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Synchronization in CDMA Systems

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Abstract

Perfect synchronization of the carrier's phase and frequency and the chip timing is required to achieve the low bit error rate required in the difficult environment of mobile communication. This paper gives an overview of the synchronization methods used in multi-user DS-CDMA. Particular emphasis is given to the chip timing and to the delay tracking. Synchronization to a fraction of a chip is needed to achieve and maintain the perfect communication.

1. Introduction

Synchronization is an important task in any kind of telecommunication. There are several levels of synchronization like carrier, frequency, code, symbol, frame and network synchronization. In all these levels synchronization can be distinguished into two phases which are acquisition (initial synchronization) and tracking (fine synchronization). A synchronization scheme where the carrier phase is known is called *coherent* and a scheme where the carrier phase is unknown is called *noncoherent*.

The DS CDMA receiver works by correlating, or despreading, the received signal with a known pseudonoise sequence. The sequence must be exactly synchronized to the received sequence in order the get a maximal output from the correlator. The signal is sampled at several times the chip frequency in order achieve a minimal delay. The synchronization process for the chip timing is performed in two stages. First, an initial coarse synchronization is done by searching the received signal for a match. Different CDMA systems aid this process by sending known pilot symbols. After an initial match the chip sequence is synchronized to the accuracy of one chip time. In this stage the carrier phase and frequency are also estimated if coherent detection is used.

Perfect synchronization requires that the receiver is synchronized to a fraction of a chip. Due to the mobility the timing is constantly changing and must be tracked. Tracking is done with a feedback-loop that will synchronize to within a fraction of a chip and that also tracks any changes due to the variable delay between the transmitter and the receiver.

In the case of a multi-user receiver, all users must be simultaneously tracked because they are moving independently of each other. Multi-user synchronization algorithms work by jointly synchronizing all users.

2. Acquisition of CDMA signals

The acquisition, or initial synchronization, involves adjusting the internal pseudorandom sequence in the receiver to the one in the received signal. Because there are no prior knowledge of received signal the sequence must be searched by testing different phases of the internal sequence against the received signal. Phase and frequency synchronization is difficult because typical spreading waveform periods are long and bandwidths are large. The uncertainty in the estimated propagation delay T_d results in a large number of symbols of code phase uncertainty. Oscillator instabilities and Doppler frequency shifts result in frequency uncertainties which also must be resolved.

There are different approaches to this operation with different acquisition times and complexities. The least complex, but also the slowest, is the completely serial algorithm which tests each phase of the internal sequence against the received signal. The most complex, but also fastest, is the completely parallel structure where different phases of the sequence is compared simultaneously. Between these two extreme solutions there are a variety of hybrid solutions using different degrees of parallelism.

2.1 Overview of the acquisition process

The received BPSK modulated DS spread spectrum signal in additive Gaussian noise (AWGN) environment without data modulation is

$$r(t) = \sqrt{S}c(t + \zeta\, T_c)\cos(2\pi f_0 + 2\pi f_D + \theta) + n(t)$$

where S is the signal power, c(t) the spreading code delayed by ξ, f_0 the center frequency, f_D the Doppler shift between the transmitter and the receiver, θ the carrier phase and n(t) additive Gaussian noise. Figure 1 shows the basic noncoherent acquisition structure for a QPSK modulated signal.

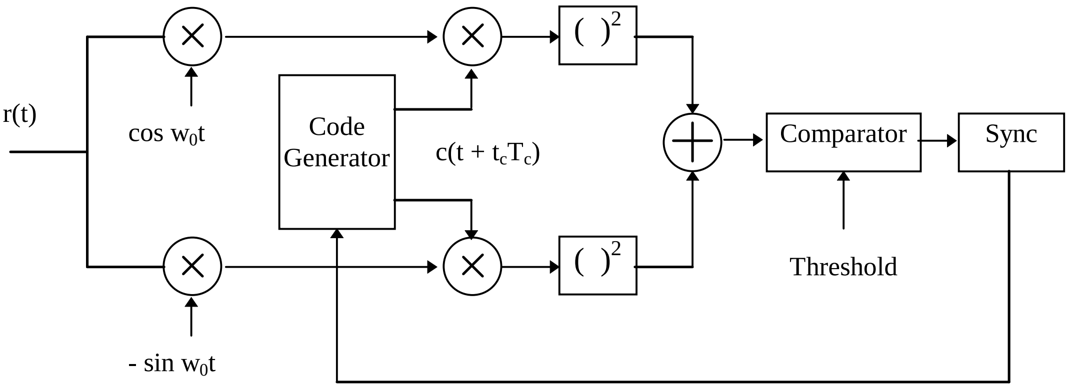

Figure 1 Noncoherent acquisition structure [1]

The receiver must find estimates for ξ, f_D and θ in order to demodulate the signal. When the code synchronization is performed independently of the carrier synchronization we have a noncoherent code synchronization. This is the usual structure.

