A SIMPLIFIED SINGLE BRANCH BPSK RECEIVER STRUCTURE EMPLOYING A NOVEL DIGITAL IMAGE REJECTION TECHNIQUE

W. Mikhael, Fellow IEEE and Tianyu Yang, Student Member, IEEE

Department of Electrical Engineering
University of Central Florida
Orlando, FL32816

ABSTRACT

A novel digital image suppression technique for Binary Phase Shift Keying (BPSK) receivers based on Independent Component Analysis (ICA) is presented. The technique requires only one antenna and a single downconversion path. The highly selective image rejection filter at the RF stage is eliminated. Also, the resulting receiver's complexity is much lower than that of quadrature or dual-antenna receivers. Simulation results confirm that the performance of the simplified receiver is comparable to the other more complex receivers.

1. INTRODUCTION

The image signal rejection problem is inherent to IF wireless receivers. The image signal can be removed by highly selective RF filters or quadrature downconversion scheme, as adopted by low-IF and zero-IF receivers. However, these analog methods substantially increase the receivers' complexity and cost. Moreover, the low-IF and zero-IF receivers suffer from the mismatch between the two downconversion paths. Hence, digital image rejection becomes desirable.

Recently, blind separation of two signals by statistical signal processing has been reported [1-3]. However, this usually requires two signal observations and necessitates the use of two downconversion paths. In this paper, a practically desirable digital image suppression scheme that requires only one downconversion path is presented for BPSK receivers. Computer simulations show that the new technique achieves equivalent performance as quadrature or dual-antenna receivers at the expense of modest additional computational cost.

2. RECEIVER STRUCTURE AND SIGNAL MODEL

Figure 1 shows the proposed architecture of the superheterodyne BPSK receiver where the front-end bandpass filter for image rejection is eliminated. First, the received signal *r(t)* is downconverted from RF to IF, followed by a bandpass filter to perform adjacent channel suppression. Then, the IF signal $r_{IF}(t)$ is downconverted to baseband and lowpass filtered. The baseband signal $r_{BB}(t)$ is digitized to obtain the signal observation *X(n)*, which is fed into the Digital Signal Processor (DSP) for further processing.

Through our signal analysis, the time dependency of the fading coefficients is dropped because it is assumed that the wireless channel is quasi-stationary, i.e., the fading coefficients can be considered constants within one processing frame. Also, frequency-flat fading is assumed. Thus, the channel's fading coefficients are defined as:

$$f_s = \alpha_s e^{j\psi_s} \quad (1)$$

$$f_i = \alpha_i e^{j\psi_i} \quad (2)$$

where f_s, f_i are the fading coefficients for the desired and image signals. α_s, α_i and ψ_s, ψ_i are the channel's amplitude and phase responses, respectively. The distributions of α_s and α_i are dependent on the type of fading channels the signals encounter. Since the signals travel random paths, ψ_s and ψ_i can be modeled as uniformly distributed random phases over the interval [0, 2π].

Let *s(t)* and *i(t)* denote the complex envelopes of the desired and image signals, respectively. Thus, the received signal *r(t)*, Fig. 1, can be expressed as:

$$r(t) = 2\mathrm{Re}\{s(t)f_s\, e^{j(\omega_0+\omega_I)t} + i(t-\tau)f_i\, e^{-j(\omega_0-\omega_I)\tau}\, e^{j(\omega_0-\omega_I)t}\} \quad (3)$$

where $Re\{.\}$ denotes the real part of a signal, ω_0 and ω_I denote the frequency of the first and the second local oscillators. τ is the timing delay of *i(t)* relative to the symbol timing reference of *s(t)*. In general, τ can be assumed uniform over the interval [0, *T*], where *T* is the symbol interval. The multiplication by 2 is introduced for convenience.

After the RF-IF downconversion, the bandpass filtered signal is given by:

$$r_{IF}(t) = s(t)f_s e^{-j\alpha} e^{j\omega_I t} + s^*(t)f_s^* e^{j\alpha} e^{-j\omega_I t} + i(t-\tau)f_i e^{-j(\omega_0-\omega_I)\tau} e^{-j\omega_I t} e^{-j\alpha} + i^*(t-\tau)f_i^* e^{j(\omega_0-\omega_I)\tau} e^{j\omega_I t} e^{j\alpha} \quad (4)$$

where the superscript * denotes complex conjugate, and α is the phase difference between the received signal and the Local Oscillator (LO) signal. It is to be noted that no phase synchronization is required in the receiver.

