Efficient linear Multiuser Detection for LEO Satellite Systems with Long Codes

Stephan Fischer, Klaus Knoche, Volker Kühn, Karl-Dirk Kammeyer

University of Bremen, Institute for Telecommunications and Higher Frequencies
Bremen, Germany
E-mail: fischer@ant.uni-bremen.de, knoche@ant.uni-bremen.de
kuehn@ant.uni-bremen.de, kammeyer@ant.uni-bremen.de

Abstract: **This paper deals with the application of linear multiuser detectors in the mobile terminal of a LEO (Low Earth Orbit) satellite system with CDMA (Code Division Multiple Access). Since, no information of the spreading sequences of other users is given and since there are no training sequences, a blind adaptive interference detector (BAID) with low complexity is needed. All concepts proposed till now are based on short spreading codes, this means that the period of the spreading sequences has the length of one symbol. However, real satellite communication systems use long codes. In this paper a new scheme is proposed, which can be applied on long codes. By cascading multiple separated BAIDs (cBAID) the adaptation is done every N symbols, when the same part of the spreading sequence appears. Also a new approach with reduced complexity is presented.**

1. INTRODUCTION

In former years, mobile wireless communication became more and more important. In order to provide global coverage for future worldwide wireless communication, satellite communication systems such as LEO (Low Earth Orbit) offer a solution. Especially in areas with low population density or low infrastructure, satellite communication is superior to terrestrial mobile communication. Satellite systems can also complement existing communication networks in order to increase the availability of services. The realization of the handover between different satellites and the multiple access is very important for a LEO satellite communication system. Both issues can be managed by using CDMA (Code Division Multiple Access) technology [1]. The problem is, that the performance of a CDMA system degrades with the number of active users. The multiple access interference (MAI) limits the capacity of a CDMA system. For our analysis the Globalstar satellite system is taken as a basic model. Globalstar is a LEO satellite communication system with CDMA technology, that is already online. Recently multi user interference suppression has become very pertinent, due to the fact that it improves the system performance significantly compared to a conventional correlation receiver. In the forward link, in which the transmission from the gateway station via the satellite to the mobile user takes place, the user has no information about the interfering signals and no trainings sequences exist. For these reasons a blind adaptive interference detector (BAID) with low complexity is needed. The adaptive algorithms are based on cyclo stationarity of the spreading sequences. If the sequences change from symbol to symbol the algorithms cannot adapt. However, in real LEO satellite communication systems long codes are applied. Therefore, a new scheme is presented which adjusts the linear detectors to long codes. A handicap of the implementation of linear multiuser detectors in the mobile terminal of a communication system is the amount of processing time needed for the algorithms. For this reason, it is very important to develop concepts with reduced complexity.

This paper is organized as follows. In chapter 2 the system outline is described and the interference problem is illustrated. Then the blind interference suppression algorithms are discussed in section 3. In section 4 the new scheme which applies the linear interference detector to a long code system is presented and some allocations with low complexity are shown. Finally, the paper is summarized.

2. SYSTEM OUTLINE

In this chapter the baseband transmission model based on the Globalstar satellite system [2, 3] is described. We focus our interest on the forward link; the transmission from the gateway station via satellite to the mobile user. The footprint of a Globalstar satellite is divided into 16 spot beams by phased array antennas. Each spot beam has a bandwidth of $B_{beam} = 16.5$MHz. This bandwidth is divided into 13 FDM (Frequency Division Multiplex) sub channels, each 1.23MHz wide. The basic structure of the Globalstar transmitter is shown in Figure 1.

The data bits d of rate 4.8kBs are convolutionally encoded (rate $R = 1/2$, constraint length $cl = 9$) and interleaved. Therefore, a 20ms block interleaver is used. The interleaver delay of 20ms is equivalent to an interleaver size *is* of 192 bits. Then the interleaved bit stream is spread by Walsh sequences of length 128 (spreading factor $N_p = 128$). This leads to a chip rate of 1.23MHz. The processing gain can be calculated as follows

$$G = \frac{1}{R}\frac{1}{ld(M)}N_p = \frac{1}{1/2}\frac{1}{ld(2)}128 = 256, \qquad (1)$$

where M is the order of the modulation scheme. Orthogonal Walsh codes are used to separate different users within a beam.

