Subchip Multipath Delay Estimation for Downlink WCDMA System Based on Teager-Kaiser Operator

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***Abstract*— Accurate detection and estimation of overlapping fading multipath components is vital for many communication systems, particularly for positioning technologies. Traditional approaches used for channel estimation generally fail in estimating closely-spaced multipath components in CDMA systems. Here, we present a highly efficient technique for asynchronous downlink WCDMA multipath delay estimation with subchip resolution capability based on nonlinear Teager-Kaiser operator concept. The behaviour of this technique is influenced considerably by the pulse shape waveform. Both rectangular and root raised cosine pulse shaping filters are considered.**

***Index Terms*—DSP for wireless communications, multipath delay estimation, positioning technologies, WCDMA.**

I. Introduction

Generally, the transmitted WCDMA signal arrives at the receiver via multiple propagation paths with different delays, which can be smaller than the chip interval, introducing overlapped multipath components. This may cause significant errors to the line-of-sight (LOS) time of arrival estimation which is the basis of WCDMA network based positioning techniques. Usually, successive paths can be solved if they are spaced at more than one chip distance [1]. Subspace-based approaches have been proposed to deal with closely-spaced paths [2]. These algorithms are quite complex to implement for WCDMA systems. Other solutions to solve closely-spaced paths are the Multipath Estimating Delay Locked Loops (MEDLL) [3] and the peak tracking with pulse subtraction (PS) method [4], [5], [7].

Here, we present the concept of Teager-Kaiser operator in the context of asynchronous WCDMA system with closely-spaced paths. We investigate the effect of multiuser interference on the performance of the proposed approach and compare it with the above mentioned methods. The Teager-Kaiser algorithm is firstly described for the ideal rectangular pulse shapes. Then, the same method is applied in the context of root raised cosine pulse shapes. The impact of the pulse shape waveform is emphasized in the simulation part.

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II. Teager-Kaiser based delay estimation

In a downlink DS-CDMA scenario with K users in the system, the received signal can be written as [9]

$$r(t) = \sum_{k=1}^{K} \sqrt{P_k} \sum_{n=-\infty}^{\infty} b_{n,k} \sum_{l=1}^{L} \alpha_{n,l} s_k^n(t-\tau_{n,l}) + \eta(t), \quad (1)$$

where P_k is the power of user k, $b_{n,k}$ is the transmitted data symbol n of user k. $\alpha_{n,l}$ and $\tau_{n,l}$ are the complex coefficient and delay, respectively, of the l^{th} path during the symbol n. L is the number of channel paths, $s_k^n(\cdot)$ is the signature of user k during the symbol n, and $\eta(\cdot)$ is a complex additive white Gaussian noise. The user signatures are expressed as follows

$$s_k^n(t) = \sum_{m=0}^{S_{F_k}-1} c_{m,k}^n p(t - mT_c - nS_{F_k}T_c), \quad (2)$$

where $c_{m,k}^n$ is the code value for m-th chip of user k during the symbol n, T_c is the chip interval, $p(\cdot)$ is the chip pulse shape, S_{F_k} is the spreading factor of user k.

In general, delay estimation is based on the cross-correlation between the received signal $r(t)$ and the replica of the desired user signature $s_k^n(t)$ [1]. The output of the correlator is given by [3]

$$y_n(\tau) = \sqrt{P_k} b_{n,k} \sum_{l=1}^{L} \alpha_{n,l} \mathcal{R}(\tau - \tau_{n,l}) + \tilde{\eta}(\tau), \quad (3)$$

where $\tilde{\eta}(\cdot)$ is an additive Gaussian noise process incorporating the effects of noise, multiuser interference, interpath and intersymbol interference, and $\mathcal{R}(\cdot)$ is the pulse shape autocorrelation function. If we assume rectangular pulse shapes, the pulse shape autocorrelation function $\mathcal{R}(\cdot)$ can be written as

$$\mathcal{R}(\tau) = \begin{cases} 1 - \frac{|\tau|}{T_c} & |\tau| \le T_c \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

Traditional DLL techniques fail to estimate closely-spaced multipaths with less than one chip interval [3]. Also, multipaths with less than one chip interval are merging and they cannot be tracked directly from the envelope of the correlation function.

