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Multipath Resistant Coherent Timing-Error-Detector for DS-CDMA applications

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Abstract — **A new coherent timing error detector (TED) for timing/code tracking loops used inside RAKE receivers in CDMA systems is presented. In contrast to the conventional TED it is well suited for the case of multipath propagation channels. In order to accomplish this task a compensation term is introduced inside the tracking loop directly behind the conventional TED. This compensation term is calculated using the knowledge on the relative delays of all paths and their respective channel coefficients. A compensation scheme like the one described here becomes necessary whenever closely spaced paths have to be tracked. This fact makes this algorithm a favorable candidate for indoor scenarios where individual paths can be spaced even more closely than one chip. The performance of the presented scheme is assessed by means of simulation.**

I. INTRODUCTION

The timing error detector (TED) is a well known structure since the early days of digital communications. It has been used for transmission systems in the presence of flat fading for systems with and without spreading. The same structure has been employed for tracking individual paths in a multipath scenario. In doing so it has been usually assumed that the individual paths are well separated and the timing error detector for each individual path is not influenced by the presence of other paths. In general this is not true and in the case of closely spaced paths, as e.g. in the case of indoor scenarios this model mismatch becomes fatal and leads to significant performance degradations. In order to avoid these limitations of the conventional TEDs a new algorithm is presented allowing the compensation of adjacent path interference on the TED.

Lately some approaches for the problem of path delay tracking in multipath scenarios have been discussed. A structure based on extended Kalman filtering was presented in [3]. A noncoherent tracking technique with removal of a reproduced interference signal was introduced in [4]. In [5], the author proposed a noncoherent scheme which jointly tracks a group of equidistant fingers. A new noncoherent low complexity scheme is presented in [8]. The necessary phasor estimation is analyzed in [7].

This paper is organized as follows: Firstly, the conventional approach is presented. Next, the multipath channel model for the next sections is presented. It is shown how the conventional approach suffers from severe degradations in this multipath scenario. In order to compensate these degradations compensations terms are calculated and the overall tracking and compensation scheme is outlined. For this scheme, the achievable performance gains compared to the conventional scheme are demonstrated. The paper finishes with a conclusion and an outlook on some open topics.

II. SYSTEM MODEL

The system we are concerned with consists of a CDMA transmitter sending a complex valued data sequence $\{a_n\}$. These data symbols are spread by the spreading factor N using the effective spreading sequence $\{d_k\}$. This spreading sequence is assumed to be complex valued by itself. (The same overall technique as described here may be applied to different spreading schemes if the despreading scheme is adapted appropriately.) The spreaded sequence is transmitted using a pulse shaping filter $g(t)$ which in the case of 3GPP [6] is a root-raised cosine filter with a rolloff factor of 0.22. The resulting baseband-equivalent transmit signal is given by

$$s(t) = \sum_{k=-\infty}^{\infty} a_{\lfloor \frac{k}{N} \rfloor} d_k g(t - kT_c), \tag{1}$$

The signal from the transmitter travels through a multipath propagation channel with N_P independent paths (WSSUS model). Each of these paths is characterized by its delay τ and channel coefficient $c^{(l)}$

$$h(\tau) = \sum_{l=0}^{N_p-1} c^{(l)}\,\delta(\tau - \tau^{(l)}) \tag{2}$$

As the signal enters the receiver white Gaussian noise $n(t)$ is added. In the first stage of signal processing in the receiver the signal is filtered by a filter matched to the pulse forming filter in the transmitter. In combination with the following RAKE [1] receiver a channel matched filter is formed. We constrain ourselves to this simple receiver type in order to show the important effects of multipath tracking that are common to all receivers relying on accurate timing estimates. The signal at the output of the pulse matched filter is given by

$$z(t) = \sum_{l=0}^{N_p-1} c^{(l)} \sum_{k=-\infty}^{\infty} a_{\lfloor \frac{k}{N} \rfloor} d_k R_g(t - kT_c - \tau^{(l)}) + \tilde{n}(t) \tag{3}$$

The noise term $\tilde{n}(t)$ represents both the noise filtered by the pulse matched filter and the interference by other users. Other user interference is modeled as additional noise in order to keep the model simple and highlight the important effects.