There are usually some a priori information about ξ and F_D with minimi and maximi limits which will limit the search space. The limits set the time uncertainty to ΔT and frequency uncertainty to ΔF.

Assuming an AWGN channel, the maximum-likelihood estimator of ξ, is t_c which maximizes the signal

$$y(t_c)=\sqrt{y_I^2(t_c)+y_Q^2(t_c)}$$

where

$$y_I(t_c)=\frac{\sqrt{2}}{T_i}\int_0^{T_i} r(t)c(t+t_cT_c)\cos(2\pi f_0+2\pi f_D t)dt$$

and

$$y_Q(t_c)=\frac{\sqrt{2}}{T_i}\int_0^{T_i} r(t)c(t+t_cT_c)\sin(2\pi f_0+2\pi f_D t)dt$$

When searching for the optimal values of t and f_D, ΔT and ΔF are divided into small cells, dt and df. The time-frequency uncertainty region is presented in figure 2 where only one cell contains the true time and frequency offsets of the incoming signal. Δt is of the order of the code chip T_c and Δf is chosen according to the data bandwidth. The code acquisition problem is to find the correct cell in the uncertainty region. Usually time and frequency are searched jointly.

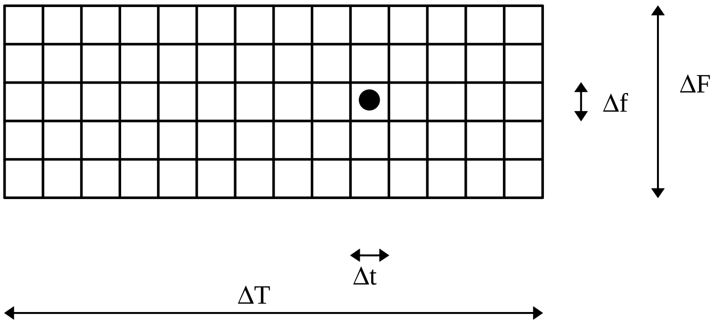

Figure 2 Time-frequency uncertainty region [1]

2.2 The Optimal Synchronizer

A filter matched to the signal c(t) has the impulse response

$h(t) = Kc^*(T_{MF} - t)$

The response of the matched filter to the signal c(t) without noise is equal to the autocorrelation function of the input signal. The matched filter is an optimal method for the detection of a signal in white nonband-limited, Gaussian noise in the sense of minimum error probability. It is also an optimal filter for the estimation of delay, Doppler shift and amplitude in an AWGN channel.

Figure 3 shows the optimal noncoherent acquisition scheme when we have only time uncertainty of L chips where L is the length of the spreading code. The impulse responses of the matched filters are time-reversed and delayed versions of the spreading codes of different phases. The bank of matched filters computes the decision variables for different code phases. This optimal structure, which contains a high degree of parallelism is very complex to implement even when short codes are used [6].

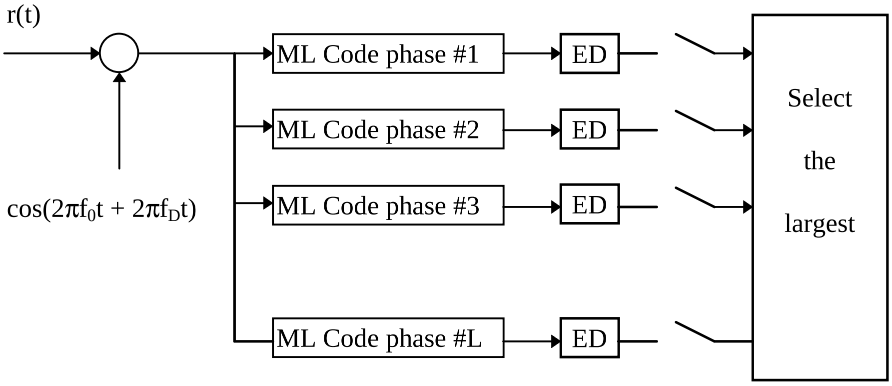

Figure 3 The Optimal Synchronizer [6]

2.3 Serial Search Synchronization Techniques

A serial search synchronization system evaluates the phase/frequency serially until the correct cell is found. In order to compute the mean and variance of the synchronization time we must know the probability of detection for the correct cell P_d and the probability for false alarm P_{fa} when an incorrect cell is evaluated [1].

