# Low Complexity Adaptive Code Tracking with Improved Multipath Resolution for DS-CDMA Communications over Fading Channels

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*Abstract* — **A new adaptive timing error detector (TED) embedded in a code-tracking loop for RAKE reception of direct-sequence-CDMA signals is presented. The loop consists of a digital coherent TED and a loop filter with lowpass characteristic. In a multipath fading environment, one such loop can be allocated for each finger in a RAKE receiver and the interference from adjacent paths can be mitigated by adaptively prefiltering the signal prior to the correlation process. The filter coefficients are computed online in order to minimize an interference cost function. Multipaths whose delays differ by as little as one chip duration become resolvable and can be tracked, resulting in significant performance gains of the overall system, especially if the channel delay spread is small. The tracking performance of the proposed loop is assessed by computer simulation.**

## I. Introduction

The RAKE receiver [1] is a well-known, low-complexity receiver structure for the reception of code-division multiple access signals and will be the receiver of choice for the first third-generation handsets. It attempts to gather as much signal power as possible by identifying several scattered and reflected replicas of the transmitted signal and assigning separate correlators to each of them, the so-called *RAKE fingers*. The finger outputs are weighted and combined constructively to yield estimates for the transmitted symbols.

One crucial task in every RAKE implementation is the *synchronization*, meaning the estimation and compensation of the channel-induced attenuation, phase shift and path delay in each RAKE finger. The concept of estimating those parameters and then using them as if they were the true values is called *synchronized detection* [2] and is used in virtually every digital receiver implementation. In the course of this paper we shall focus on the task of estimating the channel path delays. Estimation of the complex-valued channel phasors is discussed i.e. in [3].

The path delay estimation is usually divided into a coarse acquisition, typically to within one chip duration, and a fine timing tracking. For AWGN or frequency-flat fading channels, one tracking structure which has received much attention in the literature is the early-late gate timing error detector (EL-TED). In frequency selective fading channels however, is was shown that the EL-TED has fundamental limitations in the sense that adjacent paths can only be tracked if their delays differ by more than a certain threshold, usually larger than the chip duration. If this is not the case, the RAKE fingers will either suffer from a significantly increased timing jitter, or the delay estimates will converge to the same value, making a reacquisition of both fingers necessary [6]. In cases where the channel exhibits a small delay spread, sufficient path delay resolution is critical for adequate receiver performance.

Several approaches for path delay tracking in frequency selective fading conditions have been proposed recently. A structure based on extended Kalman filtering was presented in [4]. A noncoherent tracking technique with interference cancellation was introduced in [5]. In [6], the author proposed a noncoherent scheme which jointly tracks a group of equidistant fingers. A novel coherent TED with coherent multipath interference cancellation is presented in [7].

In this paper, a new adaptive coherent timing error detector is presented which is able to track adjacent paths delays as close as one chip duration or less, by using information about adjacent path locations to adaptively prefilter the signal in the early-late branch. It significantly outperforms the conventional EL-TED and it offers a reasonable tradeoff of performance versus complexity.

The paper is organized as follows. In Section II, the system model is introduced. In Section III, the conventional coherent EL-TED and its limitations in a multipath fading environment are presented. The new timing error detector is presented in Section IV and its performance is evaluated by means of computer simulations.

## II. System Model

In CDMA communications, the user data symbols $\{a_k\}$ are oversampled by the spreading factor $N = T/T_c$ and then multiplied by a user spreading sequence $\mathbf{d}$, which in the case of the third-generation standard draft from 3GPP [8] consists of length $N$ user-specific OVSF spreading sequences as well as much longer basestation-specific scrambling sequences. $T$ and $T_c$ are the symbol and chip duration, respectively. Throughout this paper we shall consider baseband-equivalent signal representation only. The transmitted CDMA signal for one user can then be expressed as

$$s(t) = \sum_{k=-\infty}^{\infty} a_{\lfloor \frac{k}{N} \rfloor} d_{k \bmod N_s} g(t - kT_c), \qquad (1)$$

where $N_s$ is the length of the scrambling sequence and $g(t)$ is the transmit pulse, for the 3GPP draft a root-raised cosine pulse with rolloff factor 0.22. We will assume a wide-sense stationary multipath fading channel model with $N_p$ uncorrelated scatterers (paths):

