# Tracking Performance of ML-Oriented NDA Symbol Synchronizers for Nonselective Fading Channels

Kaj GOETHALS, *Student Member, IEEE*, and Marc MOENECLAEY, *Member, IEEE*

***Abstract*— In this paper we investigate the tracking performance of two maximum-likelihood (ML)-oriented nondecision-aided (NDA) symbol synchronization algorithms, operating on a noisy M-PSK signal ($M > 2$) transmitted over a time-varying nonselective Rician fading channel. The first algorithm is nonchannel-aided (NCA): timing is acquired independently of the channel gain estimation. The second algorithm is channel-aided (CA): it makes use of (an estimate of) the instantaneous channel gain. As the channel gain estimator requires timing information, use of the CA algorithm implies that the timing and the channel gain must be acquired jointly. Both algorithms are suitable for fully digital implementation, and have a similar complexity. For $E_s/N_0$ values of practical interest, we show that the NCA algorithm is to be preferred over the CA algorithm.**

## I. Introduction

THIS paper deals with the symbol synchronization of an M-PSK signal ($M > 2$), transmitted over a slowly time-varying nonselective fading channel [1]. The fading channel is characterized by a sequence of complex-valued correlated random variables, with the $m^{th}$ variable denoting the channel gain experienced by the $m^{th}$ transmitted pulse. Such a channel description is appropriate for several mobile communication systems [2]–[6]. Mainly for simplifying the numerical computations, we have assumed that the magnitude of the channel gain has a Rician distribution; this includes the Rayleigh distribution as a special case.

Starting from the likelihood function, we derive two nondata-aided (NDA) symbol synchronization algorithms; NDA algorithms have the advantage over data-aided (DA) algorithms that no preamble is needed to acquire timing. The first algorithm is nonchannel-aided (NCA): timing is acquired independently of the channel gain estimation. The second algorithm is channel-aided (CA): timing and channel gain estimation have to be performed jointly. A few implementation issues of these algorithms are briefly discussed.

For both algorithms we analytically determine the tracking performance in terms of the signal-to-noise ratio, the carrier-to-multipath ratio and the fading bandwidth. For most cases of practical interest, we find that the NCA algorithm is to be preferred over the CA algorithm.

Paper approved by Costas N. Georghiades, the Editor for Synchronization and Optical Detection of the IEEE Communications Society. Manuscript received February 18, 1993; revised September 30, 1993. This paper was presented in part at Globecom'92, IEEE Global Telecommunications Conference, Orlando, Florida, December 1992.

Both authors are with the Communication Engineering Laboratory, University of Ghent, St-Pietersnieuwstraat 41, B-9000 Ghent, Belgium. They gratefully acknowledge the support from the Belgian National Fund for Scientific Research (NFWO).

IEEE Log Number 9410913.

0090-6778/95$4.00 

## II. System Description

The complex envelope $r(t)$ of the received signal can be represented as

$$r(t) = \sum_m a_m d_m h(t - mT - \tau) + n(t) \qquad (1)$$

where $\{a_m\} \equiv \underline{a}$ is a sequence of independent equiprobable M-PSK symbols with $M > 2$; $h(t)$ is a unit-energy square-root cosine rolloff pulse with rolloff factor $\alpha$; $n(t)$ is white Gaussian noise with independent real and imaginary parts, each having a power spectral density of $N_0/(2E_s)$. The complex-valued channel gains $\{d_m\} \equiv \underline{d}$ are correlated Gaussian random variables with independent identically distributed real and imaginary parts, and with mean $s = \mathrm{E}[d_m]$ and autocovariance $\mathrm{R}(k) = \mathrm{E}[d_m^* d_{m+k}] - |s^2|$; the channel gains are normalized such that $\mathrm{E}[|d_m^2|] = 1$. Hence, the magnitude $|d_m|$ has a Rician distribution with a carrier-to-multipath ratio $(C/M)$ equal to $|s^2|/\mathrm{R}(0)$. The case of Rayleigh fading corresponds to $C/M = 0$ (or $-\infty$ dB), whereas $C/M = +\infty$ dB characterizes the additive white Gaussian noise (AWGN) channel.