The combined transmit and receive filter pulse form is denoted by $R_g(t)$, being the effective pulse form at the output of the pulse matched filter:

$$R_g(t) = \int_{-\infty}^{\infty} g^*(\tau) g(t+\tau)\, d\tau \tag{4}$$

The matched filter output signal is used as input for the RAKE receiver (see Fig. 1).

The RAKE implementation shown here operates on samples from the matched filter output taken at an arbitrary rate $1/T_S$ (at least Nyquist sampling). From this point on, the implementation is fully digital. In each of the M branches of the RAKE the samples are processed by means of interpolation and decimation [2] in order to obtain intermediate samples with a rate of $1/T_C$ and to compensate for the estimated delay $\hat{\tau}^{(l)}$. Alternatively, instead of interpolation and decimation one could adapt the code phases in order to compensate the

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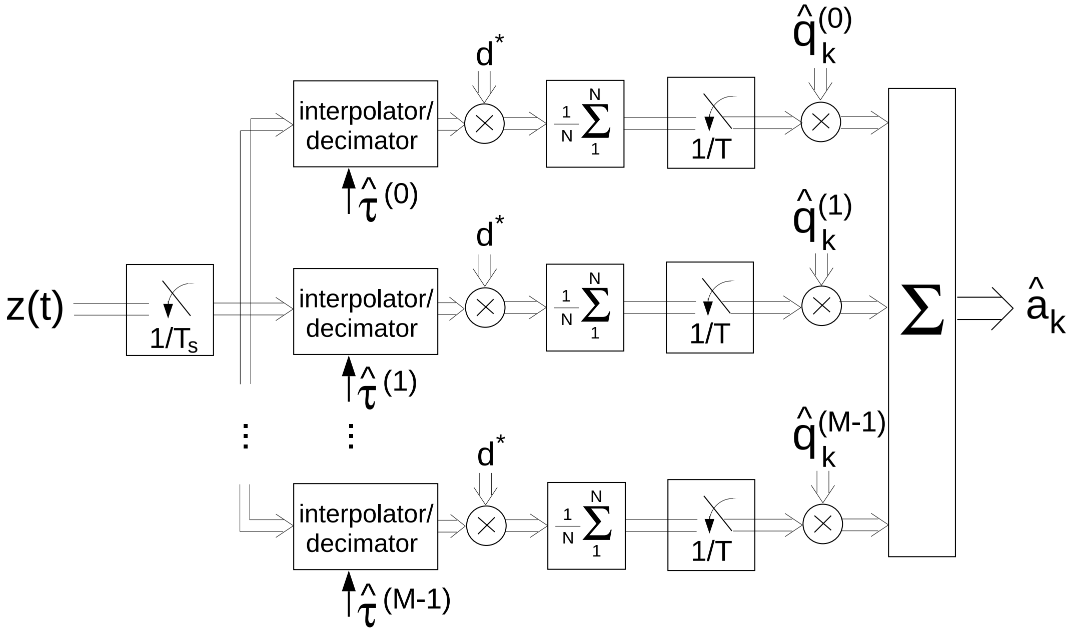

Figure 1: RAKE receiver model

delays in the individual paths. Further operation is straightforward: The time compensated signal is correlated with the effective spreading sequence and accumulated over one symbol length. The signals from the individual paths are combined with appropriate weights q in order to obtain one estimate $\hat{a}$ at the output of the RAKE for each transmitted symbol. In the simulation section of this paper, maximum ratio combining based on estimates of the channel coefficients ($\hat{c}^{(l)}$) is used for determining the proper weights q.

In order to be functional, a RAKE receiver needs estimates for the path delays ($\hat{\tau}^{(l)}$) and the channel coefficients ($\hat{c}^{(l)}$). The task of the timing/code tracker we are concerned with here is to keep track of changes in the $\tau^{(l)}$ during normal operation. Therefore, each branch of the RAKE has its own timing tracking loop.