The mean synchronization id computed by considering all possible events leading to a correct synchronization. The total synchronization time for a particular event can be written as

$T(n,j,k) = nT_i + jCT_i + kT_{fa}$

where T_i is integration time for the evaluation of each cell and T_{fa} is the time to reject an incorrect cell when a false alarm occurs and $C = \Delta T/\Delta t$. The mean synchronization time can be written as

$T_s = \Sigma\, T(n,j,k)\, \Pr(n, j, k)$

after some calculations we get

$$T_s = (C-1)T_{da}\left(\frac{2-P_d}{2P_d}\right)+\frac{T_i}{P_d}$$

where $T_{da} = T_i + T_{fa}P_{fa}$ is the average dwell time at an incorrect phase cell.

The variance of T_s can be written as

$$\sigma_{T_s}^2 = T_{da}^2 C^2\left(\frac{1}{12}-\frac{1}{P_d}+\frac{1}{P_d^2}\right)$$

3. Time Tracking of CDMA signals

The initial synchronization, or acquisition, will synchronize the receiver timing to within a fraction of the chip time. The second stage of synchronization, the code tracking, shall make the timing error approach zero. Because there is a continuous relative motion of transmitter and receiver and instability in clocks the timing corrections must be made continuously. Code tracking is accomplished using phase-locked techniques in somewhat the same manner as in carrier tracking applications.

The most common approximation of the optimal solution in delay tracking in DS-CDMA receivers is probably the delay-locked loop (DLL). The delay-locked loop uses two different phases of the codewords, early and late, when correlating with the received signal. The DLL performs well in single-user single-path channels but have some problems in the case of multipath fading. There are also multiuser synchronization algorithms for DLLs.

The EM algorithm and subspace methods have also been applied to multiuser delay tracking.

If the amplitudes and the data are estimated separately from the delays, they can be used in estimation of the delays. This results in a suboptimal estimators, but has been efficiently utilized in single-user RAKE receivers.

3.1 Baseband Delay-Lock Tracking Loop

The function of a baseband DLL is to track the time varying phase of the received spreading waveform c(t - T_d). The function T_e(t) will denote the receiver estimate of T_d. The received waveform consists of the spreading waveform and additive white Gaussian noise n(t).

$$s_r(t)=\sqrt{P}c(t-T_d)+n(t)$$

Figure 4 presents a block diagram of the DLL. The received waveform is correlated with an early spreading waveform, c(t - T_e + (Δ/2)T_c), and a late spreading waveform, c(t -T_e - (Δ/2)T_c). The parameter Δ is the time difference between early and late channels. We have for the early correlator output

$$y_1(t,T_d,T_e)=K_1\sqrt{\frac{P}{2}}c(t-T_d)c(t-T_e+\frac{\Delta}{2}T_c)$$

and for the late correlator output

$$y_2(t,T_d,T_e)=K_1\sqrt{\frac{P}{2}}c(t-T_d)c(t-T_e-\frac{\Delta}{2}T_c)$$

the delay-lock discriminator output is the difference of y_2(t) and y_1(t) and is

$$\varepsilon(t,T_d,T_e)=K_1\sqrt{\frac{P}{2}}\,c(t-T_d)\left[c(t-T_e+\frac{\Delta}{2}T_c)-c(t-T_e+\frac{\Delta}{2}T_c)\right]$$

This function can be written in terms of the autocorrelation function $R_c(\tau)$ of c(t)

$$\varepsilon(t,T_d,T_e)= R_c\left[\left(\delta-\frac{\Delta}{2}\right)T_c\right]-R_c\left[\left(\delta+\frac{\Delta}{2}\right)T_c\right]$$

$= D_\Delta(\delta)$

where $\delta = (T_d - T_e) / T_c$.

The filtered dc component of $D_\Delta(\delta)$ is used as the control signal for the VCO.