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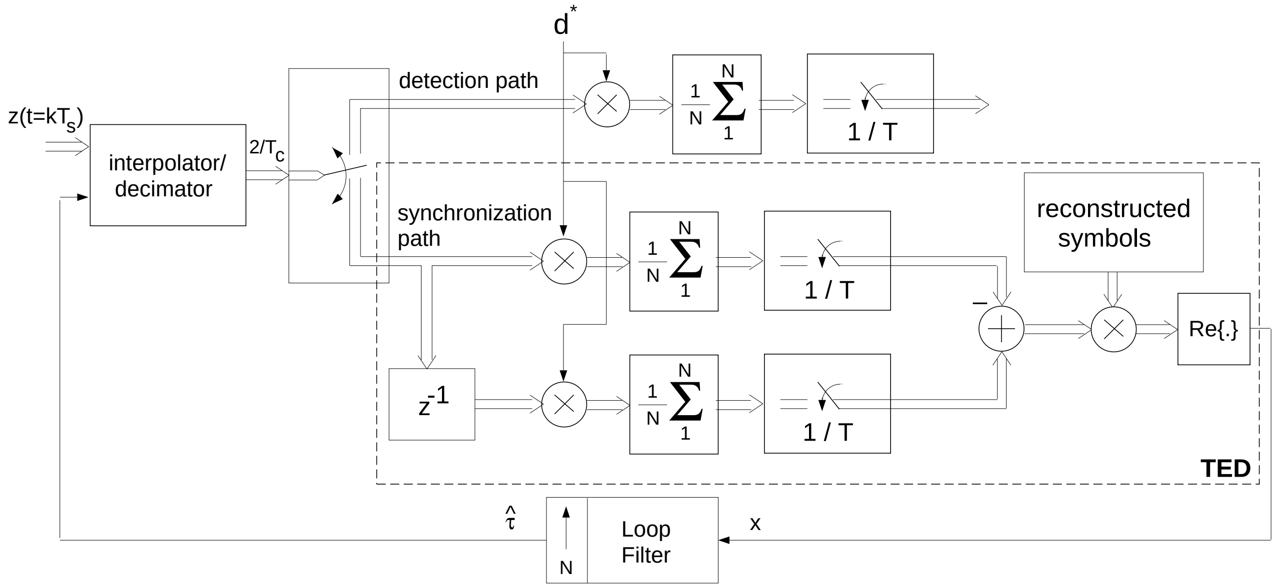


Figure 1: Conventional coherent EL tracking loop

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

with $c^{(l)}$ being the $l$-th complex path tap and $\tau^{(l)}$ the respective path delay. The received signal is pulse-matched filtered with the receive filter $g^*(-t)$ and is given by

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

$\tilde{n}(t)$ is complex valued coloured noise and includes additive white gaussian channel noise as well as other-user interference. $R_g(t)$ is the pulse filter autocorrelation function:

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

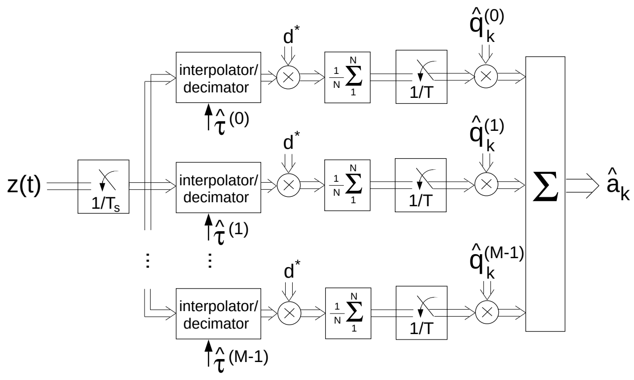


Figure 2: RAKE receiver model

The RAKE receiver is depicted in Figure 2. The received signal is first sampled at the sampling rate $1/T_s$, which must be at least equal to $2/T_c$ to guarantee sufficient statistics for detection and synchronization [2], and subsequently fed to all $M$ RAKE fingers. In each finger, an interpolation/decimation unit provides a data stream on chiprate $1/T_c$ which is sampled at the estimated timing instant $\hat{\tau}$. The latter is provided by the code tracking loop, one for each finger, which will be presented in the next section. It is noted that instead of interpolating and decimating the data signal, the delay estimates can just as well be used to shift the spreading sequence (code-) phase in each finger. Throughout this paper we shall only address the scenario where acquisition of the multipath delays has been performed for each finger and the initial delay estimates only need to be tracked. After correlation with the complex conjugate of the spreading sequence and summation over one symbol interval, the symbol estimates in each finger are weighted according to some optimization criterion. In this paper the maximum-ratio criterion has been chosen, where each weighting coefficient is given by

