency offset. Here, the loop filter gain is the most important parameter which controls the tracking speed and accuracy. The loop filter output is input to the frequency mapper block. The frequency offset corresponding to the loop filter output is measured and then the hopping rate of the ROM table is evaluated in this block.

The numerically controlled oscillator(NCO) has a digitalized table structure storing values of a quarter of a sine period and compensates for the input frequency offset every symbol period by using the ROM table value corresponding to the hopping rate indicator from the frequency mapper block. The size of ROM table determines the resolution of AFC loop. In this paper, we have chosen a ROM table having 256 levels for implementation. For higher resolution, the size of ROM table should be increased.

3.6. Multi-stage Tracking Mode

The multi-stage tracking mode supported in the mode transition block consists of the three modes: initial, acquisition, and tracking modes. Each mode has its own threshold. This is possible due to the normalization of the CP-FDD output. The mode transition is achieved by changing the loop filter gain. The mode transition is done when the measured value (period of measurement = 1 time / 6 frames) is in the same state for 3 consecutive times for a stable operation.

When AFC operates for the first time, the initial mode is applied. In the initial mode, we determine which mode is suitable next. In the acquisition mode, the frequency offset is acquired rapidly using a large gain, but the steady state jitter becomes large. The slow and stable frequency offset tracking is performed using a small gain in the tracking mode.

4. Results and Performance Analysis

In this performance analysis, the radio channel model considered is AWGN and fading (slow: 5.556Hz, fast: 370.37Hz) channel. Spreading and data modulation applied to reverse link physical channels follow 3GPP TS 25.213. DPCCH slot format number 2 with minimum pilot bits in normal mode is adopted. The loop filter gain is chosen as 1/512 for initial mode, 1/32 for acquisition mode and 1/256 for tracking mode. We add a clipping circuit to CP-FDD for preventing a sudden unwanted operation by variable channel environment.

Fig. 6, and 7 indicate the excellence of the normalized CP-FDD algorithm by comparing between the proposed algorithm and the conventional CP-FDD algorithm in terms of the normalized rms output jitter and tracking speed. We can find that the jitter performance and the tracking speed of the normalized CP-FDD are superior to the conventional CP-FDD.

Fig. 8 shows the tracking performance of the multi-stage tracking mode. The tracking performance of the AFC loop for variable loop filter gain is used in the multistage tracking mode. The efficient compensation of the frequency offset is possible by using the multi-stage tracking mode. The mode transition criterion is based on the CP-FDD output relative to the frequency offset of 100Hz. The multi-stage tracking has more rapid tracking performance than no mode transition tracking and the AFC loop has good stability even in the poor channel environment.

Fig. 9 is the performance in the multi-path channel. The multi-path (1 Ant. 4 path) case considered is assumed to have an equal power at each path. We can see that the performance of the proposed algorithm in the multi-path case has better tracking speed and stability than the 1 path case in poor environment like fading.

5. Conclusions

In this paper, design of the normalized CP-AFC for WCDMA reverse link receiver is presented. We proved analytically that the proposed CP-FDD algorithm is not sensitive to a variation in the random signal amplitude and has better performance than the conventional CP-FDD in the tracking speed and the steady state jitter. We adopted a multi-stage tracking mode transition scheme to improve the tracking speed. We have shown that the tracking speed and stability are much enhanced due to the multi-stage tracking scheme by extensive computer simulation. The proposed algorithm is more rapid and stable than the conventional CP-AFC in complexity and performance.

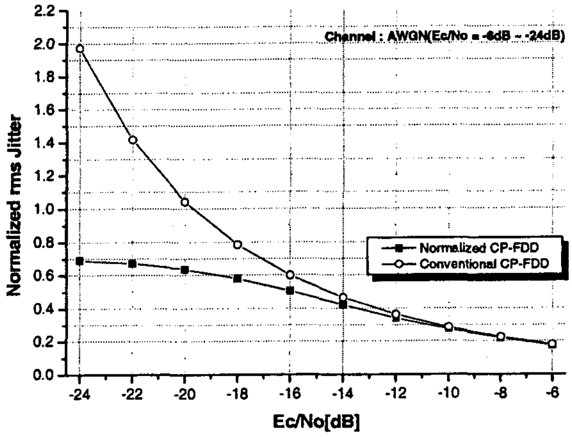

Fig. 6 Comparison of the normalized rms FDD-output jitter

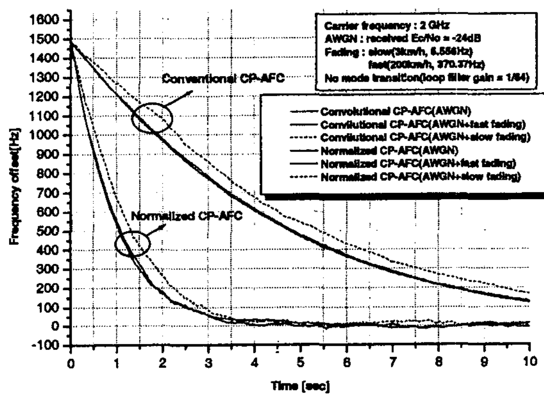

Fig. 7 Comparison of the tracking speed

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