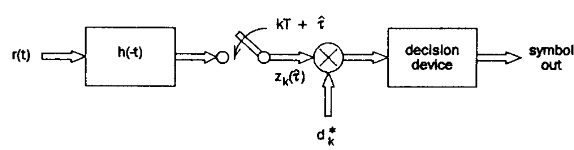


Fig. 1. Receiver structure

A conceptual receiver structure is shown in Fig. 1. The received complex envelope $r(t)$ is applied to a matched filter with impulse response $h(-t)$. The matched filter output signal is sampled at the estimated decision instants $kT + \hat{\tau}$, where $\hat{\tau}$ is an estimate of the unknown time delay $\tau$. The resulting matched filter output sample $z_k(\hat{\tau})$ is multiplied with the complex conjugate $d_k^*$ of the (estimate of) the channel gain, and the result is fed to the decision device. In a fully digital implementation, the analog matched filter and sampler from Fig. 1 are replaced by a digital interpolating matched filter [7].

We consider the following two ML-oriented algorithms for estimating the unknown time delay $\tau$. Their derivation is based upon the likelihood function $L(\underline{a}, \underline{d}, \tau)$ of the received signal $r(t)$ in terms of the channel symbols $\underline{a}$, the channel gains $\underline{d}$ and the unknown time delay $\tau$; this likelihood function is given by

$$L(\underline{a}, \underline{d}, \tau) = \exp\left(-\frac{E_s}{N_0}\sum_{k=0}^{K-1}\left(|a_k d_k|^2 - 2\mathrm{Re}[a_k^* d_k^* z_k(\tau)]\right)\right) \quad (2)$$

where $K$ is the number of data symbols within the observation window, and $\tau$ is assumed to be essentially constant over the observation interval $KT$.

The two considered algorithms are the following :

- *Nonchannel-aided (NCA) algorithm:*

The truly ML NCA algorithm maximizes $\mathrm{E}_{\underline{a},\underline{d}}[L(\underline{a}, \underline{d}, \tau')]$ over all trial values $\tau'$ in the interval $(-T/2, T/2)$. As the statistical expectation of the likelihood function over $\underline{a}$ and $\underline{d}$ is hard to evaluate, and would yield an algorithm requiring knowledge about the operating $E_s/N_0$, we replace $\mathrm{E}_{\underline{a},\underline{d}}[L(\underline{a}, \underline{d}, \tau')]$ by its limit for $E_s/N_0$ approaching zero. This limit can be obtained using the method outlined in [8], which involves a term by term averaging of the Taylor series expansion of the likelihood function about $E_s/N_0 = 0$. Denoting the timing estimate by $\hat{\tau}$, this approach yields the following ML-oriented NCA algorithm:

$$\hat{\tau} = \arg\left\{\max_{\tau'}\left(L_{nca}(\tau')\right)\right\} \quad (3)$$

with

$$L_{nca}(\tau') = \sum_{k=0}^{K-1}|z_k(\tau')|^2 \quad (4)$$

Note that application of the resulting algorithm requires no knowledge about $C/M$, nor about the fading autocovariance function $\mathrm{R}(k)$. This algorithm is the same as the (low $E_s/N_0$ limit of the) NDA maximum-likelihood (ML) algorithm for an additive white Gaussian noise (AWGN) channel [9].

- *Channel-aided (CA) algorithm:*

The truly ML CA algorithm makes use of an estimate $\hat{\underline{d}}$ of the channel gains, and maximizes $\mathrm{E}_{\underline{a}}[L(\underline{a}, \hat{\underline{d}}, \tau')]$ over all trial values $\tau'$ in the interval $(-T/2, T/2)$. In order to avoid an algorithm that requires knowledge about the operating $E_s/N_0$, we again use the same method from [8] to obtain the low $E_s/N_0$ limit of the function to be maximized. This yields the following ML-oriented CA algorithm:

$$\hat{\tau} = \arg\left\{\max_{\tau'}\left(L_{ca}(\tau'; \hat{\underline{d}})\right)\right\} \quad (5)$$

with

$$L_{ca}(\tau'; \hat{\underline{d}}) = \sum_{k=0}^{K-1}|\hat{d}_k|^2|z_k(\tau')|^2 \quad (6)$$

The interpretation of this CA algorithm is that the more noisy samples $z_k(\tau')$, corresponding to small instantaneous channel gains $|d_k|$, are taken less into account. To analyze this algorithm, we assume that perfect channel gain estimates are available. Application of this algorithm does not explicitly require knowledge about the fading statistics $(C/M, \mathrm{R}(k))$.

