A LOW COMPLEXITY DS/CDMA ACQUISITION TECHNIQUE FOR LARGE FREQUENCY OFFSETS

Mark C. Reed
Ascom Systec AG
Applicable Research and Technology
Gewerbepark, Mägenwil CH-5506
Switzerland
e-mail: mark.reed@ascom.ch

Abstract

This paper discusses a code acquisition technique, for use in spread-spectrum communication system with large frequency offsets, where the frequency offset is similar to the symbol rate. This is the situation typically in satellite communications systems. The technique uses a very efficient method of performing the correlation where the frequency and time space can be searched with very little performance loss. This means a low complexity, high performance solution to the problem of code (time) acquisition with frequency offset can be achieved.

1 Introduction

In the acquisition of direct-sequence code-division multiple-access signals it is well known that frequency offset has an impact on signal acquisition performance, for example, a 4dB loss occurs when the frequency offset is half the symbol rate [1]. The problem is primarily due to oscillator crystals with poor accuracy, and the Doppler frequency offset.

Our acquisition method is primarily aimed at the basestation receiver of a satellite mobile communication system, where fast acquisition procedures are needed. In this situation the frequency offset is due to the frequency difference between terminal and gateway and the Doppler frequency due to the movement of the satellite. For the system in question the frequency offset can be as large as the pilot symbol frequency of the system.

Timing acquisition with no frequency offset is present is a well researched area. The fundamental references on code acquisition can be found in [2, 3], where these papers discuss the technique and analyse code acquisition. A paper that discusses acquisition when a-priori information on the timing offset is [4], by knowing the timing a-priori the search time can be reduced. Other papers that discuss acquisition for DS/CDMA are [5, 6]. In all these papers, frequency offset is not considered. Work that does discusses code acquisition for satellite systems with frequency offset include [7, 8, 9, 10]. In [7, 10] a FFT correlator for PN code acquisition from LEO satellites is considered. We show later that this method is computationally complex and not as flexible in terms of frequency bin selection, compared to our method. In [8] a design study for CDMA-based LEO satellites is discussed. Here the authors assume the use of a continuous wave pilot carrier for Doppler estimation and compensation. In this proposal such assumptions are not used. In [9] a similar low complexity approach to ours is used, however the frequency resolution of this method is less than ours and the expected loss is greater.

As is always the case the receiver knows the spreading code transmitted by the DS/CDMA transmitter. We assume an unknown phase and frequency of the known signal and that other users are present; which generates multiple access interference. Finally we assume that the technique has to function in an additive white Gaussian noise (AWGN) channel with or without the presence of fast and slow fading (Rician or Rayleigh, and log-normal respectively). Multi-path can also be considered to be present.

The paper is organised as follows. In Section 2 we discuss the system model, including the transmission and channel. Section 3 describes the acquisition unit and implementation issues. In Section 4 we show results for the correlator in terms of performance and complexity.

2 System Model

We model the channel as a discrete-time system with binary phase shift keying (BPSK) modulation. The channel adds zero-mean white Gaussian noise $n(t)$

with variance $\sigma_n^2 = N_0/2$, where N_0 is the single sided noise power spectral density. The bits are represented as $d_t \in \{+1, -1\}$ and the phase offset is represented as ϕ. The channel output signal is then equal to

$$y(t) = d(t) \exp(j(\phi + \theta(t))) + n(t) \qquad (1)$$

where the phase shift at time t due to frequency offset is $\theta(t) = 2\pi f(t)/f_s$, and f_s equals the sampling frequency of the system.

3 Fast, Efficient DS/CDMA Acquisition

Signal acquisition with frequency offsets as large as the symbol rate requires a multi-dimensional search over frequency bins and time bins to determine the timing and frequency offset acquisition points. The basic method would be to provide a separate frequency rotator for each frequency bin to generate the frequency corrected input signals and then to have a single correlator for each frequency rotator.

The frequency rotation can be incorporated into the spread-spectrum code instead of including it as a separate frequency rotator function. With this implementation the spreading code is rotated by the frequency required. If this is done for any random frequency then the spreading code becomes a complex number instead of a binary value as before. This approach turns out to have even lower implementation complexity as code segments can be re-used by multiple frequency correlators.

In our system a special constraint is placed on the rotation of the spreading code. This constraint is not on the possible frequencies. The spreading code will be only allowed to be rotated by amounts of 45 degrees. This means that the spreading code can take the following values as shown in Table 1. The values at 45,135,225 and 315 degrees are simplified by taking $1 + j$ instead of $\sqrt{2}(1 + j)$. This means the possible rotation points for the frequency compensation are the four corners of the unit square plus the axis crossing points, instead of points on the unit circle. This increase in amplitude on the corners of the unit square causes, on average, only a change in the gain of the correlator result.