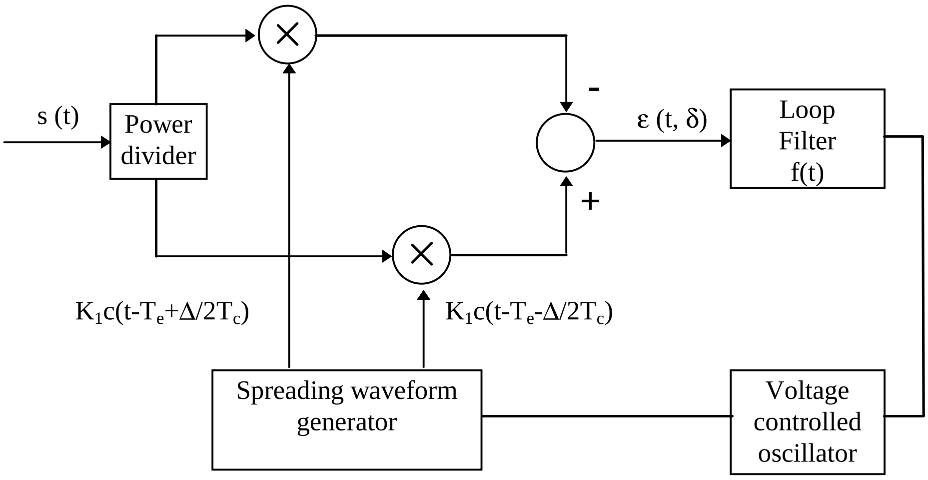

Figure 4. Baseband delay-lock tracking loop. [1]

The tracking loop filter is a linear, time-invariant filter defining the loop bandwidth and noise rejection. The mean square tracking error or tracking jitter can be expressed as

$$\sigma_\delta^2=\begin{cases}\frac{1}{2}\left(\frac{K_1}{K_d}\right)^2 N_0\left(1+\frac{1}{N}\right)W_L & \Delta >= 1.0\\[2ex] \frac{1}{2}\left(\frac{K_1}{K_d}\right)^2 N_0 \mathrm{A}\left(1+\frac{1}{N}\right)W_L & \Delta < 1.0\end{cases}$$

where W_L is the loop bandwidth and N_0 is the noise density [1].

3.2 Noncoherent Delay-Lock Tracking Loop

In the previous section the baseband DLL was introduced. In an actual receiver the signal must first be demodulated before it can be processed by the baseband loop. Since spread-spectrum typically operate at very low signal to noise ratios, this demodulation will be difficult. In addition, the modulation is coherent and therefore a coherent carrier reference must be generated prior to demodulation. The generation of this coherent reference at extremely low signal-to-noise ratios is also difficult. The second difficulty is that the signal is data modulated.

Neither of these difficulties are present for the noncoherent delay-lock tracking loop discussed in this section. The phase discriminator contains two energy detectors which are not sensitive to data modulation or carrier phase and thus enable the discriminator to ignore data modulation and carrier phase. Figure 5 shows the general idea of the noncoherent tracking loop with BPSK modulation [1].