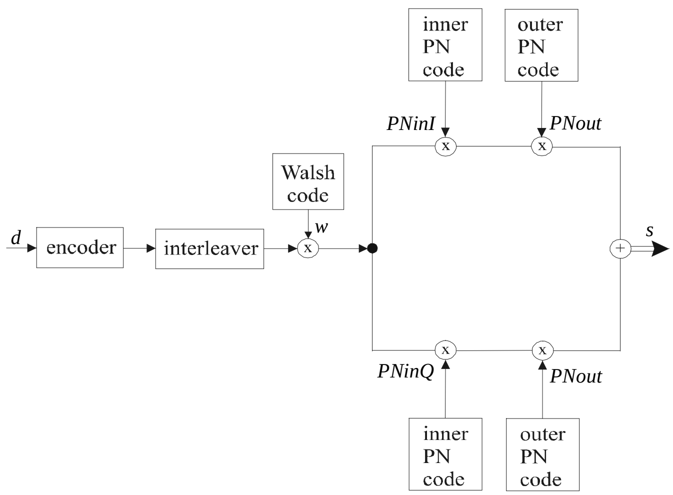

Fig. 1. Transmitter of the Globalstar system

In the next step the bits are split between the I and Q branches and multiplied with two different inner PN (Pseudo Noise) sequences. Two independent PN sequences are used for the inphase and the quadrature phase in order to manage imperfect carrier synchronization and nonlinear distortions [4]. After that an outer PN sequence is overlaid on the I and Q components. Both multiplications do not lead to further spreading. The PN codes are used to scramble the signals in order to distinguish different beams and different satellites. According to this description, the signature sequence c of the user of interest, consisting of the user specific Walsh code w and the beam and satellite specific inner PN codes (*PNinI* and *PNinQ*, the outer PN sequences are omitted) can be denoted as follows

$$c_i = w_i \cdot (PNinI + j * PNinQ) \quad i=0,\dots N_p. \quad (2)$$

A common problem for CDMA systems is the multiuser interference. By applying just one sub beam, there is no interference because of the orthogonal Walsh codes, which provide perfect user separation. However, the different spot beams of a satellite overlap and other satellites in view can interfere as well. This leads to interference due to the imperfect separation properties of the PN codes [5]. The spot beam geometry of a satellite is shown in Figure 2 [6].

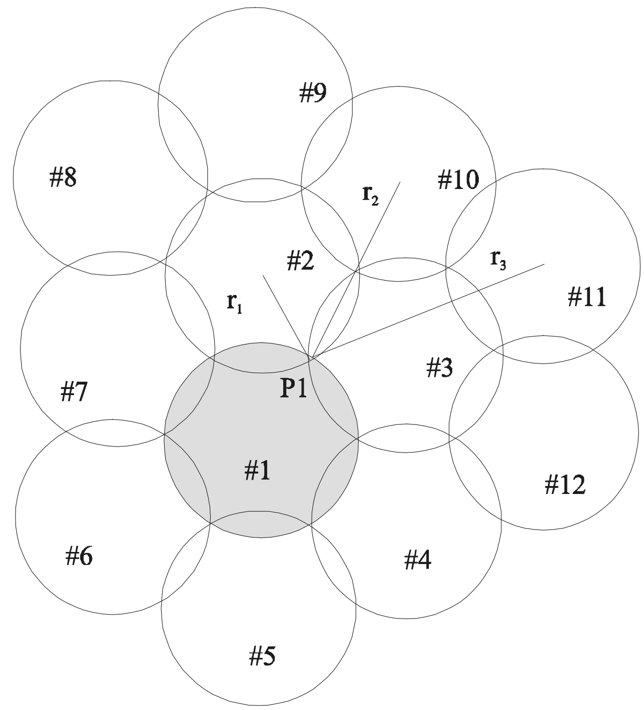

Fig. 2. Spot beam geometry

On the circle around each spot beam the signal energy is 3dB lower than in the center of the spot beam. A worst-case position is given, if the user of the reference spot beam (#1) is at point P1, where the power of the interfering two neighbor spot beams (#2 and #3) is as high as his/her own. The other spot beams are more attenuated depending on their distance from point P1 [7].