$$q_k^{(i)} = \frac{c_k^{(i)*}}{\sum_{l=0}^{N_p-1} |c_k^{(l)}|^2} \tag{5}$$

## III. The Coherent Early-Late Tracking Loop

The conventional coherent EL tracking loop with the coherent TED is shown in Figure 1 for one RAKE finger. The digital interpolator/decimator generates a data stream at the estimated timing instant $\hat{\tau}$ at twice the chiprate, which is subsequently demultiplexed and fed to the *detection path* and to the *synchronization path*, the latter being shifted by $\Delta = T_c/2$ with respect to the former. $\Delta$ is often called the *early-late gate timing offset* of the TED. In the synchronization path, correlation with the spreading sequence and symbol-rate sampling are performed on early and late data streams, the early stream being generated by delaying the late stream by one sample. Furthermore, data modulation and complex channel phasor effects are compensated for by multiplying with complex conjugately reconstructed symbols, the latter being generated by complex conjugately multiplying either

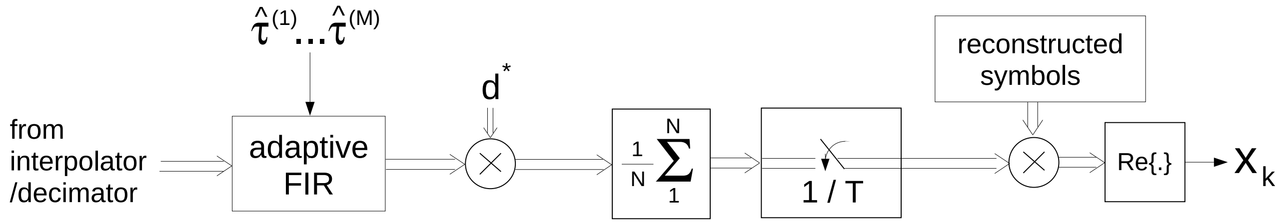


Figure 3: Adaptive timing error detector

pilot symbols or data decisions with channel phasors. The real part of the resulting signal constitutes the error signal $x_k$ on symbol rate:

$$x_k = x(kT) = Re\left\{ \hat{a}_k^* \hat{c}_k^* \sum_{j=kN}^{(k+1)N-1} \left( z(jT_c + T_c/2 + \hat{\tau}) - z(jT_c - T_c/2 + \hat{\tau}) \right) d_{j \bmod N_s} \right\} \qquad (6)$$

It is fed through a loop filter with lowpass characteristic to yield the estimate for the path delay.

One considerable drawback of the conventional early-late structure is its sensitivity in multipath fading environments. Apart from being subject to an increased timing jitter, delay estimates from adjacent RAKE fingers tend to converge to the same value if their delay difference lies in the order of the chip duration (see e.g. [6]). In that case, a central control unit would then remove the RAKE finger with the weaker power from the detection process. The resulting bit-error performance is severely degraded due to two facts: firstly, the receiver loses signal power because one finger has been dropped, and secondly, the remaining finger is subject to severe multipath distortion, because it will track the resulting envelope of the two paths. A structure which allows tracking of close path delays is therefore necessary in order to increase the receiver performance.

## IV. The New Timing Error Detector

The new code tracking loop includes an adaptive TED which mitigates the effect adjacent propagation paths have on the error signal of each RAKE finger by prefiltering the signal in the synchronization path. The structure of the TED is shown in Figure 3. Instead of using a fixed 2-tap FIR filter as in the early-late case $(1-z^{-1})$, an adaptive FIR filter is employed and its coefficients are updated reflecting the current channel scenario.