III. CONVENTIONAL TED

The conventional timing error detector often used in CDMA systems is the early late (EL) timing error detector. This timing error detector operates on two classes of samples of the matched filter output: one taken early and one late with respect to the detection path. For a good compromise between performance and implementation complexity the early and late branches are usually spaced half a chip apart ($T_c/2$) from the detection branch. In the case of no timing error everything is obviously balanced, hence resulting on average in no signal at the output of the timing error detector at all. In the case the signal is delayed by $T_c/2$ the late branch is perfectly aligned and therefore delivers a large positive output. The output of the overall timing error detector is calculated as the difference between late and early branch outputs. In the aforementioned case this leads to a positive value at the TED output for positive delays of the signal. In the case of negative delays with respect to the receiver time base the output becomes negative.

The output of the conventional EL-TED is given by:

$$x_k = x(kT) = Re\left\{ \hat{a}_k^* \hat{c}_k^* \sum_{j=kN}^{(k+1)N-1} \left(z(jT_c + T_c/2 + \hat{\tau}) - z(jT_c - T_c/2 + \hat{\tau}) \right) d_j \right\} \quad (5)$$

If we assume a flat fading channel ($N_P = 1$) the output of the timing error detector, conditioned on the channel coefficient and dependent on the uncompensated timing error ($\hat{\tau} - \tau$), is on average given by

$$\begin{aligned} E[x|c] &= Re\left\{ E[|a|^2]\, |c|^2 \left[R_g(T_c/2 + \hat{\tau} - \tau) \right.\right. \\ &\qquad \left.\left. - R_g(-T_c/2 + \hat{\tau} - \tau) \right] \right\} \\ &= E[|a|^2]\, |c|^2\, S(\hat{\tau} - \tau) \end{aligned} \quad (6)$$

The dependence $S(\hat{\tau} - \tau)$ of the average TED output on the residual timing error $\hat{\tau} - \tau$ can be illustrated as the open loop S-curve (see Fig. 3).

The conventional TED obviously operates correctly as expected in the case of a flat fading scenario. But in the case of multipath propagation ($N_P > 1$) the channel model changes, and therefore the output of the TED, conditioned on the set of channel coefficients $\mathbf{c}$, becomes strongly influenced by the additional paths:

$$E[x^{(m)}|\mathbf{c}] = E[|a|^2] Re\left\{ c^{*(m)} \sum_{l=0}^{N_p-1} c_l S(\hat{\tau}^{(m)} - \tau^{(l)}) \right\} \quad (7)$$

$$= E[|a|^2] Re\left\{ \left| c^{(m)} \right|^2 S(\hat{\tau}^{(m)} - \tau^{(m)}) \right\} \quad (8)$$

$$+ E[|a|^2] Re\left\{ c^{*(m)} \sum_{l=0..N_p-1, l \neq m} c^{(l)} S(\hat{\tau}^{(m)} - \tau^{(l)}) \right\} \quad (9)$$