3. Interference suppression algorithms

The Globalstar system applies a conventional correlation receiver. In this section two blind interference suppression algorithms are presented. An appliance of the least mean squares (LMS) algorithm was derived in [8]. Using this detector a scheme with an adaptive step size (AS-LMS) was developed in [9].

LMS

A minimum mean-square-error (MMSE) linear multiuser detector computes the signal h that minimizes the mean square error (MSE)

$$E\left\{(Ab - r^T \cdot h)^2\right\} \qquad (3)$$

where A denotes the received amplitude, b stands for the encoded bits and r is the received signal (T denotes transposition). User 1 is the user of interest and so the indices are omitted $(h_1 = h, d_1 = d, ...)$. The signal h can be written in its canonical form

$$h = c + x \tag{4}$$

where c is the signature waveform of user 1 and x is orthogonal to c.

$$c^T \cdot x = 0 . \tag{5}$$

Furthermore, the following normalization is adopted

$$h^T \cdot c = \| c \|^2 = 1 . \tag{6}$$

Utilizing this canonical form a detector that tries to minimize the mean output energy (MOE) of the detector given by

$$E\left\{ (r^T \cdot (c + x))^2 \right\} \tag{7}$$

can be developed [8]. The energy at the output consists of the energy of the desired signal and the energy of the interfering signals plus AWGN (Additive White Gaussian Noise). It can be shown that minimizing the mean output energy leads to a MMSE solution [8].

The signal x can be adaptively determined with the help of the stochastic gradient method

$$x_{n+1} = x_n - \gamma\left(r_n^T \cdot h_n\right)\left[r_n - \left(r_n^T \cdot c\right)c\right] \tag{8}$$

whereas the step-size γ has to be a compromise between the acquisition speed and the steady state jitter.

AS-LMS

When applying the LMS detector by starting the reception of a signal a large step size for acquisition is helpful. However, if the steady state is reached a larger step-size leads to larger jitter problems. Thus, an adaptive step size would be desirable. The AS-LMS algorithm computes the signal x like the LMS detector and in addition to that it utilizes a second LMS algorithm minimizing $E\left\{\left(h_n^T \cdot r_n\right)^2\right\}$ with respect to γ to adjust the step-size. This leads to the following estimate of the step-size [9]

$$\gamma_{n+1} = \left[\gamma_n - \alpha r_n^T h_n r_n^T Y_n\right]_{\gamma-}^{\gamma+} \tag{9}$$

where α stands for the learning rate of the second LMS algorithm and Y is the derivative $\partial h / \partial \gamma$. The values γ- and γ+ denote a lower limit for the step size and an upper limit. In [9] it is shown that the derivative Y can be calculated as follows

$$Y_{n+1} = \left[I - \gamma_n r_n r_n^T\right]Y_n + \gamma_n r_n^T Y_n \left(r_n^T c\right)c - r_n^T h_n \left(r_n - \left(r_n^T c\right)c\right) \tag{10}$$

where I is the identity matrix.

4. LINEAR DETECTORS FOR LONG CODES

In the Globalstar system the outer PN sequences do not change during the duration of a symbol. For this reason they do not influence the correlation properties of the inner spreading sequences. These sequences consist of the Walsh codes and the inner PN codes. The Walsh codes have a period of one symbol duration and the inner PN codes span over 8 symbols. This means that every 8 symbols the same part of the spreading sequence is used. Therefore, 8 different adaptation processes can be cascaded. Figure 3 illustrates this approach.