The baseband signal after downconversion to baseband and lowpass filtering is expressed as:

$$r_{BB}(t) = Re\{s(t)f_s e^{-j\alpha}\} + Re\{i(t-\tau)f_i e^{-j(\omega_0-\omega_I)\tau} e^{-j\alpha}\} \quad (5)$$

For BPSK signals, $s(t)$ and $i(t)$ are real-valued, so (5) can be written as:

$$r_{BB}(t) = as(t) + bi(t-\tau) \quad (6)$$

In (6), the coefficients $a = Re\{f_s e^{-j\alpha}\}$, and $b = Re\{f_i e^{-j(\omega_0-\omega_I)\tau} e^{-j\alpha}\}$.

Thus, after A/D converter, the baseband observation is:

$$X(n) = as(n) + bi(n) \quad (7)$$

Each of $s(n)$, $i(n)$ and $X(n)$ in (7) represents a one sample signal. Since the signals are typically processed in frames of length N, s_N, i_N and X_N are used to represent frames of N successive samples. Hence,

$$X_N = as_N + bi_N \quad (8)$$

In the next section, a method is proposed that utilizes only X_N to recover both s_N and i_N.

3. PROPOSED TECHNIQUE

Since one antenna is employed, only one observation $X(n)$ is available. A second linearly independent observation $Y(n)$ is artificially generated from $X(n)$. Then two signals $s(n)$ and $i(n)$ can be separated based on $X(n)$ and $Y(n)$.

In this contribution, $Y(n)$ is obtained by raising $X(n)$ to a power $p = 3$.

The binary signals $s(n)$ and $i(n)$ assume values of either +1 or –1. Thus, $s^2(n) = 1$ and $i^2(n) = 1$. Consequently,

$$\begin{aligned} Y(n) &= [as(n) + bi(n)]^3 \\ &= a^3s(n) + b^3i(n) + 3a^2bi(n) + 3ab^2s(n) \\ &= (a^3 + 3ab^2)s(n) + (b^3 + 3a^2b)i(n) \end{aligned} \quad (9)$$

where $n = 1, 2, \ldots, N$.

When Y_N is appended to X_N, the signal observation matrix **X** becomes:

$$\mathbf{X} = \begin{bmatrix} X_N \\ Y_N \end{bmatrix} = \begin{bmatrix} a & b \\ a^3+3ab^2 & b^3+3a^2b \end{bmatrix} \begin{bmatrix} s_N \\ i_N \end{bmatrix} = \mathbf{AS} \quad (10)$$

The determinant of the mixing matrix **A**, det(**A**), is given by:

$$\det(\mathbf{A}) = ab(b^2+3a^2) - ab(a^2+3b^2) = 2ab(a^2-b^2) \quad (11)$$

Due to the randomness of the wireless channel, $a \neq b$ and det(**A**) $\neq 0$. Thus, **A** is full rank and s_N, i_N can be recovered from **X** using ICA.

It can be easily shown that $Y(n)$ is linearly independent of $X(n)$ for $p = 2m + 1$, where m is an integer and $m \geq 1$. It is interesting to note that other methods of theoretical interest exist to obtain $Y(n)$, such as $Y(n)$ = Odd function of $X(n)$.

Below is a brief description of the kurtosis-based Fast-ICA algorithm [4] to extract two components from two observations X_N and Y_N. The purpose is to find a 2 by 2 separation matrix W, so that s_N and i_N can be obtained when W is applied to the 2 by N observation matrix X given by (10).

Step 1. Get the whitened data $\mathbf{X_1}$ by decomposing the **X**'s covariance matrix;

Step 2. Initialize the 1st row of the separation matrix $\mathbf{w_1}$ to a random vector of unity length;

Step 3. Set

$$\mathbf{w_1} = \frac{1}{N}\sum_{n=1}^{N}\{[\mathrm{w_1 X_1(n)}]^3 \mathrm{X_1(n)}\} - 3\mathrm{w_1};$$

Step 4. Normalize $\mathbf{w_1}$ to unity length;

Step 5. Check the convergence of $\mathbf{w_1}$. If it is not reached, go back to Step 3, otherwise proceed;

Step 6. Set the second row of the separation matrix to $\mathbf{w}_2 = [\mathrm{w}_{12} \quad -\mathrm{w}_{11}]^T$.