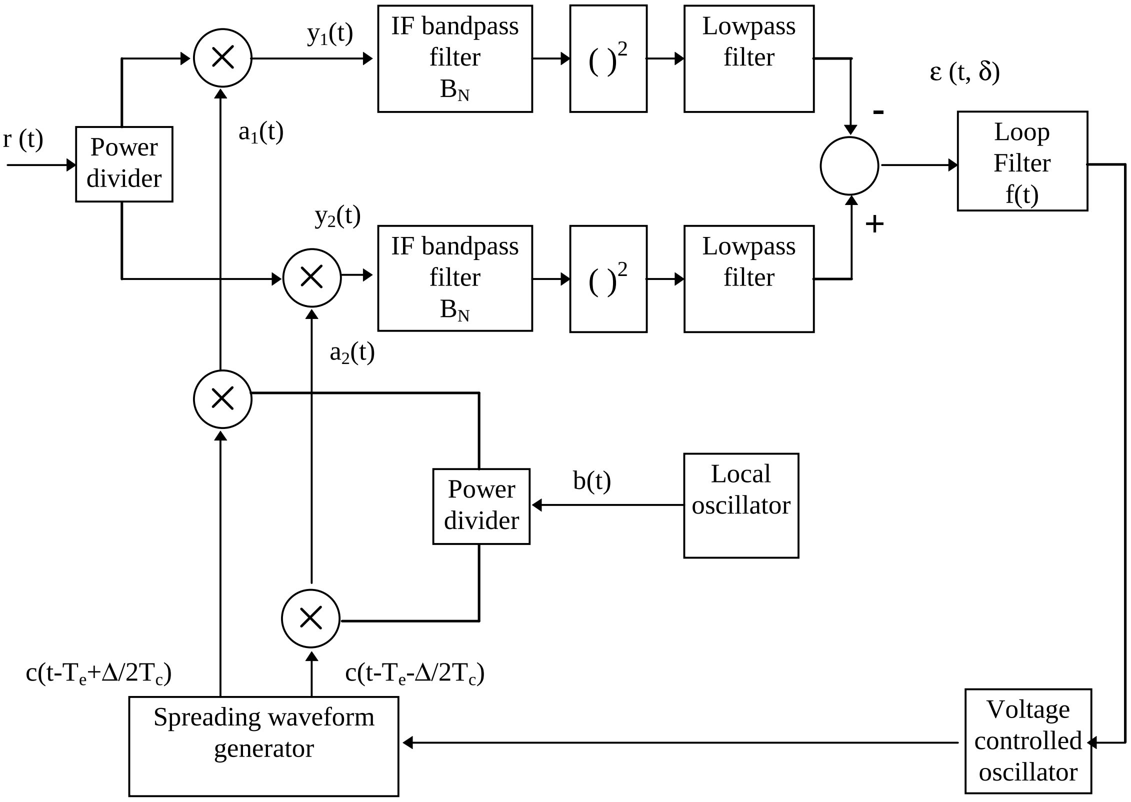

Figure 5. Noncoherent delay-lock code tracking loop [1]

The received BPSK signal is a data and spreading-code modulated carrier in bandlimited AWGN represented by

$$r(t)=\sqrt{2P}c(t-T_d)\cos\left[w_0t+\theta(t-T_d)+\phi\right]+n(t)$$

where P is the received signal power, θ_d(t-Td) is the data phase modulation, T_d is the transmission delay, ϕ is received carrier phase, w_0 is the carrier frequency and n(t) is white Gaussian noise.

The received signal is power divided and then correlated with early and late spreading waveforms. The reference local oscillator output is

$$b(t)=2\sqrt{2K_1}\cos\left[(w_0-w_{IF})t+\phi^{'}\right]$$

and

$$a_1(t)=2\sqrt{K_1}c\left(t-T_e+\frac{\Delta}{2}T_c\right)\cos\left[(w_0-w_{IF})t+\phi^{'}\right]$$

$$a_2(t)=2\sqrt{K_1}c\left(t-T_e-\frac{\Delta}{2}T_c\right)\cos\left[(w_0-w_{IF})t+\phi^{'}\right]$$

where w_{IF} is intermediate frequency and ϕ’ is local oscillator phase.

The difference frequency mixer outputs are

$$y_1(t)=2\sqrt{K_1}c(t-T_d)c\left(t-T_e+\frac{\Delta}{2}T_c\right)\cos\left[w_{IF}t+\phi-\phi'+\theta_d(t-T_d)\right]$$

$$y_2(t)=2\sqrt{K_1}c(t-T_d)c\left(t-T_e-\frac{\Delta}{2}T_c\right)\cos\left[w_{IF}t+\phi-\phi'+\theta_d(t-T_d)\right]$$

The output of the squaring circuit has a component at baseband and a component centered at $2w_{IF}$ which will be rejected by the lowpass filters. The signal of the delay-locked dicriminator will be

$$\begin{aligned}\varepsilon(t,\delta)&=\left[x_2^2(t)-x_1^2(t)\right]_{lowpass}\\&=\frac{1}{2}K_1P\left\{R_c^2\left[\left(\delta-\frac{\Delta}{2}\right)T_c\right]-R_c^2\left[\left(\delta+\frac{\Delta}{2}\right)T_c\right]\right\}\\&=\frac{1}{2}K_1PD_\Delta(\delta)\end{aligned}$$

where R_c is the autocorrelation product of the spreading waveform and

$$D_\Delta(\delta)=R_c^2\left[\left(\delta-\frac{\Delta}{2}\right)T_c\right]-R_c^2\left[\left(\delta+\frac{\Delta}{2}\right)T_c\right]$$