## III. Implementation of the Algorithms

Let us denote by $L(\tau')$ the function to be maximized, i.e. $L(\tau') = L_{nca}(\tau')$ for the NCA algorithm and $L(\tau') = L_{ca}(\tau'; \hat{\underline{d}})$ for the CA algorithm.

The maximization of $L(\tau')$ can be accomplished by means of a search. This involves evaluating the function $L(\tau')$ for a sufficient number (say $N$) of trial values $\tau'$ in the interval $(-T/2, T/2)$, and selecting the trial value yielding the largest $L(\tau')$. This can be achieved straightforwardly by means of a digital matched filter which produces samples at a rate $N/T$; for each of the $N$ "sampling phases" at the matched filter output, the corresponding $L(\tau')$ is computed. The drawback of this approach is the small computational efficiency, especially for large $N$, because of the large number of operations required in the matched filter. The computational efficiency of the search method can be improved by reducing the rate at which the matched filter produces samples, and interpolating between available matched filter output samples to obtain $N$ samples per symbol; as sufficiently accurate interpolators exist which have far fewer taps than the matched filter [10], computational efficiency is increased as compared to the previous solution. In order to avoid aliasing, the matched filter should produce samples at a rate of at least $(1+\alpha)/T$.

As the considered algorithms are quadratic in the matched filter output samples and the one-sided signal bandwidth does not exceed $1/T$, the timing estimate $\hat{\tau}$ can also be obtained by direct computation. This involves the digital filter and square synchronizer, introduced in [11]. The performance of the search method and the direct method are essentially the same [12], but the direct method requires much less computation.

The search method and the direct method are implementations of a feedforward symbol synchronization algorithm. In a feedback algorithm, the timing estimate $\hat{\tau}(k+1)$ for the $k+1^{th}$ symbol is obtained by adding to $\hat{\tau}(k)$ a fraction of the derivative with respect to $\tau'$, of the $k^{th}$ term in the sum (4) or (6).

## IV. Tracking Performance Evaluation

For both algorithms we theoretically evaluate the linearized variance of the timing error normalized to the symbol duration $T$, by using the method outlined in [13]. This involves the approximations

$$\hat{\tau} - \tau \approx -\frac{L'(\tau)}{L''(\tau)} \approx -\frac{L'(\tau)}{\mathrm{E}[L''(\tau)]} \quad (7)$$

In (7), $L(.)$ is the function to be maximized by the timing estimate, and $'$ and $''$ denote first and second derivative, respectively. The first approximation in (7) is a linearization illustrated in Fig. 2. The second approximation involves replacing $L''(\tau)$ by its statistical expectation $\mathrm{E}[L''(\tau)]$ over noise, data symbols and channel gains and is equivalent with substituting a time average by a statistical average. This second approximation is valid when $K$ is large and the correlation time of the channel gains is much smaller than the observation interval $KT$, in which case the variance of $L''(\tau)$ is much smaller than the squared expected

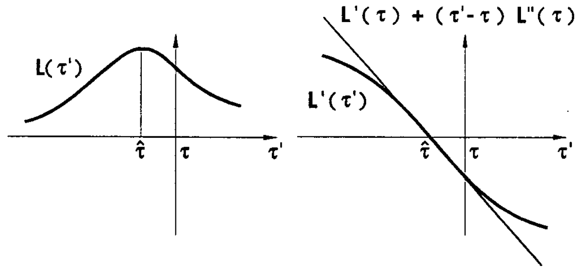


Fig. 2. Linearization of $L'(\tau')$ around $\tau$

value $(\mathrm{E}[L''(\tau)])^2$. Under these conditions, the linearized variance becomes

$$Var = \mathrm{E}\left[\left(\frac{\hat{\tau}-\tau}{T}\right)^2\right] \approx \frac{\mathrm{E}[(L'(\tau))^2]}{\mathrm{E}^2[L''(\tau)]T^2} \tag{8}$$