Consider the expected value of the error signal $x$ (S-curve) for the conventional TED and a flat fading channel, conditioned on the channel phasor $c$ and the estimated phasor $\hat{c}$. Assuming perfect autocorrelation properties of the effective spreading sequence **d** and root-raised cosine transmit and receive filters, it can be written as

$$E[x|c,\hat{c}] = E[|a|^2]\, Re\left\{ c\hat{c}^* \left[ R_g(T_c/2+\hat{\tau}) - R_g(-T_c/2+\hat{\tau}) \right] \right\} \qquad (7)$$

The S-Curve is shown in Figure 4 for $c\hat{c}^* = 1$. Imagining one additional path with a delay difference of $\tau_\Delta$ with respect to the current path, we can either compute a resulting S-curve which will be severely distorted, or we can intuitively assess the paths

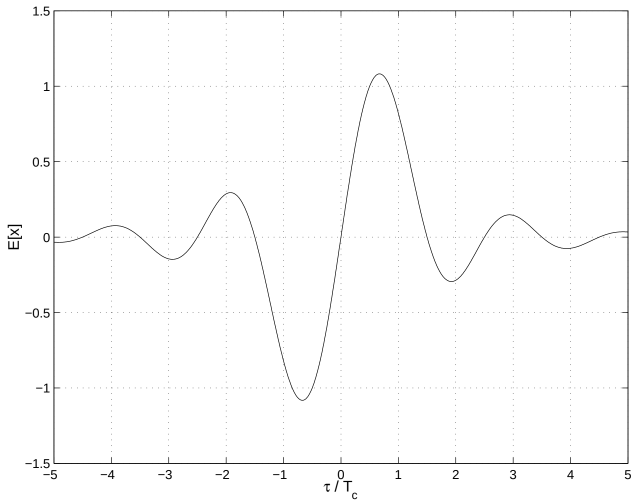


Figure 4: Conventional early-late S-curve

contribution to the current RAKE finger. It will be proportional to its power times the square of the value of the S-curve at $\tau = \tau_\Delta$. The basic idea of mitigating adjacent path interference is thus to reshape the flat-fading-equivalent S-curve of the TED so as to shift its zero-crossings to the locations of adjacent paths. If this is achieved, then those paths will not contribute to the error signal of the current RAKE finger *on average*.

If we filter the synchronization path samples with an FIR filter $\xi = [\xi_0 \cdots \xi_{L-1}]$, instead of using the early-late structure, the S-curve for the flat fading case becomes

$$E[x|c,\hat{c}] = E[|a|^2]\, Re\left\{ c\hat{c}^* \sum_{l=0}^{L-1} \xi_l R_g(\delta_l + \hat{\tau}) \right\} \qquad (8)$$

with $\delta = [\delta_0 \cdots \delta_{L-1}]$ being the filter tap locations with respect to the detection path samples (i.e. for the EL-TED we have $\delta = [T_c/2, -T_c/2]$). If we assume symmetrical FIR filters in the sense that there are equally many "early" and "late" taps, the following relation holds:

$$\delta_l = \left[ \frac{L-1}{2} - l \right] T_c \qquad (9)$$

In this paper, we shall consider a symmetric FIR filter with 4 taps as a straightforward extension to the conventional TED: $\xi = [-\lambda, 1, -1, \lambda]$ and $\delta = [3T_c/2, T_c/2, -T_c/2, -3T_c/2]$. This leaves us with one design parameter - the outer tap magnitude $\lambda$ - and thus with one zero-forcing condition for one adjacent path. Inserting $\xi$ and $\delta$ into (8), setting it to zero for $\hat{\tau} = \tau_\Delta$ and solving for $\lambda$ yields

$$\lambda(\tau_\Delta) = \frac{R_g(-T_c/2+\tau_\Delta) - R_g(T_c/2+\tau_\Delta)}{R_g(-3T_c/2+\tau_\Delta) - R_g(3T_c/2+\tau_\Delta)} \tag{10}$$

This characteristic, which is fixed once the FIR structure is known, can be stored in memory and the outer FIR taps can be modified online, depending on the current adjacent path locations. Different resulting S-curves for the chosen FIR structure are shown in Figure 5 for $\tau_\Delta = 0.9 \cdot T_c, 1.0 \cdot T_c$ and $2.0 \cdot T_c$. It is noted that for the conventional TED ($\lambda = 0$), $\tau_\Delta = 1.5T_c$.