Due to the inherent order ambiguity of ICA, a training sequence needs to be inserted into the symbol streams, which is used at the receiver's detector to identify the order of the extracted components. In most communication standards, such training sequence is available. For example, within each IS-54/IS-136 burst and the GSM normal burst, there are 28 symbols and 26 symbols that are arranged into eight possible training sequences, respectively [5].

The kurtosis-based Fast-ICA has cubic convergence, and there is no learning rate to be determined. It can also be shown that the computational complexity in terms of the number of multiplications is of O*(N)*.

4. SIMULATION RESULTS

Computer simulations are carried out to examine the performance of the proposed technique. Sample representative results for BPSK modulated signals experiencing Rayleigh fading are given here for illustration. It is worth mentioning that the results will not be altered if other types of fading channels are assumed, even for the case where *s(t)* and *i(t)* are experiencing different types of fading. This is because the principal requirement for successful ICA separation is that the mixing matrix **A** is nonsingular. As a result, the nature of the coefficients in **A** is not significant. Due to the same reason, the performance is not affected by the relative strength of *s(t)* and *i(t)*.

The performance is measured by the Signal-to-Interference Ratio (SIR) defined as:

$$\text{SIR} = 10\log_{10}\left(\frac{1}{N}\sum_{n=1}^{N}\frac{s(n)^2}{[s(n)-y(n)]^2}\right) \qquad (12)$$

where *s(n)* is the *n*th sample of the desired signal, *y(n)* is the estimate of the *s(n)* obtained at the output of the ICA processing unit. The SIR represents the average ratio of the desired signal power to the power of the estimation error.

The frame length *N* is varied from 50 to 1000 symbols with a step size of 50. For each frame length, 100 simulation runs are performed. The resulting average SIR is plotted in Fig. 2. The performance of quadrature or dual-antenna receivers, where two observations are directly available, is also plotted for comparison.

It is clearly seen from Fig. 2 that the proposed technique achieves equivalent performance as quadrature or dual-antenna receivers. This means that the hardware complexity of the receiver can be substantially simplified without affecting the performance.

5. CONCLUSIONS

A novel digital image rejection technique based on Fast-ICA is proposed for IF BPSK wireless receivers which requires only one antenna and one downconversion path. The method achieves substantial reduction in hardware complexity without any performance degradation, compared with quadrature or dual-antenna receivers. Computer simulations confirm the effectiveness of the technique.

6. REFERENCES

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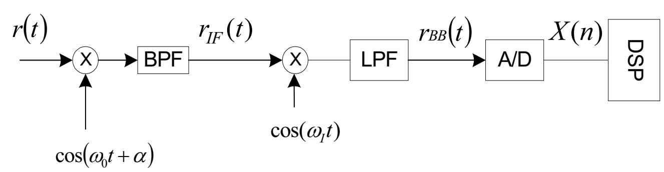

Figure 1. Proposed IF wireless receiver architecture

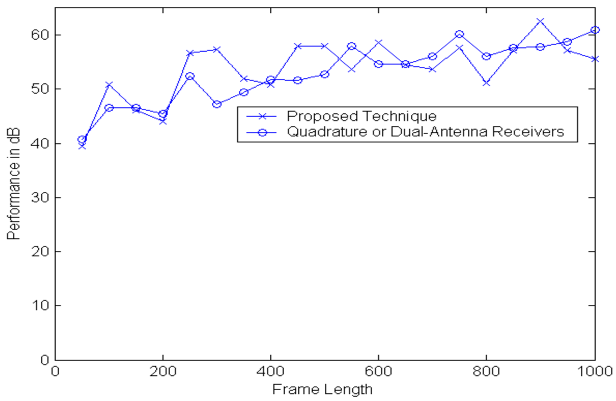

Figure 2. Performance comparison of the proposed technique and quadrature or dual-antenna receivers