Blind Interference Suppression for DS/CDMA LEO Satellite Communication Systems

Stephan Fischer, Bernd-Ludwig Wenning, Volker Kühn, Karl-Dirk Kammeyer

University of Bremen - Department of Communications Engineering - P.O. Box 330440
D-28334 Bremen - Germany

Phone: (49)421 / 218-7485 / Fax: (49)421 / 218-3341,
e-mail: fischer@comm.uni-bremen.de

ABSTRACT

This paper focuses on interference suppression aspects for DS/CDMA (Direct Sequence / Code Division Multiple Access) LEO (Low Earth Orbit) satellite communication systems. The interference of other users represents a serious problem for LEO satellite CDMA systems. The application of interference suppression systems is a promising approach to mitigate the multiuser problem. With the concentration on the forward link the user has no information about the other users and so a blind algorithm is needed. Furthermore, due to the movement of the satellite the user's constellation in a beam varies and therefore an adaptive algorithm must be implemented. In this paper three blind adaptive interference algorithms are applied to a LEO satellite communication system and their performance is compared. The LMS (Least Mean Squares) detector has a good performance compared to the conventional receiver, aside from having a slower convergence. The AS-LMS (Adaptive Step Size Least Mean Squares) algorithm is based on the LMS detector with an adaptive step-size. Its adaptation rate is improved and also in the steady state it performs better than the LMS. The best performance was that of the RLS (Recursive Least Squares) algorithm, however, this method requires an increased processing power.

1. INTRODUCTION

In the last years, mobile wireless communication became more and more important. In order to provide for future worldwide wireless communication, satellite communication systems such as LEO (Low Earth Orbit) offer a possible 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 issuses can be managed by using CDMA (Code Division Multiple Access) technology [1]. Unfortunately 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, which 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, the user has no information about the interfering signals. This is why a blind algorithm is implemented. Also, in LEO satellite communication systems the satellites are in the view of each user for only a short time. Due to this fact the interference for each user varies and the interference suppression detector must adapt. Concerning obstacles in the line of sight between the satellite and the mobile user, one satellite can be shadowed or even blocked. Since there are always two or more satellites in view, shadowing leads to heavy changes in the interference scenario. Compared to the terrestrial multi user interference the satellite interference situation is subject to stronger changes, thus, the adaptation speed becomes even more important. Besides the adaptation speed and the performance in the steady state the computing time has to be researched as well. The multi user detection has to be performed in the mobile phone of the user and due to this fact the complexity of the algorithms must be low.

The paper is organized as follows. In chapter 2 the system outline is described and the interference problem is illustrated. The blind interference suppression algorithms are then discussed in section 3. Lastly, the simulation results are presented in section 4. 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 $B_{beam} = 16.5MHz$. This bandwidth is divided into 13 FDM (Frequency Division Multiplex) sub channels, each $1.23MHz$ wide. The basic structure of the transmitter is shown in Figure 1.

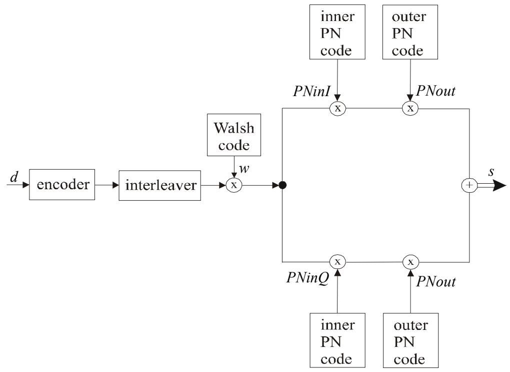

Fig. 1. Transmitter of the Globalstar system

The data bits d of rate 4.8*kB/s* are convolutionally encoded (rate $R = 1/2$, constraint length $cl = 9$) and interleaved. Therefore, a 20ms block interleaver is used. The interleaver delay of 20*ms* is equivalent to an interleaver size of $is = 192 bits$. The interleaved bit stream b is then spread by Walsh sequences of length 128 (spreading factor $N_p = 128$). This leads to a chip rate of 1.23*MHz*. 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 in a beam. In the next step the bits are split between the I and Q branches and are 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. After that an outer PN sequence is overlaid on the I and Q component. Both multiplications do not lead to further spreading. The PN codes are used 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

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

In order to apply blind interference suppression detectors we assume short spreading sequences, which means that the signature sequence is the same for all symbols. This is not the case in the Globalstar system, where long PN sequences are utilized with a length of 2^{10} chips. Additionally no outer PN sequence is assumed.

