VOLTERA FILTER APPLICATION IN DS–SS RECEIVER FOR BROADBAND AND NARROWBAND INTERFERENCE SUPPRESSION

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Direct sequence spread spectrum (DS-SS) transmission systems offer a promising solution to an overcrowded frequency spectrum amid the growing demand for mobile and personal communication service. The overlay of DS-SS signals on the existing broadbands and narrowbands implies strong interference for DS-SS systems. In this paper, it will be shown how the application of linear or non-linear estimators in DS-SS receivers can suppress this interference. In our consideration, Wiener filters (WF) and Volterra filters (VF) will be used as estimators. In order to demonstrate the ability of the discussed DS-SS receivers to suppress interference, a number of computer experiments will be done. The results of these experiments will show that the application of VF in DS-SS receivers can outperform the DS-SS receivers based on simple application of the matched filter (MF) or on the WF application in a significant way.

Key words: DS-SS receiver structures, Volterra filter, Wiener filter, broadband and narrowband interference

1 INTRODUCTION

In modern mobile communication systems, reutilization of the frequency band already allocated to some fixed broadband communication system is a promising opportunity. Here, the application of DS-SS transmission systems for mobile communication systems offers a very good solution. The DS-SS systems can share also a common spectrum with a currently operating cellular or fixed microwave system in order to achieve efficient bandwidth utilisation. In this case, the signals of coexisting users appear as narrowband interference in the spectrum of DS-SS signals. The DS-SS transmission systems can operate successfully in the presence of the strong co-channel interference (e.g. in the case of broadband BPSK broadcasting or narrowband interference) if the processing gain is high enough. If the interference due to co-channel transmission is very strong or if the processing gain is limited due to bandwidth constraints, DS-SS receiver based on a simple MF usually cannot provide an acceptable bit-error-rate (BER). In order to solve this problem, some advanced structures of the DS-SS receivers can be applied [1–3].

In this paper, the DS-SS receivers based on linear and non-linear estimators will be described. In the conventional receiver structure the estimator is included between the demodulator and the despreading stage. The estimator provides extraction of the demodulated spreaded signal from the noise. Because of signal pre-processing performed by the estimator, signal to noise ratio before the signal despreading operation is higher than that of a conventional receiver based on simple MF application. It can result in an improvement of BER characteristics in a significant way.

In this paper, WF and VF will be applied as the above-mentioned estimators. In order to demonstrate the performance of the properties of VF and WF based DS-SS receivers, a number of computer experiments have been done. The main intention of these experiments was to show the ability of tested DS-SS receivers to suppress broadband interference represented by BPSK broadcasting. The results of experiments, expressed as BER vs signal to interference ratio (SIR), have shown that in the case of DS-SS receivers based on the third order VF outperform DS-SS receivers based on MF, WF or the second order VF. These results can be considered to be very interesting and stimulating. With regard to these facts we have tested the same DS-SS receivers for narrowband interference suppression represented by the second order autoregressive process. The results obtained here have shown that DS-SS receivers based on the third order VF also in this case can provide better results than receivers based on MF or WF.

2 INPUT SIGNAL MODEL
OF DS–SS RECEIVER

The signal that appears at the input of the receiver consists of three components. They are the BPSK DS-SS signal distorted by a linear transmission channel \( x(t) \), broadband or narrowband interference \( i(t) \) and additive white Gaussian noise (AWGN, \( n(t) \)) with power spectral density at the receiver input \( N_0 \). The AWGN level will be expressed by ratio \( E_b/N_0 \) (information signal energy per bit to noise power spectral density). All three signal components are supposed to be independent and stationary signals. Then, the input signal to the receiver is given
by
\[ g(t) = x(t) + i(t) + n(t). \] (1)

The BPSK DS-SS signal \( s(t) \) can be modelled as
\[ s(t) = U \cdot PNS(t) \cdot d(t) \cdot \cos(\omega t), \] (2)
where \( U, \omega_0, PNS(t) \) and \( d(t) \in \{+1,-1\} \) represent the amplitude and angular frequency of the carrier, the pseudo-noise sequence (spreading code) of chip duration \( T_C \) and transmitted information baseband signal of bit duration \( T \), respectively. Then, BPSK DS-SS signal distorted by a linear transmission channel with an impulse response \( h(t) \) is given by
\[ x(t) = h(t) * s(t), \] (3)
where \(*\) denotes the convolution operation.