From (8), the following result is obtained for large $K$ (see Appendix):

$$Var_{NCA} = \frac{C_{NCA}^{N\times N}}{K}\left(\frac{E_s}{N_0}\right)^{-2} + \frac{C_{NCA}^{S\times N}}{K}\left(\frac{E_s}{N_0}\right)^{-1} + \frac{C_{NCA}^{S\times S}}{K^2} \tag{9}$$

$$Var_{CA} = \frac{C_{CA}^{N\times N}}{K}\left(\frac{E_s}{N_0}\right)^{-2} + \frac{C_{CA}^{S\times N}}{K}\left(\frac{E_s}{N_0}\right)^{-1} + \left[\frac{C_{CA}^{S\times S,1}}{K^2} + \frac{C_{CA}^{S\times S,2}}{K}\right] \tag{10}$$

In the above, the subscripts NCA and CA denote the type of synchronization algorithm, while the superscripts NxN, SxN and SxS refer to the noise x noise, signal x noise and signal x signal contributions to the timing error variance. For both synchronizers, the NxN and SxN contributions are inversely proportional with the number of symbols $K$ in the observation interval. For the NCA synchronizer, the SxS contribution is inversely proportional to $K^2$, whereas for the CA synchronizer the SxS contribution consists of two terms that are inversely proportional to $K^2$ and $K$, respectively. Both algorithms become equivalent when $C/M \rightarrow +\infty$ dB, i.e. for the AWGN channel.

Assuming that the channel gain has an autocovariance function given by $\mathrm{R}(m) = \mathrm{R}(0)\exp(-2\pi^2(B_fT)^2m^2)$, we have investigated how the various contributions in (9) and (10) depend on the rolloff factor $\alpha$, the normalized fading bandwidth $B_fT$ and the $C/M$ ratio; a few cases are shown in Figs. 3–5. We have verified that the results depend very little on the specific shape of the channel gain autocovariance function. The timing error variance is furthermore independent of $M$, the number of modulation levels of the M-PSK signal, with $M > 2$.

For the NCA symbol synchronizer, the following observations can be made.

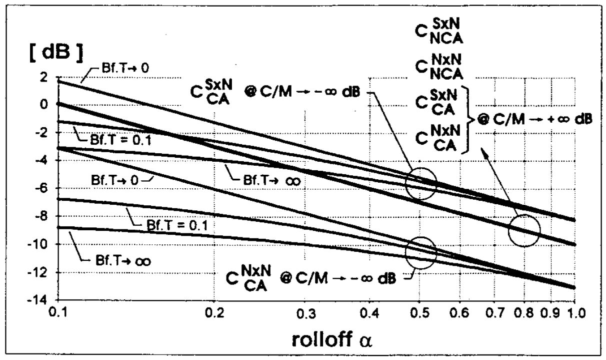


Fig. 3. NxN and SxN contributions

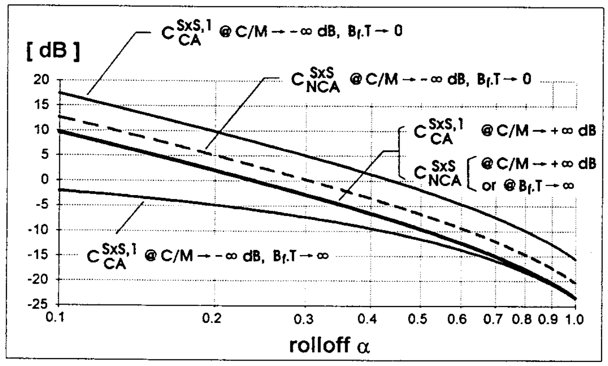


Fig. 4. $C_{NCA}^{S\times S}$ and $C_{CA}^{S\times S,1}$

- The NxN and SxN contributions are independent of the fading characteristics, and are inversely proportional to $\alpha$; these contributions are the same as for the AWGN channel.