At the receiver a conventional Rake receiver [4] is proposed. Due to the small delay time of the reflection paths of the satellite channel no distinguishable echo paths exist. The Rake fingers (two fingers are advised) point to distinct satellites to gain diversity [3,5]. The output of the Rake fingers can be combined or the stronger signal can be selected. Furtheron, for simplification purposes just one Rake finger is assumed.

One common problem for CDMA systems is the multiuser interference. When 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 seperation properties of the PN codes. Orthogonal codes can be applied in the sub beam due to the fact that all signals are synchronized. This is not the case considering the transmission from two satellites. If the signals are asynchronous PN codes have a better performance than the Walsh codes. Also, the orthogonal codes have a limited code book size. The spot beam geometry of a satellite is shown in Figure 2 [6].

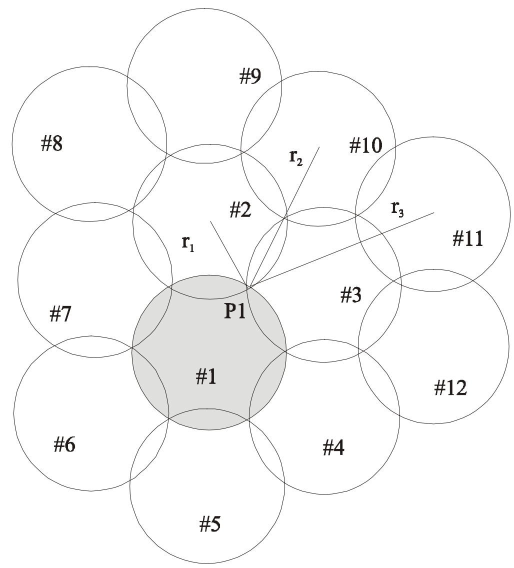

Fig. 2. Spot beam geometry

On the circle around each spot beam the signal energy is 1dB 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. The attenuations are given in table 1 [7]. In Figure 3 it is shown how the bit error rate (BER) increases if the user is in the worst-case position and different numbers of users are transmitting on the spot beams of one satellite.

	Normalized distance from center of spot beam	Normalized antenna gain (dB)
$r1$	1	-1
$r2$	2	-10
$r3$	$\sqrt{7}$	-15

Table 1. Antenna characteristics

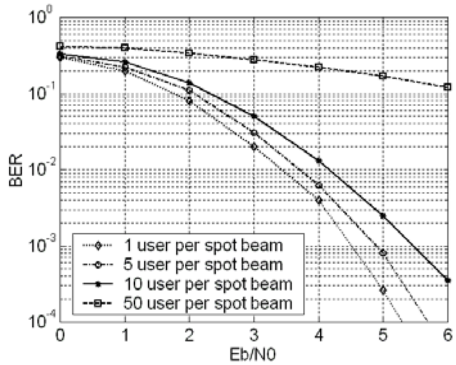

Fig. 3. Multiuser interference for one satellite with spot beams

3. INTERFERENCE SUPPRESSION ALGORITHMS

The Globalstar system applies a conventional correlation receiver. As depicted in Figure 3 the BER increases dramatically with the number of active users. In this section three 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]. The third algorithm is a recursive least squares adaptive algorithm (RLS) [10].

LMS

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

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

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 $(h_1 = h, d_1 = d, \ldots)$. The signal h can be written in 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. 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 denotes 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.