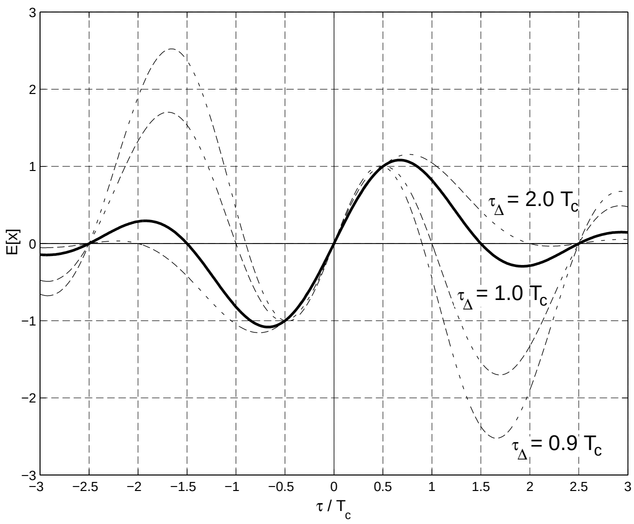


Figure 5: S-curves for adaptive TED

For the chosen FIR structure, one additional zero-crossing of the S-Curve can be influenced (shifted) for each additional FIR tap pair. A general structure of this kind is shown in Figure 6. The locations of adjacent paths (relative timing offsets) are used to compute the outer FIR filter taps. For this approach, knowledge about the instantaneous complex channel phasors is not required for the computation of the FIR coefficients, i.e. the method is purely noncoherent.

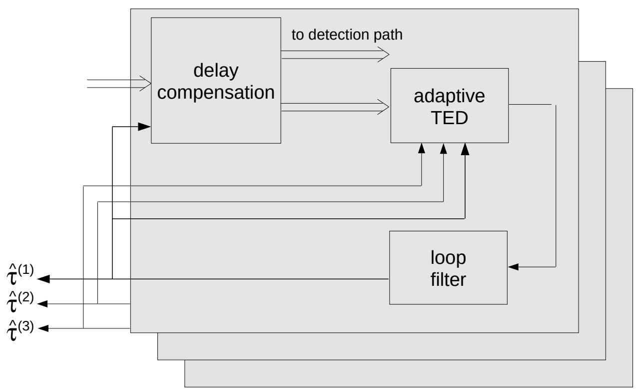


Figure 6: RAKE implementation of adaptive TED

## V. Performance Evaluation

The performance of the new adaptive TED was assessed by means of computer simulations. A CDMA transmission system was implemented using the following key parameters from the 3GPP standard draft [8]:

- QPSK modulation
- Chip rate 3.84 Mcps – $T_c = 260.42$ ns
- 16 pilot bits per slot (1280 bits)

Perfect knowledge of the channel phasors $c_k$ was assumed. The data symbol estimates were switched periodically between hard-decisions from the RAKE combiner output and pilot symbols, depending on the current location within the slot. Furthermore, the RAKE fingers were given the (known) path delays as start values, modelling a "perfect" timing acquisition. For a spreading factor of 4 with a vehicle speed of 10 km/h and a bit-energy to noise-power ratio of 12.0 dB, a two-tap channel profile was used:

| rel. delays [ns] | avg. tap power [dB] |
|---|---|
| 0 | 0 |
| 260.42 | -10 |

It is seen that the two paths are exactly one chip apart. In the RAKE receiver, one finger was allocated for each channel path. The tracked path delays for both fingers are shown for the conventional and the adaptive TED in Figures 7 and 8, respectively. In the latter case, the FIR filters for both paths were optimized for $\tau_\Delta = T_c$, resulting in $\lambda = 1.53$. While the two paths merge in the first case after about 0.3 s, the adaptive TED is able to keep both paths separated. Furthermore, and in contrast to [6], each finger is tracked separately and can be followed if for instance the two paths in the channel model diverge.

In order to quantify the bit-error performance gain over the conventional TED, Figure 9 shows the result of simulations for the 2-path channel and N = 4. For an uncoded BER of $10^{-2}$, around 4 dB can be gained by employing an adaptive TED in the tracking loop. The performance gain is explained by the fact that the RAKE can now be assigned one more finger and both fingers then experience significantly less timing jitter.