The interference \( i(t) \) is defined as
\[ i(t) = \begin{cases} \pi_B(t) & \text{for broadband interference} \\ \pi_N(t) & \text{for narrowband interference}. \end{cases} \] (4)

The broadband interference \( i_B(t) \) is modelled as a broadband BPSK signal expressed as
\[ i_B(t) = U_S d_S(t + \tau) \cdot \cos[(\omega_0 + 2\pi f_1)t + \theta], \] (5)
where \( U_S, f_1, \tau, d_S(t) \in \{+1,-1\} \) and \( \theta \) are interference amplitude, offset carrier frequency, random data bit delay, interference data and initial carrier phase, respectively. It is assumed that \( \tau \in (0,T) \) and \( \theta \in (0,2\pi) \) are uniformly distributed.

The narrowband interference \( i_N(t) \) is modelled by
\[ i_N(t) + \sum_{i=1}^{p} a_i i_N(t-i) = c(t), \] (6)
where \( c(t) \) is a white Gaussian process with variance \( \sigma_c^2 \). The process \( i_N(t) \) generated by the above model is known as the \( p^{th} \) order autoregressive process (AR(\( p \))). In accordance with [4] the power spectrum of \( i_N(t) \) is
\[ s(\omega) = H(\exp(\jmath \omega))H(\exp(-\jmath \omega)) \sigma_c^2, \] (7)
where
\[ H(z) = \frac{1}{1 + a(1)z^{-1} + a(2)z^{-2} + \cdots + a(p)z^{-p}}. \] (8)
The poles of \( H(z) \) are located inside the unit circle.

3 DS-SS RECEIVER STRUCTURES

The simplest DS-SS receiver is based on MF filter application (correlation receiver) [3]. Its structure is illustrated in Fig. 1. Here, as the MF, L-tap linear FIR filter is applied. Its impulse response is equal to the spreading code \( PNS(t) \). It follows from the MF theory that a MF is optimum when the filtered signal is impaired by AWGN. However, this assumption is not valid in the case of broadband or narrowband interference or in the case of multi-user interference (e.g., CDMA communication systems). Therefore, the receiver structure based on the MF application (Fig. 1) cannot be considered as optimum generally.

In order to improve the receiver performance, the modified structure of DS-SS receivers equipped by an estimator can be applied. Figure 2 shows how the estimator fits into DS-SS receiver structure. The estimator extracts the demodulated spreaded signal from the noise. This signal pre-processing operation can improve the signal to noise ratio before signal despreading. It can result in improvement of BER characteristics of the receiver in a significant way. As the estimator a number of conventional or advanced digital filters can be used. In the next, WF and VF will be proposed for that purpose.

4 VOLterra FILTERS, WIENER FILTERS

The VFs are minimum mean-square non-linear estimators. Their mathematical model is represented by a truncated discrete Volterra series [5, 6]. The mathematical model of the \( M^{th} \) order VF memory the span of which is \( N = N_1 + N_2 + 1 \) samples long (VF \((M, N)\)) is given by
\[ w(n) = h_0 + \sum_{i=1}^{M} \sum_{k_1=-N_1}^{N_2} \sum_{k_2=-N_1}^{N_2} \cdots \sum_{k_i=-N_1}^{N_2} h_{i,k_1,k_2,...,k_i} v(n-k_1)v(n-k_2)\cdots v(n-k_i). \] (9)
In this expression, \( v(n) \) and \( w(n) \) are the input signal and the filter response, respectively. The \( i \)-dimensional sequence \( h_{i,k_1,k_2,...,k_i} \) is called the Volterra kernel of the \( i \)-th order. The order \( M \) of the VF is defined by the number of the highest order of the Volterra kernel which
can be found in (9). The length of the VF memory span is given by the number of mutually different samples of the input signal which can be applied in the VF response computation. Under condition that $N_1 > 0$, VF($M, N$) is non-causal.