RLS

The afore mentioned MMSE detector can be given as

$$\hat{b} = sign\left(h^T \cdot r\right) \tag{11}$$

where

$$h = \frac{1}{c^T R^{-1} c} R^{-1} c \tag{12}$$

and R is the autocorrelation matrix of the received signal r. In order to find an adaptation rule for the RLS algorithm a vector h is searched that minimizes the exponentially weighted output energy

$$\min\left\{\sum \lambda^{n-1}\left[h^T r\right]^2\right\} \quad (13)$$

where $c^T h = 1$ and λ is the forgetting factor, which ensures that the data of the past cannot influence the adaptation for too long. This minimization problem can be solved by

$$h_n = \frac{1}{c^T R_n^{-1} c} R_n^{-1} c \quad (14)$$

$$R_n = \sum_{i=1}^{n} \lambda^{n-i} r_i r_i^T \ . \quad (15)$$

Basing on this solution an adaptive algorithm can be derived:

$$k_n = \frac{R_{n-1}^{-1} r_n}{\lambda + r_n^T R_{n-1}^{-1} r_n} \quad (16)$$

$$l_n = R_n^{-1} c = \frac{1}{\lambda}\left[l_{n-1} - k_n r_n^T l_{n-1}\right] \quad (17)$$

$$h_n = \frac{1}{c^T l_n} l_n \quad (18)$$

$$R_n^{-1} = \frac{1}{\lambda}\left[R_{n-1}^{-1} - k_n r_n^T R_{n-1}^{-1}\right]. \quad (19)$$

The complexity of the AS-LMS is justifiably higher than the complexity of the LMS due to the fact that a second LMS algorithm is needed for adjusting the step size. Both computational complexities are functions of N_p. The complexity of the RLS is proportional to $O(N_p^2)$ and due to this fact the RLS algorithm requires the most computing time.

4. NUMERICAL RESULTS

In order to implement the described interference suppression algorithms in a LEO satellite system some points have to be kept in mind. Due to the different PN sequences for the real and the quadrature part of the signal, two different detectors are necessary. For simplification purposes we assume the transmission via one satellite with a spot beam geometry as depicted in Figure 2. The user of interest is in the described worst-case position. In order to focus on the interference suppression aspects an AWGN channel is considered and no encoding is performed.

First the adaptation speed of the three detectors is compared. Therefore the algorithms are in the steady state with 10 users on each spot beam and an E_B / N_o (Bit Energy per Noise) of 10dB. The bits are transmitted block by block whereby each frame contains 192 bits. At the 50th frame the number of users per beam increases to 40. This is of course an unrealistic situation, however, if we consider a two-satellite case with one shadowed or blocked satellite, the end of the shadowing period can be compared with the situation in this simulation. The adaptation process has been computed several times and the number of frame errors was averaged. The MMSE solution (11) was computed with the help of the autocorrelation matrix of the received signal (12). It is given in the following figures for comparison purposes.

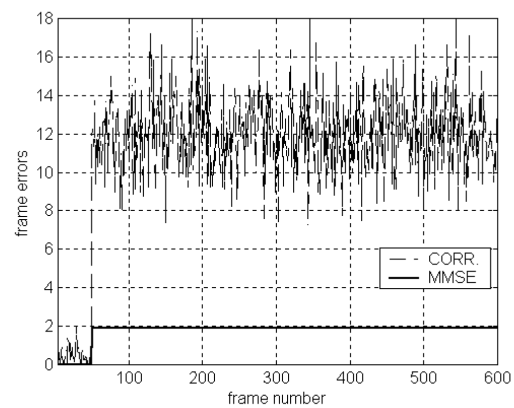

Figure 4. Performance of the conventional correlation receiver

The performance of the conventional correlation receiver is shown in Figure 4. As the number of users increases, so does the number of frame errors. This number also stays constant at a high level. The LMS detector with a step size of $\gamma = 1 \cdot 10^{-4}$ also has an increased number of frame errors at frame 50, however, approximately 100 frames later the number of frame errors decreases to a lower level as depicted in Figure 5.