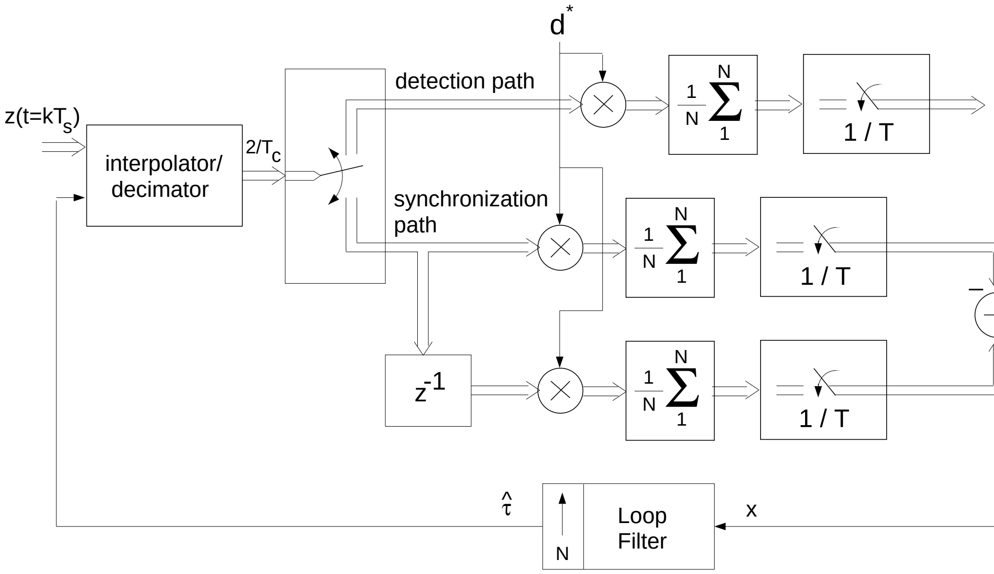

Figure 2: Conventional coherent EL tracking loop

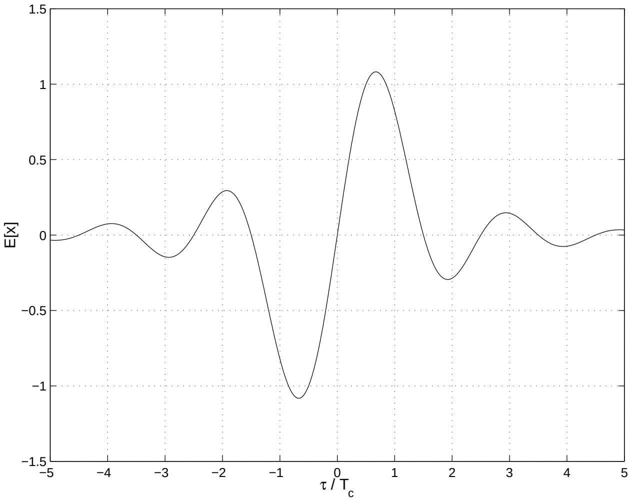

Figure 3: Conventional early-late S-curve

The deteriorating effects described above do have a larger impact on the overall system than one might expect from their amplitude compared to the underlying noise processes of similar amplitude. This is the case because these effects originate from the bandlimited fading processes and therefore are band-limited to twice the bandwidth of the fading process. The bandwidth of this fading process, on the other hand, is usually much smaller than the overall signal and noise bandwidth, even for large mobile speeds. Therefore, the lowpass filter effect of the timing tracking loop filter will reject significant amounts of noise but cannot be as effective on the low frequency distortions in our case.

For a visualization of system performance in the presence of uncompensated multipath distortions see Fig. 9.

The term (7) not only consists of the desired term (8) as in the flat fading case (6), but it includes several additional terms (9). These additional terms can easily influence the signal at the timing error detector output in a way that it becomes completely useless. For each instance in time the output of the TED appears to be biased, depending on the present constellation of delays and channel coefficients of other paths. In the long term as the channel is assumed to be fading, this short term bias can be modelled as an increased estimator variance. But for low mobile speeds this approximation may be misleading, as, based on the biased estimate, the receiver may already have lost lock in the meantime. Therefore, averaging is not the method of choice in order to combat these effects.

IV. EXTENSION TO MULTIPATH TRACKING

As seen above, on one hand each individual TED output is influenced by a large amount of unwanted terms from each adjacent path that depend on the combination of the channel coefficients and the relative delays between those paths. But on the other hand, almost every variable in the unwanted terms is known in the tracking mode that we are dealing with here. The channel coefficients **c** have to be estimated with sufficiently low variance in order to perform decoding and coherent timing tracking, anyway. The path delays are not known exactly - otherwise we would not have to track them - but still $S(\hat{\tau}^{(l)} - \tau^{(m)})$ can be well approximated by $S(\hat{\tau}^{(l)} - \hat{\tau}^{(m)})$.