3.3 Multiuser Synchronization by Succesive Interference Cancellation

In a conventional CDMA system, all users interfere with each other. In a multiuser detector there is an interference cancellation scheme which weaken the influence of other users. The theoretical potential of performance and capacity improvements are significant. It is also known that the optimal multiuser detector is too complex to implement practically and most of the current work concentrates on suboptimal solutions. In this section a succesive interference cancellation is considered in the noncoherent tracking loop. The idea is to detect the strongest user with a conventional detector and then to subtract the signal due to that user from the received waveform. Figure 6 presents the basic structure of this scheme [3], [4].
The received waveform is

$$r(t)=\sum_{i=1}^{M}\sqrt{2P_i}\,d_i(t-\tau_i)c_i(t-\tau_i)\cos\left[w_c(t-\tau_i)+\Phi_i\right]+n(t)$$

where M is the total number of users, Pi is the power of the ith user, $c_i(t)$ is the normalized signature waveform of the ith user, τ_i and Φ_I are the time delay and the random carrier phase of the ith user respectively, n(t) is additive white Gaussian noise and wc is the carrier frequency. The signal component of the delay-locked discriminator output is

$$\varepsilon(t,\tau_1-\tau_1^{\wedge})=\frac{1}{2}K_1\sum_{i=1}^{M}P_i\left[R_{i1}^2(\tau_i-\tau_i^{\wedge}-\frac{\Delta}{2}T_c)-R_{i1}^2(\tau_i-\tau_i^{\wedge}+\frac{\Delta}{2}T_c)\right]$$

where K1 is the gains of the mixers, Δ is total normalized time difference between the earle and late discriminator channels, $\tau_1^{\wedge}$ is the estimate of τ_1, Ri1(t) is the correlation function of the signature waveforms of user 1 and user i and T_c is the chip duration.
Simulations have been carried out to determine the performance of the interference canceller [4]. Positive results have been reported that indicate that the tracking jitter can be reduced considerable.

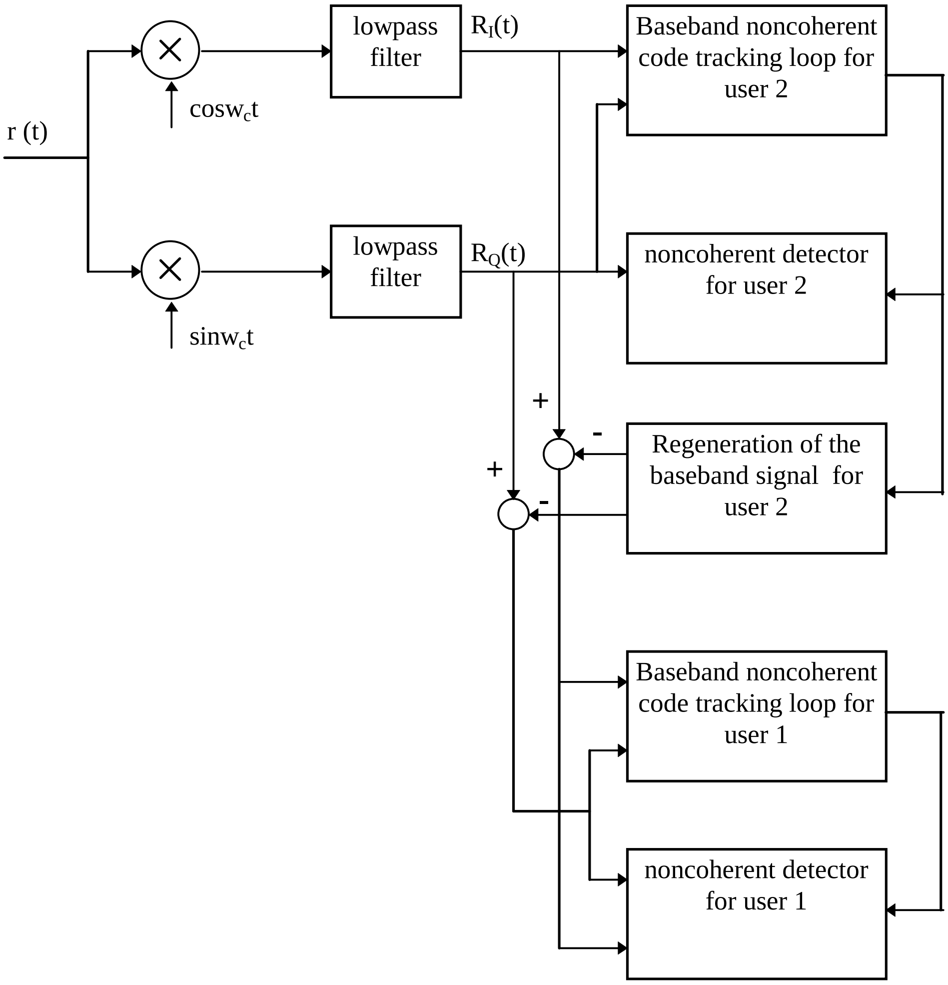

Figure 6. Interference canceller for two-user case. [4]