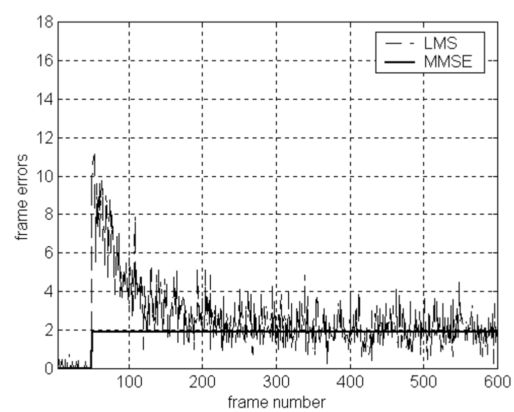

Figure 5. Adaptation of the LMS algorithm

It is apparent that the adaptation of the signature sequence works. The Adaptation could be sped up by increasing the step size, however, this would lead to a higher number of errors in the steady state.

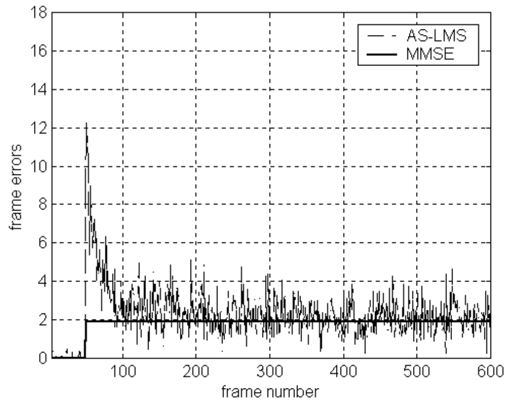

Figure 6. Adaptation of the AS-LMS algorithm

In order to solve this problem the AS-LMS algorithm was invented. It can be seen in Figure 6 that this algorithm reaches the steady state around 50 frames after the number of users increased. Furthermore, the number of frame errors is lower compared to the LMS detector.

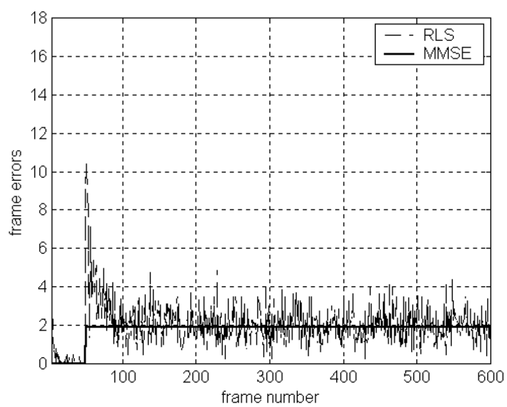

Figure 7. Adaptation of the RLS algorithm

As shown in Figure 7 the performance of the RLS algorithm is the most efficient. It adapts the new interference scenario very fast and also in the steady state the number of errors is low.

The bit error rates of the interference suppression detectors are compared to the error rates of the conventional receiver and the case with no MAI in Figure 8. The number of users is set to 20 users per beam. The three adaptive algorithms have almost the same performance. For the LMS algorithm a step size of $\gamma = 1 \cdot 10^{-4}$ is set. Utilizing this low step size the adaptation speed is low but the steady state error rate is good. Compared to the MMSE solution the blind adaptive detectors perform well. Only a small degradation is viewable. Also one can recognize the influence of the step size of the LMS algorithm in the steady state. Its frame error rate is slightly higher than the error rate of the other adaptive detectors. The three adaptive detectors perform significantly better than the conventional correlation receiver. However, the bit error rate of the adaptive detectors is worse than in the case of no MAI. As an important point, one must keep in mind that the signature sequence *c* is composed by the Walsh sequence *w* and the PN sequences *PNinI* and *PNinQ*. The Walsh sequence guaranties no interference in a spot beam due to the orthogonaltiy of the Walsh codes. Adapting the signature sequence the interference of the other beams is reduced, however, also the orthogonality in user beam is destroyed and this results in additional interference.