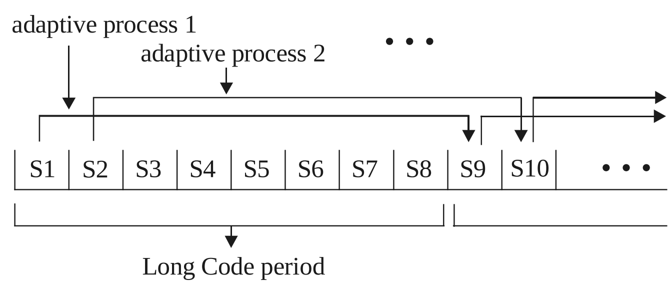

Fig. 3. Adaptive process at Long Code spreading

The new concept does not lead to a higher complexity, since the same detector can be used. After every symbol the adapted sequence is stored in the memory and the data for the next process is loaded. Due to the storage of the data for the different adaptation steps the memory has to be increased compared to the short code case. However, for the LMS algorithm only the 128 chips of each spreading sequence have to be stored. The new scheme which is called cBAID (cascaded Blind Adaptive Interference Detector) is depicted in figure 4. In the Globalstar system the channel coefficient $f(k)$ can be estimated with the help of a pilot channel. This estimate is used for maximum ratio combining (MRC).

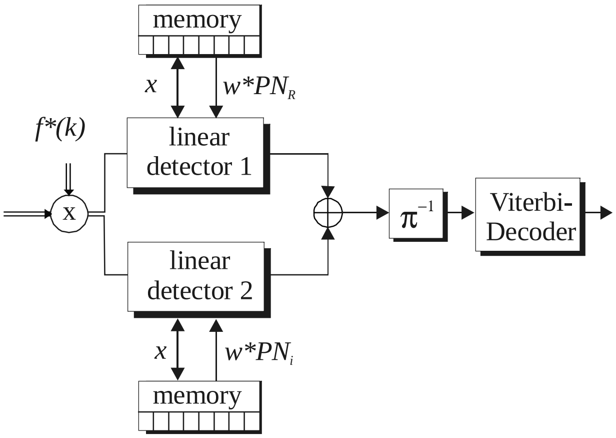

Fig. 4. Implementation of linear detectors for long codes

In figure 5 the bit error rate (BER) of the new cBAID concept is compared to the 1-user case and to the correlation receiver with 10 users per spot beam. In order to focus on the interference suppression an AWGN channel and no coding is assumed. The LMS and the AS-LMS detector outperform the correlation receiver significantly. Both detectors reach the BER of the MMSE-curve, which was derived by solving equation 3 for a system with short codes.

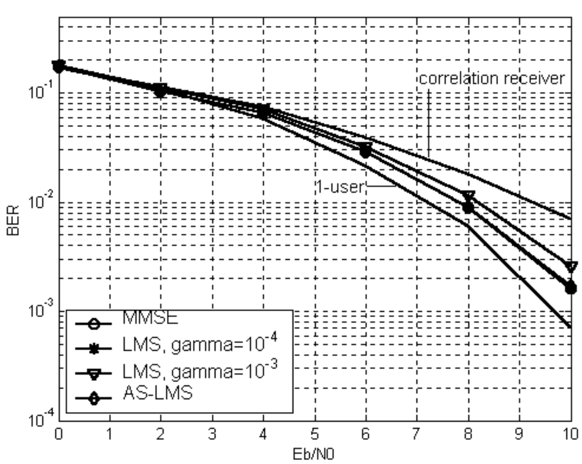

Fig. 5. Performance of the linear detector for long codes (worst case position, 10 users per spot beam, no coding, AWGN)

A disadvantage of the new concept for long codes is that it needs 8 times longer to adapt to a new user-constellation than a short code system. This is especially crucial for the LMS-detector, due to the fact, that increasing the step-size for a faster adaptation leads to a higher BER (see figure 5). For this reason the implementation of the AS-LMS algorithm is more suitable for a long code scenario than the LMS. The adaptation of the spreading sequence can be sped up with the adapted step-size [5]. However, due to the calculation of the second LMS the complexity of the AS-LMS detector is about 3 times higher than the complexity of the simple LMS scheme. For this reason we propose two new concepts with reduced complexity and faster adaptation.

The first approach corresponds to the AS-LMS algorithm. For this detector the computation of the actual step-size is very expensive. However, it can be assumed that the signal space of the disturber changes in the same way at the I and Q branch. If for example, a fast adaptation with a large step size is needed for the I branch it is also necessary for the Q branch. Based on this behavior, it is not necessary to calculate the step-size twice. The derived step-size of one branch can be taken for the other one too. In the end, two LMS algorithms per Rake finger are needed for the adaptation of the correlation vector *h*, and just one LMS algorithm per Rake finger in order to adapt the step-size. This concept is depicted in figure 6.