We notice that, for rectangular pulse shape, the output $y_n(\tau)$ of the correlator is a superposition of shifted triangular pulses weighted by the complex channel tap coefficients and the data modulation within some additive noise. We can exploit the structure of the correlation function with the aid of the non-linear Teager-Kaiser (TK) [6] operator $\Psi[\cdot]$ defined bellow:

$$\Psi_C[x(t)] = \dot{x}(t)\dot{x}^*(t) - \frac{1}{2}[\ddot{x}(t)x^*(t) + x(t)\ddot{x}^*(t)]. \quad (5)$$

Similarly, the discrete-time Teager operator of a complex valued signal is given by [6], [7]

$$\begin{aligned}\Psi_D[x(n)] &= x(n-1)x^*(n-1) \quad (6)\\ &- \frac{1}{2}[x(n-2)x^*(n) + x(n)x^*(n-2)].\end{aligned}$$

By applying the continuous TK operator to (3), we obtain

$$\begin{aligned}\Psi_C[y_n(\tau)] &= \frac{1}{T_c}\sum_{l=1}^{L}\sum_{j=1}^{L}\mathrm{Re}\{\alpha_{n,l}\alpha_{n,j}^*\}\mathcal{R}(\tau-\tau_{n,l}) \times \\ &\delta(\tau-\tau_{n,l}) + \frac{1}{T_C^2}\sum_{l=1}^{L}\sum_{j=1}^{L}\alpha_{n,l}\alpha_{n,j}^* \times \\ &\mathrm{sign}\big((\tau-\tau_{n,l})(\tau-\tau_{n,j})\big)\Pi(\tau-\tau_{n,l},T_c) \times \\ &\Pi(\tau-\tau_{n,j},T_c) + \tilde{\eta}_{TK}(\tau), \quad (7)\end{aligned}$$

where $\Pi(\tau, T_c)$ stands for a rectangular function with unit amplitude and duration $2T_c$ centered at $\tau = 0$;

$$\Pi(t, T_c) \triangleq \begin{cases} 1 & |t| \leq T_c \\ 0 & \text{otherwise,} \end{cases} \quad (8)$$

$\delta(\tau)$ stands for the Dirac function, and $\tilde{\eta}_{TK}(\cdot)$ is the additive white Gaussian noise at the output of the TK operator.

Obviously, (7) shows that the TK operator applied to the output of the correlator provides clear time-aligned peak locations of the closely-spaced paths in the presence of a certain 'noise' floor (second and third terms of (7)). The block diagram of the proposed TK-based approach is illustrated in Fig. 1. Here, the discrete TK operator is applied at the output of the correlator (I&D stands for the integrate-and-dump filter). The property derived for continuous TK operator (7) is also valid for discrete TK operator. A discrete-time implementation as given in Fig. 1 is however more suited for digital CDMA receivers. As seen in Fig. 1, after the square envelope detection, we perform non-coherent averaging over several symbols in order to reduce the effect of noise. The first L maxima of the averaged output are the estimated multipath delays. Although the TK algorithm was derived for rectangular pulse shapes, the same method can be extended to the root raised cosine (RRC) pulse shapes. In the simulation part, we will show that RRC waveform deteriorates the performance of TK algorithm, but TK algorithm still outperforms most of the other techniques.

III. Simulation results

A downlink multiuser WCDMA scenario with QPSK modulation is considered in the simulations [8]. The channel is a 3-path Rayleigh fading channel, with delay separation between successive paths uniformly-distributed in $[T_c/N_s : T_c]$. Here, N_s denotes the number of samples per chip and in the simulations $N_s = 8$. The average path powers are $0, -2, -4$ dB. The correlation function is computed over one symbol interval, which corresponds to a non-data aided approach. The block averaging length is equal to 5 symbols. The code sequences are superposition of Walsh spreading codes and scrambling code [8]. All the users have the same spreading factor ($S_F = 64$). The near-far ratio is defined by [2] $NFR = 10log_{10}\frac{P_k}{P_1}$, where P_k is the power of the interfering user k (all interfering users have the same power), and P_1 is the power of the desired user. The probability of acquisition is defined as the probability that all the 3 paths are estimated correctly within $+/-\ 1$ sample error. There are 200 delay estimates used in the statistics.

The results are shown in Fig. 2. For closely-spaced paths, TK algorithm is clearly better than pulse subtraction (PS) algorithm [4], [5] and MEDLL algorithm [3] for both rectangular and RRC pulse shapes (rectangular pulse shape is showed here only as an upper bound on the achievable performance with these algorithms; in a practical WCDMA system, RRC pulse shaping with rolloff factor 0.22 is employed). MUSIC [2] and TK algorithms have similar performance in terms of the probability of acquisition, but the advantage of TK algorithm comes from its much simpler implementation (as it can be seen from Fig. 1). Both TK and MUSIC algorithms show near-far resistance for interfering user up to 10 dB stronger if only two users are present in the system. However, for heavily-loaded systems (e.g., 30 users), all these algorithms suffer of fast deterioration in performance when the power of interfering users increases (near-far resistance is lost). This is due to the fact that the orthogonality property of the pseudo-random codes of the users is lost in asynchronous CDMA transmission.