- The SxS contribution depends only weakly on the fading characteristics; it increases with decreasing $C/M$ or decreasing $B_fT$. Except for $\alpha$ close to 1, the SxS contribution is essentially inversely proportional with $\alpha^2$.

For the CA symbol synchronizer, the following dependence is observed.

- The NxN contribution is smaller than for the NCA algorithm, and increases with increasing $C/M$, decreasing $B_fT$ or decreasing $\alpha$. The dependence on the fading bandwidth becomes less with increasing $C/M$ or increasing $\alpha$.

- Except for small $\alpha$ and large $B_fT$, the SxN contribution is larger than for the NCA algorithm, and increases with decreasing $C/M$, decreasing $B_fT$ or decreasing $\alpha$. The SxN contribution becomes less dependent on the fading bandwidth with increasing $C/M$ or increasing $\alpha$.

- The SxS contribution contains two terms that are inversely proportional to $K^2$ and $K$, respectively. The first term increases with decreasing $B_fT$; for small (large) $B_fT$, it increases with decreasing (increasing) $C/M$. The second term depends strongly on the fading characteristics; it decreases with increasing $C/M$, and becomes vanishingly small when $C/M \rightarrow +\infty$ dB or $B_fT \rightarrow 0$.

- When $B_fT \rightarrow 0$, all contributions exhibit the same dependence on $\alpha$ as for the AWGN channel.

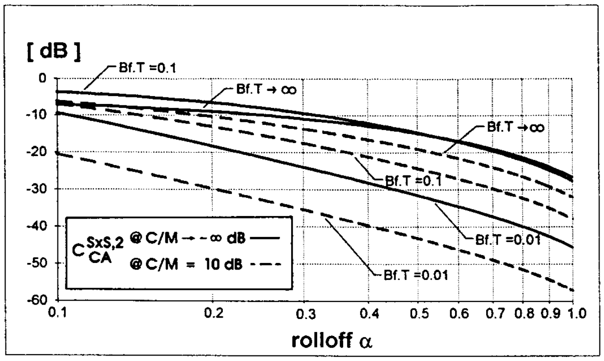


Fig. 5. $C_{CA}^{S \times S,2}$

## V. Examples

In this section we consider two specific fading statistics, i.e. Rician fading with $C/M = 10$ dB (which is typical for mobile satellite communications) and Rayleigh fading ($C/M = -\infty$ dB). For both cases, the rolloff is taken to be 50%, and $K = 100$. The resulting timing error variances for $B_fT$ equal to 0.1 and 0.01 are shown in Figs. 6 and 7 as a function of $E_s/N_0$. For the considered range of $E_s/N_0$, the following observations are made. The timing error variance of the NCA algorithm increases with decreasing fading bandwidth, whereas the CA algorithm exhibits the opposite behavior. The dependence on the fading bandwidth is much stronger for the CA algorithm than for the NCA algorithm; for both algorithms, this dependence becomes less pronounced for increasing $C/M$. The CA algorithm performs worse than the NCA algorithm, especially for large values of $B_fT$ and small values of $C/M$.