A simplified example is now shown in Table 2 for the case when the spreading code equals 1 for all chips. The first column is the spreading code for the 0Hz correlator. We assume a processing gain of 8 for this example and a symbol rate of 100 Hz. The second column shows a modified code for +100 Hz (one full clockwise rotation) and the third column shows a modified code for the -100 Hz (one full anti-clockwise rotation). Column four and five shows a modified code for a positive and negative 50 Hz (half of one rotation), respectively. Note this is an example with unrealistic processing gain and frequency offset but it is shown to illustrate the technique. These ”rotated” codes are then used by the various frequency offset correlators to perform correlation at the different frequencies.

Angle	Spreading Code Value
0 degrees	$1 + j0$
45 degrees	$1 + j$
90 degrees	$0 + j$
135 degrees	$-1 - j1$
180 degrees	$-1 + j0$
225 degrees	$-1 - j1$
270 degrees	$0 - j1$
315 degrees	$1 - j1$

Table 1: Possible Spreading Code Values

0 Hz	100 Hz	-100 Hz	50 Hz	-50 Hz
1	1	1	1	1
1	1 + j	1-j	1	1
1	+j	-j	1+j	1-j
1	-1 - j	-1-j	1+j	1-j
1	-1	-1	j	-j
1	-1 - j	-1+j	j	-j
1	-j	+j	-1+j	-1-j
1	1-j	1+j	-1+j	-1-j

Table 2: Example of Rotated Spreading Codes for Correlator

As can be seen here correlation of these values is simply the addition or subtraction of real and imaginary components. Complex multiplication functions are avoided and the complexity is therefore the same as the 0 Hz frequency offset correlator.

3.1 Practical Implementations

In a practical implementation, a number of correlator taps are combined into segments and these segments are then rotated. The length of segments depends on the frequency offset required. The rotated segments $I + jQ$ are built according to the following formula:

$$I + jQ = (a + jb)(i + jq)$$

where $(a + jb)$ is the rotation vector for the different angles, as shown in Table 1 and $(i + jq)$ is the complex spreading code segment before rotation(complex spreading code). This leads to the calculation rule for I and Q where the result is shown in the columns of Table 2.

To build the segments for the different frequency bins, an adder tree is built and the sums for the different segments can be taken out of this tree. This method reduces complexity further as segment correlation results can be used for more than one frequency offset.

Our technique is substantially more flexible than the FFT approaches [7] as our frequency bins can be selected at any value and are not restricted to multiples of the inverse of the sampling rate. Our implementation has less loss than the method in [9] as they only use the unit square corner points and therefore suffers a greater loss of up to 3dB, as reported. Our loss is restricted to less than 1dB and the minimum loss of each correlator is less than 0.5 dB.

4 Performance and Complexity

Performance of the correlator under noiselessionditons with the correct timing point is shown in Figure 1. Here the loss over frequency is shown. The specific example is for a maximum of +/-15 kHz frequency offset with an assumed symbol rate of 15 kHz. The 0Hz correlator output has to be normalised against frequency offset correlators as the absolute amplitude of the correlations is 1 compared to on average $(1.414+1)/2$ for the other frequency bins. This is evident from Table 2. What can be noted from this diagram is that no more than 1 dB of loss occurs over the entire frequency range.

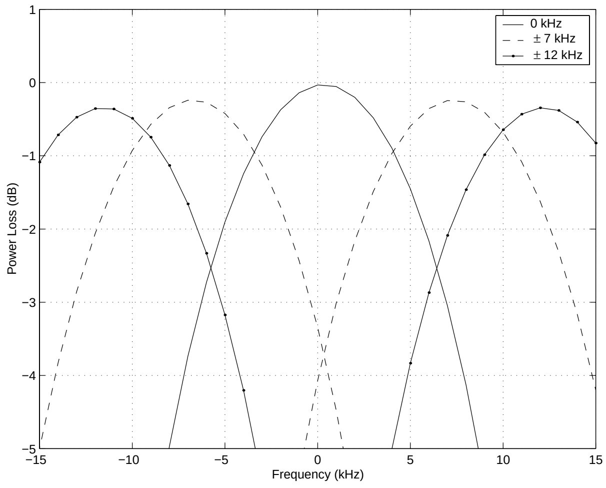

Fig. 1: Power Loss of Correlators over Frequency

The technique discussed here can be successfully used for non-coherent correlation and combinations of coherent and non-coherent correlation techniques, signals are unmodulated in the implementation but modulated signals can also be used (in this case the coherence length can be no longer than one symbol). The system can select un-evenly spaced frequency bins with no impact on the design complexity or implementation.

In Figure 2 the performance of the correlator system as a function of probability of detection is shown. This test was performed at an $E_s/N_0 = 1$dB on an AWGN channel for 30 experiments at each frequency point. For each experiment the maximum value in each frequency bin at the correct timing point was selected. The graph shows the probability of each correlator producing the maximum value at a particular frequency offset. It is clear to see from this that the correct frequency bin would be selected at the correct time, given there is no false alarms and missed detections.