With regard to (9), the well-known WF of the $N^\text{th}$ order (VF($N$)) can be defined as the first order VF (i.e. VF(1,$N$)). The details concerning the design and performance properties of time-invariant and adaptive VF and WF can be found eg in [5-7].

5 EXPERIMENTAL RESULTS

In this section, a comparison of performance properties of the BPSK DS-SS receiver based on a simple MF (Fig. 1.) with its modified version that includes estimator (Fig. 2.) is presented.

In all experiments, the transmission model described in section 2 was used. The parameters of the BPSK DS-SS signal $s(t)$ were $U = 1$ and $\omega_0 = 2\pi F_S / 4$, where $F_S$ stands for the sampling frequency. The Gold sequence of the $7^\text{th}$ order (7 chips) was applied as the pseudo-noise sequence (spreading code) of chip duration $T_C = 4/F_S$. The bit duration of information baseband signal was set to $T = 28/F_S$.

The power spectral density of AWGN at the receiver input was set in such a way as $E_b/N_0 = 13\, \text{dB}$. As the channel model, the linear time-invariant system represented by the FIR filter of the $15^\text{th}$ order was used. The filter passband was centered at the carrier frequency $\omega_0$ and its bandwidth was set to $B_{CH} = 1.2B_{MIN}$, where $B_{MIN}$ is the minimum bandwidth for the BPSK DS-SS signal transmission.

In the case of the estimator based receivers (Fig. 2) time-invariant WF and VF were applied. For their design the methods described in [5-7] were used. In order to estimate the correlation and crosscorrelation functions (conventional as well as higher-order ones) necessary for the WF and VF design, the training sequence consisting of 200 information bits was transmitted before each information date sequence transmission. The original training sequence was available at the receivers for the purpose of filter design. In all experiments, perfect synchronization of the BPSK modulator and demodulator and the DS-SS modulator and MF is assumed.

As the performance indices of the tested DS-SS receivers, BER vs SIR and BER vs $E_b/N_0$ at different conditions of interference were used. These conditions as well as the results corresponding to the particular interference signal are described in the next subsection.

5.1 Broadband interference

In the first experiment, the interference $i(t) = i_B(t)$ was synchronized with BPSK DS-SS signal. The parameters of $i_B(t)$ were $U_S = 1$, $f_1 = 0$, $\tau = 0$ and $\theta = 0$. The bit duration of baseband interference signal was set to $T_B = T_C$. Therefore, the BPSK DS-SS signal bandwidth ($B_S$) to interference signal bandwidth ($B_I$) ratio was $B_S / B_I = 1$.

For the purpose of receiver performance property evaluation, the data stream consisting of $10^6$ information bits (excluding training sequence) was used. The results obtained for the MF, WF($N$) ($N = 5, 7$) and VF($M, N$) ($M = 2, 3$ and $N = 1, 3, 5$) are given in Figs. 3 and 4. In Figs. 3 and 4, signal to noise ratio (SNR) at the MF input vs SIR and BER vs SIR are given, respectively. SNR and SIR are defined as

$$SNR = 20 \log \frac{E[d^2(n)]}{E[(d(n) - d(n))^2]}, \quad (10)$$

$$SIR = 20 \log \frac{E[s^2(t)]}{E[x^2(t)]}, \quad (11)$$

where $x(t)$ is BPSK DS-SS signal distorted by a linear transmission channel defined by (3) and $i(t)$ represents interference.

It can be seen from these figures that for $SIR \in (-35, -2)\, \text{dB}$ the best and similar results are provided by VF(3,3) and VF(3,5). For $SIR \in (-2, 10)\, \text{dB}$ all tested receivers provide almost the same results. The obtained results support our considerations presented in section 3 concerning the correlation between SNR and...
BER, too. It can be seen from Fig. 3 that the application of VF(3, N) (N = 1, 3, 5) can improve the level of SNR. Based on this improvement, significantly better results provided by VF(3, N) are obtained in comparison with that of the MF, WF(N) and VF(2, N).