3.4 Sample-Correlate-Choose-Largest (SCCL) based Delay Tracker

The SCCL Delay Tracker is based on parallel correlators which are spaced one sample apart. The correlator outputs are filtered over LF symbol intervals in a regular I & D filter. The outputs of the I & D filters are then passed to a nonlinear device, which selects the maximum correlation value to be the timing estimate for the next LF symbol intervals. If the maximum correlation value came from one sample before the middle one, the local code phase is shifted one sample ahead, respectively. Similarly, the local code phase is retarded if the maximum came from a one sample advanced correlator. The timing correction principle of the SCCL loop is the same as in lead-lag PLLs.

These principles can be applied to parallel interference cancellation based delay trackers. The parallel correlator outputs are first weighted by the conjugate of the channel coefficient and then the effect of data is removed. The resulting structure is presented in figure 6.

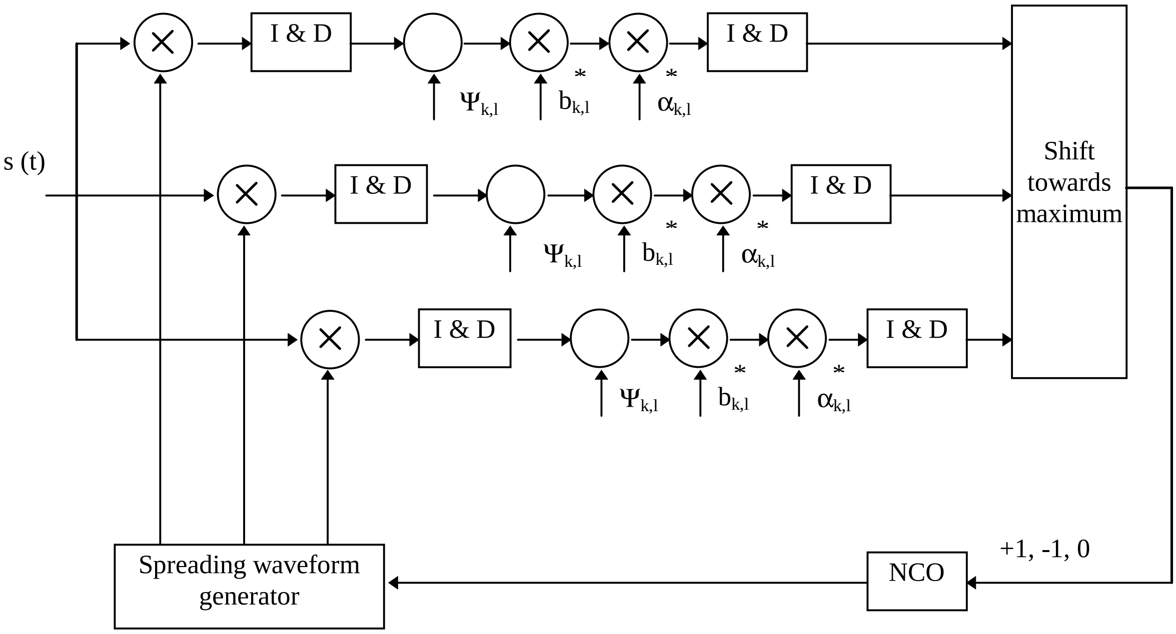

Figure 7. Near-far resistant SCCL loop [5]

Simulation results show that the SCCL loop performs well in multiuser delay tracking [5].

4. Conclusions

This paper contains a short presentation of different synchronization problems and their solutions in single and multiuser CDMA. The synchronization is a complex process containing different levels of synchronization. Acquisition as well as tracking solutions have been addressed. Research reports and simulations show that multiuser algorithms perform significantly better than single user methods in multiuser environments but they are more complex to implement.

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