IV. Conclusions

Teager-Kaiser operator based technique for solving closely-spaced multipaths in asynchronous downlink CDMA transmission over multipath fading channels has been presented and its performance is compared with existing algorithms. This technique applies a non-linear operator to the correlation function between the received signal and the code replica at the receiver. Also, it can be used both in a data-aided and non-data aided mode. The proposed approach outperforms PS and MEDLL techniques and has similar performance to the MUSIC algorithm requiring much lower computational complexity and simpler implementation. TK technique can be a viable solution for code synchronization and Rake-based receivers. However, for applications such as accurate mobile positioning, all the compared techniques provide rather low probability of acquisition when RRC pulse shaping is used. The estimation of closely-spaced multipaths is a rather new research topic and remains still an open area for research work.

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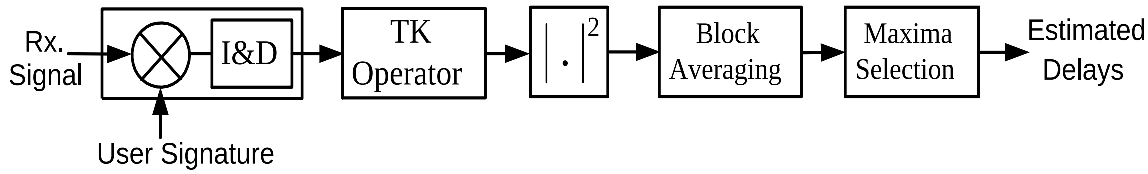

Fig. 1. TK approach for multipath delay estimation.

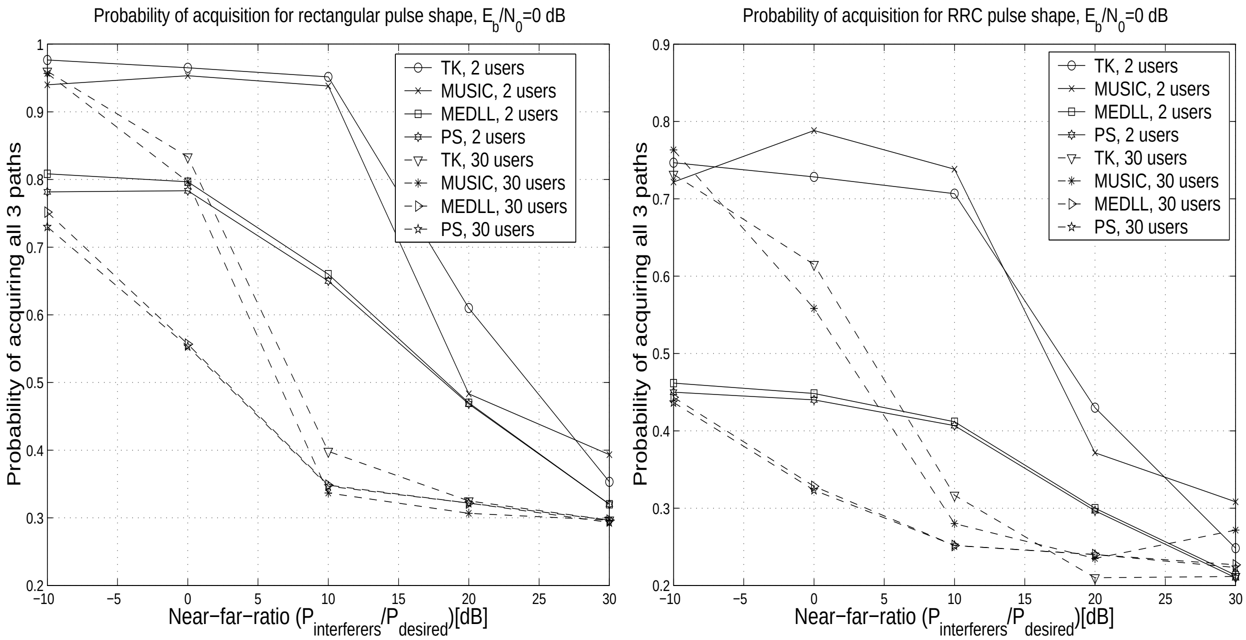

Fig. 2. Probability of acquisition of closely-spaced paths for an asynchronous downlink CDMA system, with rectangular and root raised cosine (RRC) pulse shapes.

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