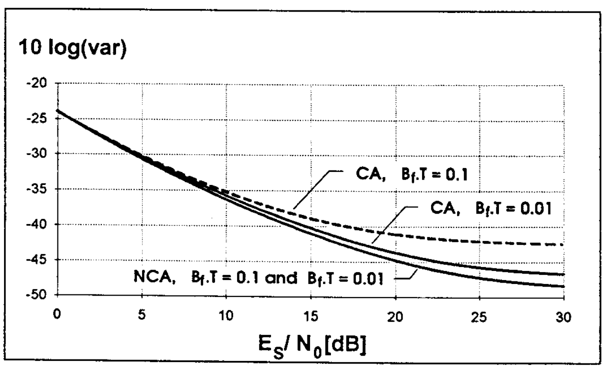


Fig. 6. Timing error variances for $C/M = 10$ dB; $K = 100$

For $C/M = 10$ dB, which is typical for mobile satellite communications, we have investigated the effect of varying the window length from $K = 100$ to $K = 200$. The rolloff factor $\alpha$ was again assumed to be 50%. The resulting timing error variances as a function of $E_s/N_0$ are shown in Fig. 8 for $B_fT$ equal to 0.1 and 0.01. The timing error variance of the NCA synchronizer is nearly independent of $B_fT$. The timing error variance of the CA synchronizer depends more strongly on $B_fT$, and increases with increasing $B_fT$. The SxS contribution is approximately proportional to $1/K^2$ for small $B_fT$, and to $1/K$ for large $B_fT$. For small and moderate $E_s/N_0$, the NCA and CA algorithm yield approximately the same tracking error variance, but for large $E_s/N_0$ the CA algorithm is worse than the NCA algorithm, especially for large $B_fT$.

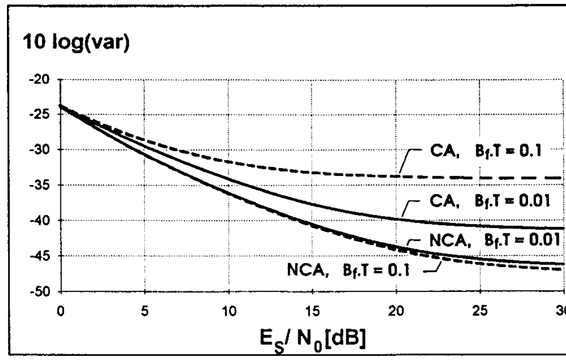


Fig. 7. Timing error variances for $C/M = -\infty$ dB; $K = 100$

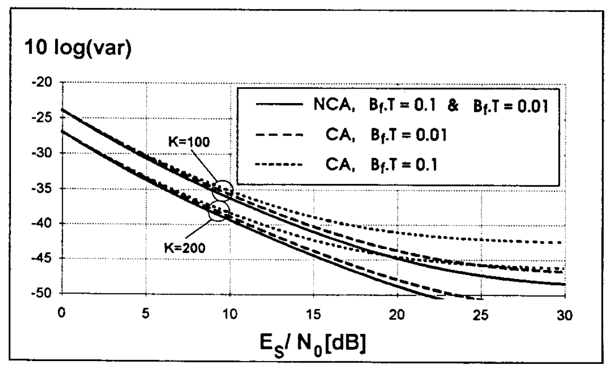


Fig. 8. Timing error variances for $C/M = 10$ dB; $K = 100$ and $K = 200$

## VI. Conclusions and Remarks

We have analyzed the tracking performance of both the NCA and CA ML-oriented NDA symbol synchronizers for time-varying nonselective fading channels.

For mobile satellite communications, $C/M$ is sufficiently large to operate the link at $E_s/N_0$ ratios at which the SxS contribution to the timing error variance is small with respect to the sum of the NxN and SxN contributions. In this region of $E_s/N_0$, both the NCA and CA synchronizer yield a similar value of the timing error variance, which depends only weakly on the fading bandwidth.

In the case of Rayleigh fading, the communication link is operated at large values of $E_s/N_0$, so that the SxS contribution dominates. In this case, the NCA algorithm performs better than the CA algorithm.

We have found that the CA algorithm (6) outperforms the NCA algorithm (4) only for values of $E_s/N_0$ well below 0 dB, whereas for moderate and large $E_s/N_0$ the NCA algorithm (4) performs better than the CA algorithm (6). This result seems counter-intuitive because the CA algorithm has perfect knowledge about the channel gains. However, the algorithms (4) and (6) are the low $E_s/N_0$ *approximations* of the true ML algorithms; therefore, for moderate and large $E_s/N_0$, the tracking performance of the algorithms (4) and (6) is degraded as compared to their corresponding true ML algorithms. While the true ML NDA CA algorithm with correct channel gain information must outperform the true ML NDA NCA algorithm for all $E_s/N_0$, this might no longer be the case for the approximate ML algorithms (4) and (6). Our finding that for moderate and large $E_s/N_0$ the algorithm (4) outperforms the algorithm (6) indicates that the performance degradation, resulting from using (4) and (6) instead of the true ML algorithms, is larger for the CA algorithm than for the NCA algorithm. This means that the NDA CA algorithm (6) does not use the channel gains in an efficient way for moderate and large $E_s/N_0$. For large $E_s/N_0$, the true ML NDA CA algorithm converges to the ML decision-aided CA algorithm (this fact is well known in the case of the AWGN channel [14]) which we have analyzed in [15], and which we have found to outperform both the algorithms (4) and (6) at moderate and large $E_s/N_0$. For Rayleigh fading with uncorrelated channel gains it can be verified that the true ML NDA NCA algorithm coincides with (4) irrespective of $E_s/N_0$, in which case the performance of (4) is not degraded as compared to the corresponding true ML algorithm.