It follows from the interference model (4) that BER is also dependent on the offset carrier frequency $f_1$. In order to follow the dependence of BER on SIR and $f_1$, the above described experiment was repeated for different values of $f_1 \in (-0.1F_s, 0)$. The normalized magnitude spectra (Norm. spec.) of BPSK DS-SS signal and broadband interference at the receiver input are shown in Fig. 5 and Fig. 6, respectively. In these figures, the
magnitude spectra of the interference signal are given for $f_1 = -0.1F_S$ and $f_1 = 0$.

The results of the second computer experiment are presented in Figs.7–9. It can be seen from these figures that also in this case $VF(3,3)$ can provide much better results than that of $WF(7)$ or $MF$.

In order to illustrate additional performance properties of the $VF(3,3)$, the third experiment was done. The intention of the experiment was to follow the $BER$ dependence on $E_b/N_0$ and $f_1 \in (-0.2F_S, 0)$ at $SIR = -13$ dB. The experiment was arranged in a similar way as the first and the second experiments described in this section. The results of the experiment are given in Figs.10 and 11. It follows from these figures that $VF(3,3)$ is able to provide meaningful improvement in $BER$ characteristics also for different values of $E_b/N_0$ comparing to MF application.
5.2 Narrowband Interference

In the experiment illustrating the narrowband interference suppression, the interference \( i(t) = i_N(t) \) was set to the AR(2) defined by (6)–(8). The magnitudes of complex conjugated poles \( p_1 \) and \( p_2 \) of \( H(z) \) were set to 0.99. The arguments \( p_1 \) and \( p_2 \) were set in such a way that the central frequency of the narrowband interference \( i_N(t) \) was \( \omega_0 + 2\pi f_1 \) for different values of \( f_1 \in (-0.1F_S, 0) \).

The normalized magnitude spectra (Norm. spec.) of BPSK DS-SS signal and narrowband interference at the receiver input are shown in Figs. 12 and 13, respectively. In these figures, the magnitude spectra of the interference signal are given for \( f_1 = -0.1F_S \) and \( f_1 = 0 \).

The results of the computer experiment described in this section are presented in Figs. 14–16. It can be observed from Fig. 15 that in the case of narrowband interference, the WF(7) can improve BER in comparison with MF application. It can be seen from Fig. 16 that also in this case WF(3,3) can provide much better results than that of WF(7) or MF.

6 CONCLUSIONS

In this paper, the BPSK DS-SS receivers based on linear and non-linear estimators have been described. The analysis of its performance properties based on computer simulations has shown that the structures of BPSK DS-SS receiver based on WF(3, N) provide the best results in the case of broadband and narrowband interference. Significant improvement of BER results provided by WF(3, N) is reached when the variance of interference is much more higher than that of information signal (eg SIR < −5 dB). This improvement of BER versus SIR is reached at the cost of much more higher computational complexity of WF(3, N) in comparison with that of the MF. If the variance of interference is comparable or smaller than that of information signal (eg SIR < −5 dB), all tested receivers have provided approximately the same results. It follows from these facts that BPSK DS-SS receiver based on WF(3, N) can be applied with advantage in the case of very strong co-channel interference.

It follows from the obtained results that the applications of WF(N) or WF(2,N) in the receiver structure does not provide any meaningful improvement in SNR and BER. In the case of the WF(3,N) design the sixth order correlation and crosscorrelation functions are also used. On the other hand, at the design of WF(N) and WF(2,N) only the second and the fourth order correlation and crosscorrelation functions are used. It follows from these facts that the obtained improvement of SNR and BER is based on information included in the sixth order correlation and crosscorrelation functions of processed signals.

In this paper, some performance properties of the BPSK DS-SS receivers based on linear and non-linear estimators have been illustrated by using simple computer experiments. The experiment results indicate that the application of VF in DS-SS receivers can provide receivers with the ability to suppress broadband and narrowband interference.

References


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