In doing so we are able to obtain a compensation term that allows us to alleviate the effect of other paths on the timing error signal $x^{(m)}$, i.e.

$$\tilde{x}^{(m)} = x^{(m)} - Re\left\{ c^{*(m)} \sum_{l=0..N_p-1, l\neq m} c_l S(\hat{\tau}^{(m)} - \hat{\tau}^{(l)}) \right\} \qquad (10)$$

The scheme presented here is not limited by any assumptions made on the minimum spacing of paths [5]. Therefore it is able to track closely spaced paths well to and below one chip apart. The paths are tracked individually and may eventually diverge again. The presented technique is not limited by the fact that it has to focus on the stronger of two paths, as often supposed in heuristic solutions for dealing with this type of scenarios.

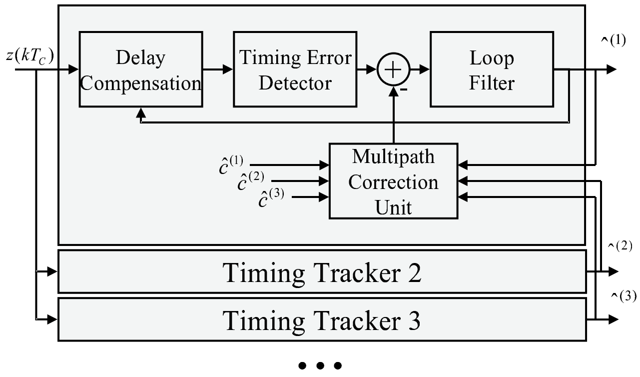

Figure 4: Structure of Compensation Mechanism

As the new compensation unit introduces additional complexity, this topic is discussed here briefly: A new compensation value has to be calculated each time the channel scenario changes significantly. This usually equals the rate at which the channel coefficients have to be estimated. Therefore the repetition rate might be well below the symbol rate. This becomes most interesting in the case of slowly moving mobiles in indoor environments with Doppler frequencies of only a few Hz. In order to further reduce the complexity of this algorithm, the compensation scheme could be limited to only the strongest interfering path.

V. SIMULATION RESULTS

The effect of adjacent paths on the open loop performance is demonstrated in Fig. 5. The output of the TED vs. the symbol time index is shown. Depicted is the stronger of two paths in an indoor scenario ($N = 4$) with mobile speed of 10km/h. No timing error was present during these simulations. Therefore, an ideal TED would produce no error signal at all. In reality the raw TED signal is influenced by two terms: a high frequency noise term (mainly self noise) and low frequency adjacent path interference. The self noise can be suppressed effectively if the TED output is sufficiently lowpass filtered. This is demonstrated for normalized lowpass filter bandwidths of $1/10$ and $1/100$. For the smallest filterbandwith the noise is suppressed almost completely but the adjacent path interference remains the same. The presented interference compensation scheme allows to remove the adjacent path interference without significantly increasing the noise term (Fig. 6). In combination with additional lowpass filtering the flat line behaviour of the ideal TED is approximated very closely.

In order to demonstrate the achievable performance gains of the overall system, the new TED has been integrated into a tracking loop inside a RAKE receiver. The simulation setup was compatible with the 3GPP proposal [6]. An indoor scenario with spreading factor $N = 4$ and mobile speed $v = 10km/h$ was used. Fig. 7 shows the estimated delays of the two paths over a simulation interval of 1 second. The original paths are located at 0 resp. $1T_C$. The weaker path moves towards the stronger one and merges within a fraction of a second. From that time on, only a combination of both paths is tracked. Even the stronger path is not tracked very well.

If the compensation scheme is active the crosseffects between the different paths are eliminated almost completely and both paths are tracked almost perfectly (Fig. 8).

Fig. 9 shows the resulting bit error rates for the scenarios described above. For the standard TED without compensation a BER degradation with resulting SNR losses as high as 5 dB can be observed. These losses are reduced to well below 1 dB if the compensation scheme is active.