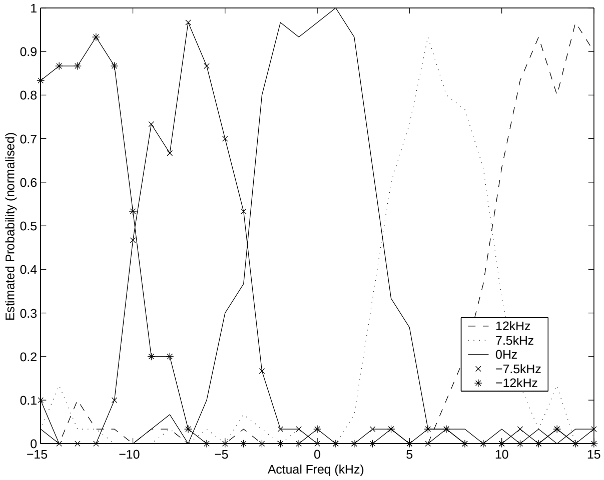

Fig. 2: Performance of Correlator at $E_s/N_0 = 1$ dB from -15kHz to +15kHz

In Table 3 the complexity of our scheme is compared to the basic method and the FFT method frequency rotation. The complexity indicated is the complexity per symbol per time position per frequency bin, where N is the processing gain of the symbol. Here it can be seen that our scheme has substantially less complexity than the other techniques. By avoiding the need for the multiplication function we dramatically reduce our implementation complexity.

5 Summary

In this paper we have discussed a new technique for acquisition of a DS/CDMA signal with large frequency offset. This technique finds application partic-

Method	Real Additions	Real Multiplies
Proposed Method	2N	-
Basic Method	4N	4N
FFT Method	$3N \log_2 N$	$2N \log_2 N$

Table 3: Comparison of complexities

ularly in satellite mobile communications at the gateway where the frequency offset is not known.

We first discussed the channel model and then described in detail our technique. The performance is shown in terms of loss and in terms of detection probability at low E_s/N_0 levels. The computational complexity is also investigated and compared to that of the basic method and the FFT method.

This technique has being implemented in a Satellite-UMTS system for the European Space Agency (ESA) and is in the process of being patented [11]. The realisation is in HDL code and runs on an FPGA.

In conclusion we have introduced a new method of acquisition for DS/CDMA with large frequency offsets and taken this design through to a hardware realisation where it is used in a UMTS testbed. We have also discussed important design issues, such as complexity, and performance such that the system can be successfully implemented.

References

[1] R. D. Gaudenzi, F. Giannetti, and M. Luise, "Signal synchronization for direct-sequence code-division multiple access radio modems," *European Trans. on Telecom.*, vol. 9, pp. 73–89, Jan./Feb. 1998.

[2] A. Polydoros and C. Weber, "A unified approach to serial search spread-spectrum code acquisition-part I: General theory," *IEEE Trans. Commun.*, vol. 32, pp. 542–549, May 1984.

[3] A. Polydoros and C. Weber, "A unified approach to serial search spread-spectrum code acquisition-part II: A matched filter receiver," *IEEE Trans. Commun.*, vol. 32, pp. 550–560, May 1984.

[4] W. Braun, "Performance analysis for the expanding search PN acquisition algorithm," *IEEE Trans. Commun.*, vol. 30, pp. 424–435, Mar. 1982.

[5] G. Corazza and A. Polydoros, "Code acquisition in CDMA cellular mobile networks," in *IEEE Int. Symp. on Spread Spectrum Techniques and Applications*, (Sun City, South Africa), pp. 454–458, 1998.

[6] S. Glisic, T. Poutanen, W. Wu, G. Petrovic, and Z. Stefanovic, "New PN code acquisition scheme for CDMA networks with low signal-to-noise ratios," *IEEE Trans. Commun.*, vol. 47, pp. 300–309, Feb. 1999.

[7] C. Spillard, S. Spangenberg, and G. Povey, "A serial-parallel FFT correlator for PN code acquisition from LEO satellites," in *IEEE Int. Symp. on Spread Spectrum Techniques and Applications*, (Sun City, South Africa), pp. 446–448, 1998.

[8] S. Glisic, J. Talvitie, T. Kumpumaki, M. Latva-aho, and T. Poutanen, "Design study for a CDMA based LEO satellite network: Downlink system level parameters," *IEEE J. Selected Areas Commun.*, vol. 14, pp. 1796–1808, Dec. 1996.

[9] M. Sust, R. Kaufmann, F. Molitor, and G. Björnström, "Rapid acquisition concept for voice activated CDMA communication," in *Proc. IEEE Globecom*, (San Diego, U.S.A.), pp. 1820–1826, Dec. 1990.

[10] U. Cheng, W. Hurd, and J. Statman, "Spread-spectrum code acquisition in the presence of Doppler shift and data modulation," *IEEE Trans. Commun.*, vol. 38, pp. 241–250, Feb. 1990.

[11] M. C. Reed and P. Eglin, "Receiver structure in a digital communication system." European Patent Application 00810856-5-2211, Sept. 2000.