The NCA algorithm can acquire timing independently of the channel gain estimation and is also suited for noncoherent detection, so that the NCA algorithm is to be preferred over the CA algorithm.

As the fading statistics enter the tracking performance only through moments of $|d_k|$ (see Appendix), the tracking performance is not affected by a small (residual) carrier frequency offset $F$, which can be incorporated by substituting $d_k \exp(j2\pi kFT)$ for $d_k$.

The statistics of the independent zero-mean data symbols enter the tracking error variance expression only through the moments $\mathrm{E}[|a_k|^2]$ and $\mathrm{E}[a_k^2]$. As $\mathrm{E}[|a_k|^2] = 1$ and $\mathrm{E}[a_k^2] = 0$ for M-PSK with $M > 2$, the tracking performance does not depend on the constellation size $M$ for $M > 2$.

Finally, it should be noted that the expressions for the NxN, SxN and SxS contributions to the tracking error variance, given in the appendix, are valid for *any* channel gain distribution. The assumption of Rician fading has been adopted mainly for simplifying the evaluation of the higher-order moments (17), which otherwise would be quite difficult.

## Appendix

For both algorithms, $L(\tau)$ is quadratic in the matched filter output samples $z_k(\tau)$, which have a signal and a noise term. The first derivative $L'(\tau)$ therefore contains a SxS term, a NxN term and a SxN term, which are uncorrelated. After squaring and averaging, each of these NxN, SxN and SxS terms contributes separately to the numerator $\mathrm{E}[L'^2(\tau)]$ of (8). The analytic expressions for the coefficients of the timing error variance in (9) and (10) are given below.

- *For the NCA algorithm:*

$$C_{NCA}^{N\times N} = C_{NCA}^{S\times N} = \frac{1}{2\left(-g_0''T^2 - \sum_{-\infty}^{+\infty} g_k'^2 T^2\right)} \tag{11}$$

$$C_{NCA}^{S\times S} = \frac{\sum_{-\infty}^{+\infty} |k| D_k^{2,2} g_k'^2 T^2}{2\left(-g_0''T^2 - \sum_{-\infty}^{+\infty} g_k'^2 T^2\right)^2} \tag{12}$$

- *For the CA algorithm:*

$$C_{CA}^{N\times N} = \frac{1}{2\left(-D_0^{4,0} g_0''T^2 - \sum_{-\infty}^{+\infty} D_k^{2,2} g_k'^2 T^2\right)} \tag{13}$$

$$C_{CA}^{S\times N} = \frac{-D_0^{6,0} g_0''T^2 - \sum_{-\infty}^{+\infty} D_k^{4,2} g_k'^2 T^2}{2\left(-D_0^{4,0} g_0''T^2 - \sum_{-\infty}^{+\infty} D_k^{2,2} g_k'^2 T^2\right)^2} \tag{14}$$

$$C_{CA}^{S\times S,1} = \frac{\sum_{-\infty}^{+\infty} |k| D_k^{4,4} g_k'^2 T^2}{2\left(-D_0^{4,0} g_0''T^2 - \sum_{-\infty}^{+\infty} D_k^{2,2} g_k'^2 T^2\right)^2} \tag{15}$$

$$C_{CA}^{S\times S,2} = \frac{\sum_{-\infty}^{+\infty} \left(D_k^{6,2} - D_k^{4,4}\right) g_k'^2 T^2}{2\left(-D_0^{4,0} g_0''T^2 - \sum_{-\infty}^{+\infty} D_k^{2,2} g_k'^2 T^2\right)^2} \tag{16}$$

with

$$D_k^{p,q} = \mathrm{E}[|d_m|^p |d_{m+k}|^q] \tag{17}$$

$$g_0'' = \frac{d^2 g}{dt^2}(0) \tag{18}$$

$$g_k' = \frac{dg}{dt}(kT) \tag{19}$$

and $g(t) = h(t) * h(-t)$ is a cosine rolloff pulse.