## VI. Conclusions and Outlook

A new adaptive code tracking loop for DS-CDMA systems has been presented. It uses knowledge about adjacent RAKE finger delays to adaptively prefilter the TED signal prior to correlation and is thus able to resolve adjacent multipaths which are as close as one chip duration apart. Its superior tracking performance compared to a conventional early-late TED in a scenario with close path spacing was outlined. As one possible realization, a design rule with little complexity for an adaptive FIR filter was presented, with only one design parameter. Other filter design rules, including the possibility to use instantaneous channel tap power or phasor information in order to mitigate more than one adjacent path, are current research topics. It is also noted that one such structure can be allocated for each finger in a RAKE implementation, or one structure can be used in time-multiplex as the path delay dynamics are usually very slow.

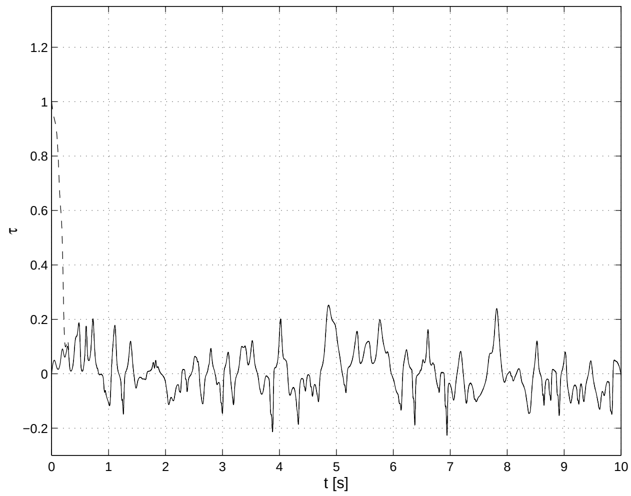


Figure 7: Delay estimates, conventional TED

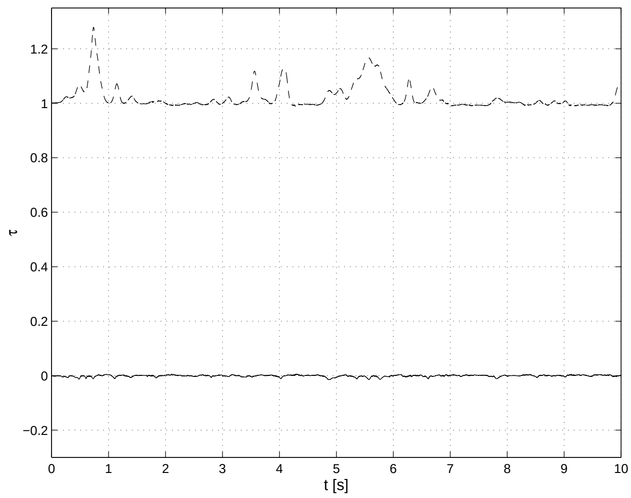


Figure 8: Delay estimates, adaptive TED

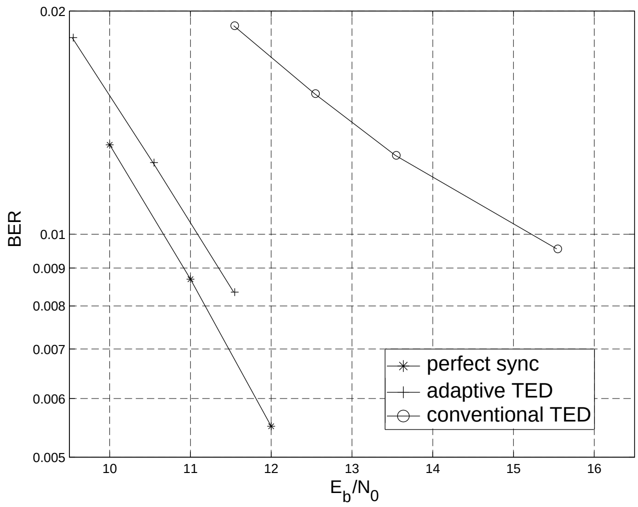


Figure 9: BER, adaptive code-tracking, N = 4

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