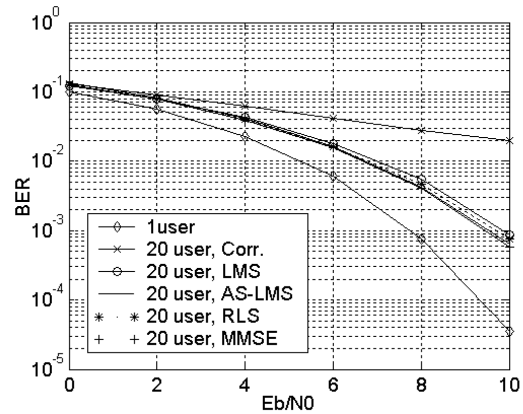

Figure 8. Bit error rates of the detection algorithms with 20 users per beam

The case of 40 users per spot beam is depicted in Figure 9. The frame error rate of the detectors increases, however, the adaptive detectors provide a large gain compared to the conventional correlation detector.

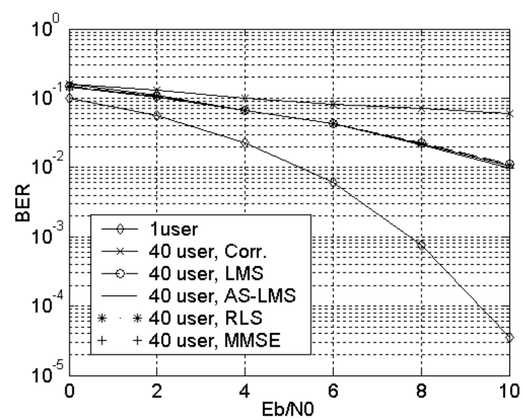

Figure 9. Bit error rates of the detection algorithms with 40 users per beam

5. SUMMARY AND CONCLUSIONS

In this paper three blind adaptive interference suppression algorithms are applied to a LEO satellite communication system. Their performance is compared to the performance of the conventional correlation receiver. The LMS, the AS-LMS, and the RLS algorithm have a significantly better bit error rate than the correlation receiver. The RLS algorithm and the AS-LMS detector react more quickly to a changed interference situation than the LMS algorithm. In considering the computational costs, one must acknowledge that the RLS is very expensive whereas as the LMS algorithm needs the least computing time. The AS-LMS is a good compromise between adaptation speed and bit error rate and on the one hand and computing costs on the other.

REFERENCES

[1] B. R. Vojcic, L. B. Milstein, R. L. Pickholtz, „Downlink DS CDMA Performance Over a Mobile Satellite Channel“, IEE Trans. Veh. Technol., vol.45, No. 3, pp 551-559, August 1996.

[2] F. J. Dietrich, P. Metzen, P. Monte, "The Globalstar Cellular Satellite System", IEEE Trans. Antennas and Propagation, vol.46, No. 6, pp.935-942, June, 1998.

[3] P. Monte, S. Carter, "The Globalstar air interface modulation and access", Proc. 15^{th} AIAA Intl. Comm. Satellite Conf., pp.1614-1621, February 1994.

[4] K. D. Kammeyer, "Nachrichtenuebertragung", ISBN: 3519161427, 1996 (in German)

[5] S. Fischer, S. Kudras, V. Kühn, K.D. Kammeyer, "Analysis of Diversity Effects for Satellite Communication Systems", accepted for in Proceedings Globecom, San Antonio, USA, 2001.

[6] E. Lutz, M. Werner, A. Jahn, " Satellite Systems for Personal and Broadband Communications", ISBN:3-540-66840-3, 2000.

[7] R. De Gaudenzi, F. Giannetti, "DS-CDMA Satellite Diversity Reception for Personal Satellite Communication: Satellite-to-Mobile Link Performance Analysis", IEE Trans. Veh. Technol., vol.47, No. 2, pp 658-672, May 1998.

[8] M. Honig, U. Madhow, S. Verdu, "Blind Adaptive Multiuser Detection", in IEEE Transactions on Information Theory, Vol. 41, No. 4, July 1995, pp 944-960

[9] V. Krishnamurthy, G. Yin, S. Singh, "Adaptive Step-Size Algorithms for Blind Interference Suppression in DS/CDMA Systems", in IEEE Transactions on Signal Processing, Vol. 49, No. 1, January 2001, pp 190-201

[10] H.V. Poor, X. Wang, "Code-Aided Interference Suppression for DS/CDMA Communications-Part 2: Parallel Blind Adaptive Implementations", in IEEE Transactions on Communications, Vol. 45, No. 9, September 1997, pp 1112-1122