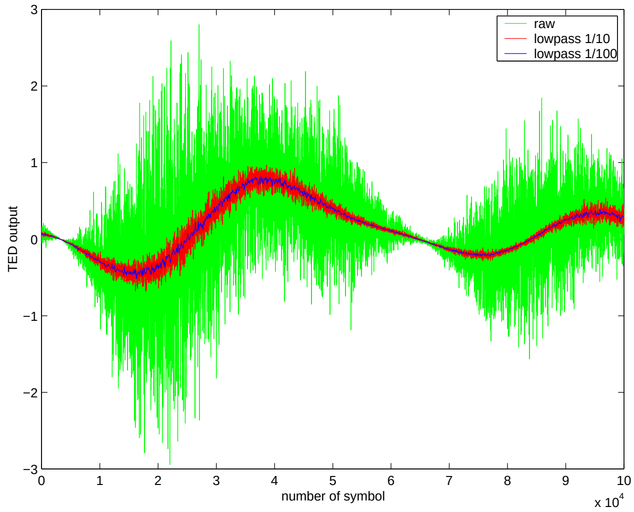

Figure 5: Output of standard TED

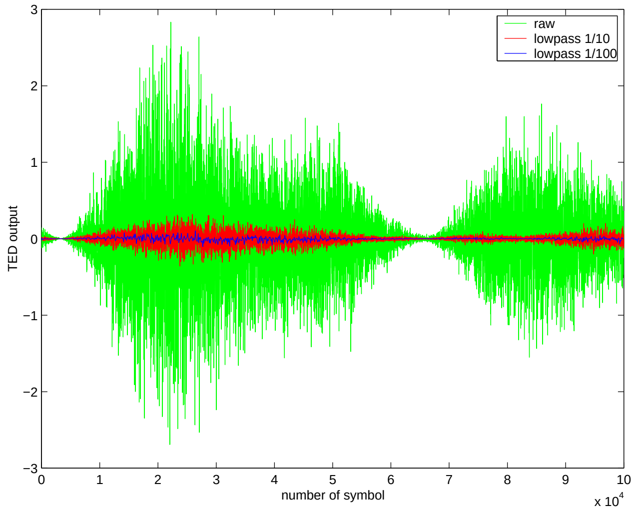

Figure 6: Output of TED with compensation

VI. CONCLUSIONS AND OUTLOOK

The effects of multipath propagation on conventional timing error detectors have been analyzed. This analysis provided the means for the derivation of a compensation scheme that eliminates most of the deteriorating effects of multipath propagation on the timing error detector during normal tracking mode. Employing a compensation scheme as described in this paper extends the field of application for timing tracking loops to the area of closely spaced propagation delays as in the case of indoor scenarios. The achievable performance gain over the conventional TED without compensation schemes was illustrated by means of simulation. Field of further research will be a concise analytical treatise of the complete tracking loop in multipath scenarios. The effect of other users (synchronous and asynchronous) will be the topic of further studies.