## References


[1] J.G. Proakis, Digital communications. New York: McGraw-Hill, 1983

[2] S. Stein, "Fading channel issues in system engineering," IEEE J. Select. Areas Commun., SAC-5, pp. 68–89, Feb. 1987

[3] W.C. Jakes, Ed., Microwave Mobile Communications. New York: Wiley, 1974

[4] A. Aghamohammadi, H. Meyr and G. Ascheid, "A new method for phase synchronization and automatic gain control of linearly modulated signals on frequencyflat fading channels," IEEE Trans. Commun., COM-39, pp. 25–29, Jan. 1991

[5] D. Haccoun and F. Gagnon, "Performance analysis of error control coding for mobile channels," Proc. of IEEE Globecom, pp. 902.2.1–902.2.5, San Diego, CA, Dec. 1990

[6] F. Davarian, "Channel simulation to facilitate mobile-satellite communications research," IEEE Trans. Commun., COM-35, pp. 47–56, Jan. 1987

[7] F.M. Gardner, "Timing adjustment via interpolation in digital demodulators," Final report, part I, Estec contract 8022/88/NL/DG, June 1990

[8] M. Moeneclaey and G. De Jonghe, "Tracking performance comparison of two feedforward ML-oriented carrier-independent NDA symbol synchronizers," IEEE Trans. Commun., COM-40, pp. 1423–1425, Sept. 1992

[9] T. Jesupret, M. Moeneclaey and G. Ascheid, "Digital demodulator synchronization, Performance analysis," Final report, Estec contract 8437/89/NL/RE, June 1991

[10] K. Bucket and M. Moeneclaey, "The effect of interpolation on the BER performance of narrowband BPSK and (O)QPSK on Rician fading channels," IEEE Trans. Commun., COM-42, Nov. 1994

[11] M. Oerder and H. Meyr, "Digital filter and square timing recovery," IEEE Trans. Commun., COM-36, pp. 605–612, May 1988

[12] L.E. Franks, "Acquisition of Carrier and Timing Data I," New Directions in Signal Processing in Communications and Control, J. K. Skwirzynski, pp. 429–447, Noordhoff International, 1975, Leiden

[13] L.E. Franks, "Carrier and bit synchronization in datacommunication - a tutorial review," IEEE Trans. Commun., COM-28, pp. 1107–1121, Aug. 1980

[14] D.D. Falconer and J. Salz, "Optimal reception of digital data over the Gaussian channel with unknown delay and phase jitter," IEEE Trans. Inform. Theory, IT-23, pp. 117–126, Jan. 1977

[15] K. Goethals and M. Moeneclaey, "ML-Oriented DA Symbol Synchronizers for Time-Varying Nonselective Fading Channels," Proc. ICC'93, pp. 448–492, Geneva, Switzerland, 1993



**Kaj Goethals** was born in Chake Chake, Tanzania, on November 18, 1967. He received the Diploma Degree in Electrical Engineering from the University of Ghent, Ghent, Belgium in 1991.

Since October 1991 he has been working at the Communication Engineering Laboratory, University of Ghent, as a Research Assistant for the Belgian National Fund for Scientific Research (NFWO). His main research interests are signal processing, digital receivers, synchronization, mobile and satellite communications.

**Marc Moeneclaey** was born in Ghent, Belgium, on October 15, 1955. He received the Diploma of Electrical Engineering and the Ph.D. degree from the University of Ghent, Belgium, in 1978 and 1983, respectively.

He is a Senior Research Associate for the Belgian National Fund for Scientific Research (NFWO) at the Communication Engineering Laboratory, University of Ghent, and part-time Professor at the same university. Presently he serves as Editor for Synchronization for the IEEE Transactions on Communications. His main research interests include statistical communication theory, carrier and symbol synchronization, spread-spectrum, mobile and satellite communication.