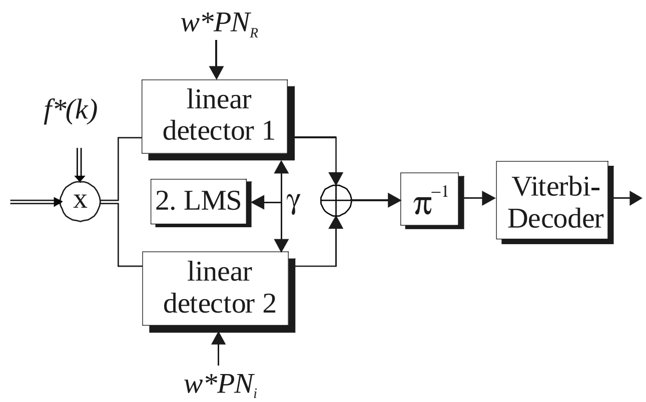

Fig. 6. AS-LMS detector with one second LMS-algorithm

The performance of this scheme with one second LMS algorithm (2D, 1 2.LMS) shows no difference concerning the BER or the adaptation speed compared to the original AS-LMS detector scheme (2D, 2 2.LMS). A possibility to speed up the adaptation is to concatenate the detectors in the way that the 8 adaptation processes use the same step-size, which is updated every symbol.

A further reduction of the complexity can be achieved if just one detector per Rake finger is used. As mentioned before, there are no different Walsh-sequences for the I and Q branch. This offers the possibility to multiply each branch with the corresponding inner PN-code, before chip-wise combining the real and the imaginary part. Now, like it is shown in figure 7, one linear detector can be used, which takes the Walsh-codes as input sequences and not the combination of Walsh-codes and inner PN-sequences like before.

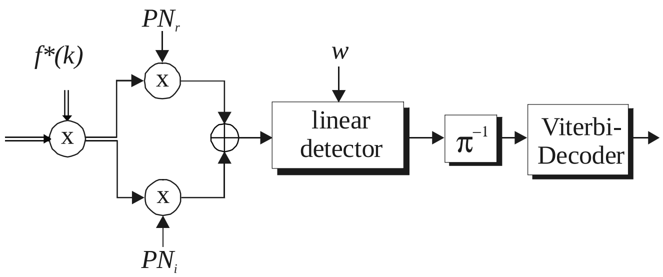

Fig. 7. Implementation of just one linear detector

This concept with one detector (1D) divides in half the computing time for the adaptation of the spreading sequence and as shown in figure 8 it achieves the same BER performance like the scheme with two detectors (2D).

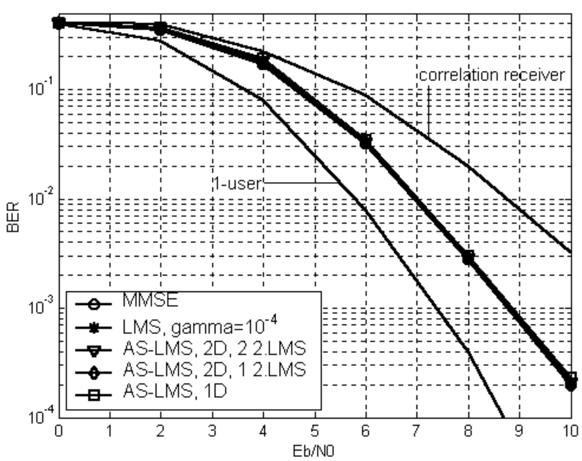

Fig. 8. Performance of the linear detector for long codes (worst case position, 30 users per spot beam, coding, Rice-channel)

5. Conclusions

The new cBAID scheme allows the application of blind adaptive interference detectors to communication systems with long code spreading sequences. This leads to no degradation of the bit error rate in the steady state compared to a short code concept. However, the adaptation speed is reduced. Furthermore the coefficients of the 8 steps of the linear detector have to be stored. The impact of these disadvantages should be small compared to the large performance gains, which can be achieved compared to the correlation receiver. The implementation of schemes with reduced complexity can decrease the computational effort for the blind adaptive detectors significantly.

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