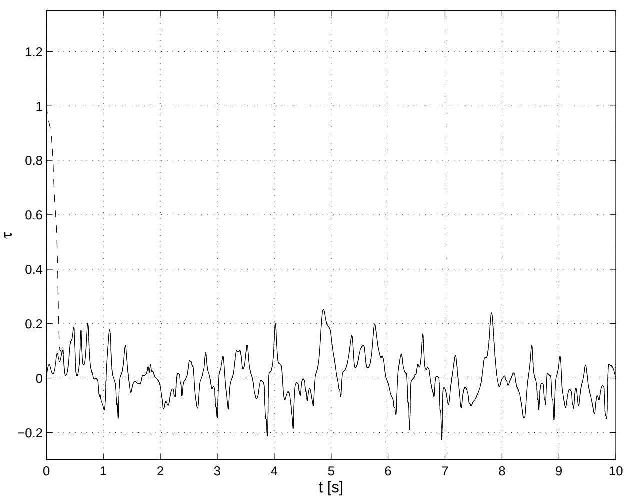

Figure 7: Delay estimates, conventional TED, N = 4

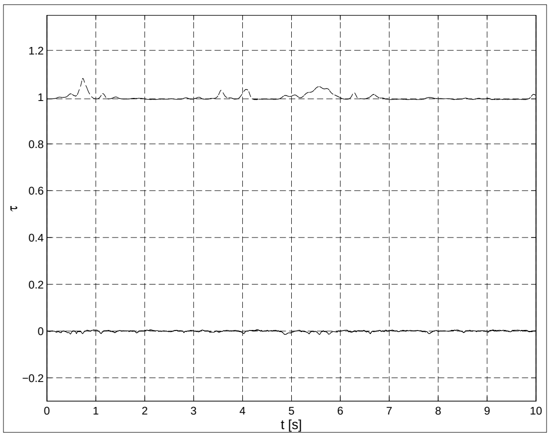

Figure 8: Delay estimates, compensated TED, N = 4

REFERENCES

[1] R. Price and P.E. Green, Jr. *A Communication Technique for Multipath Channels*, Proceedings of the IRE, March 1958

[2] Heinrich Meyr, Marc Moeneclaey and Stefan Fechtel, *Digital Communication Receivers: Synchronization, Channel Estimation and Signal Processing*, John Wiley and Sons, New York, 1998.

[3] R. A. Iltis, *An EKF-Based Joint Estimator for Interference, Multipath, and Code Delay in a DS Spread-Spectrum Receiver*, IEEE Transactions on Communications, Vol. 42, No. 2/3/4, February-April 1994.

[4] W. H. Sheen and C. H. Tai, *A Noncoherent Tracking Loop With Diversity and Multipath Interference Cancellation for Direct-Sequence Spread-Spectrum Systems*, IEEE Transactions on Communications, Vol. 46, November 1998.

[5] Volker Aue and Gerhard P. Fettweis, *A Non-Coherent Tracking Scheme for the RAKE Receiver That Can Cope With Unresolvable Multipath*, Proceedings of the International Conference on Communications, Vancouver, Canada, 1999.

[6] 3GPP Technical Specification Group Radio Access Network, Spreading and modulation (FDD), 3G TS 25.213 version 3.0.0, October 1999

[7] J. Baltersee, G. Fock, P. Schulz-Rittich, H. Meyr. “Performance Analysis of Phasor Estimation Algorithms for a FDD-UMTS RAKE Receiver”, ISSSTA2000, Newark, New Jersey, September 2000.

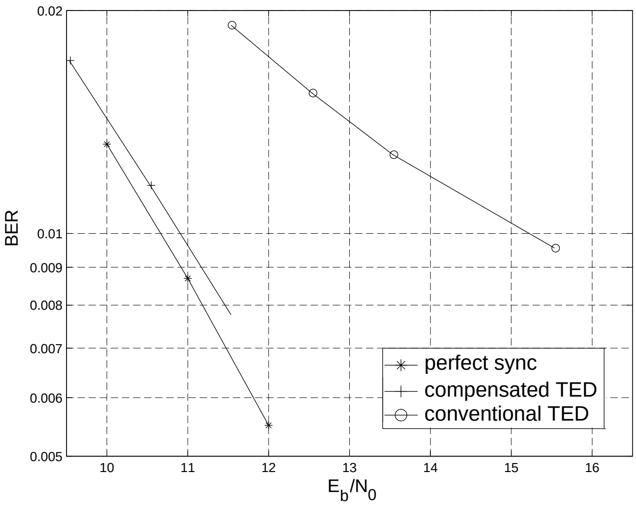

Figure 9: BER, adaptive code-tracking, N = 4

[8] P. Schulz-Rittich, G. Fock, J. Baltersee, H. Meyr. “Low Complexity Adaptive Code Tracking with Improved Multipath Resolution for DS-CDMA Communications over Fading Channels”, ISSSTA2000, Newark, New Jersey, September 2000.