Block ICA for Image Suppression and Carrier Frequency Offset Correction in Diversity BPSK Receivers

THOMAS YANG
Department of Electrical and Systems Engineering
Embry-Riddle Aeronautical University
600 S. Clyde Morris Blvd.
Daytona Beach, Florida 32114, USA

WASFY MIKHAEL
Department of Electrical and Computer Engineering
University of Central Florida
Orlando, Florida 32816, USA

Abstract: - The image rejection and Carrier Frequency Offset (CFO) compensation are two important radio receiver functionalities. In this paper, the two problems are approached digitally at baseband adopting block ICA algorithms. For diversity BPSK receivers, the proposed technique results in simplified analog front-end. Simulations are performed assuming typical CFO and fading conditions. Satisfying performance is achieved with reasonable computational complexity.

Key-Words: - Image rejection; Carrier frequency offset; ICA; BPSK; Diversity receiver

1 Introduction

In future Software Defined Radios (SDR), Digital Signal Processors (DSP's) are required to perform most radio functionalities. Novel techniques in this area offer great potential in achieving increased receiver flexibility and greater degree of integration.

RF image rejection has always been a challenging requirement for wireless receivers. Traditionally, highly selective RF bandpass filters have to be used, which make the analog front-end costly and difficult to be integrated [1]. Although zero-IF and low-IF structures are able to alleviate the image problem, the perfect match between *I* and *Q* paths are not possible. The amplitude and phase mismatches cause insufficient image rejection. Therefore, additional techniques are needed to perform mismatch compensation [2-3]. The resulting receiver complexity is thus increased.

Carrier synchronization is another important but difficult task [4]. Even if Phase Lock Loop (PLL) circuits are adopted, the frequency offset between the local oscillator signal and the incoming signal is always present. This causes a time-varying rotation of the signal constellation.

In this paper, a novel digital technique is presented to perform image suppression and CFO compensation jointly by block ICA algorithms. For dual-antenna BPSK receivers, the well-known Fast-ICA [5] and the recently proposed Optimum Block Adaptive ICA (OBA/ICA) [6] are simulated. The results indicate that the proposed technique is successful in accomplishing these two challenging tasks.

2 Receiver Structure and Signal Model

The diversity BPSK receiver structure is shown in Fig. 1. Two antennas are used which, after identical downconversion stage, generate two baseband observations.

The channel's fading coefficients are defined as:

$$f_{sk} = \alpha_{sk} e^{j\psi_{sk}} \tag{1}$$

$$f_{ik} = \alpha_{ik} e^{j\psi_{ik}} \tag{2}$$

where $k=1, 2$ is the antenna index; f_{sk}, f_{ik} are fading coefficients for the desired and image signals, respectively; α_{sk}, α_{ik} and ψ_{sk}, ψ_{ik} are the channel's amplitude and phase responses, respectively.

Let $s(t)$ and $i(t)$ denote the desired and image signals, respectively. Thus, the received signal of the kth antenna $r_k(t)$ could be expressed as:

$$r_k(t) = 2\mathrm{Re}[s(t)f_{sk} e^{j(\omega_C+\omega_I)t} + i(t)f_{ik} e^{j(\omega_C-\omega_I)t}] \tag{3a}$$

where $Re\{.\}$ denotes the real part of a signal, ω_C is the nominal frequency of the first mixer, and ω_I denote the frequency of the second local oscillator. The multiplication by 2 is introduced for convenience.

Equation (3a) can be rewritten as:

$$r_k(t) = s(t)f_{sk} e^{j(\omega_C+\omega_I)t} + s^*(t) f^*_{sk} e^{-j(\omega_C+\omega_I)t}$$
$$+ i(t)f_{ik} e^{j(\omega_C-\omega_I)t} + i^*(t)f^*_{ik} e^{-j(\omega_C-\omega_I)t} \qquad (3b)$$

where * denotes complex conjugate.

Since CFO is present at the receiver, the first mixer signal is expressed as:

$$x_{LO}(t)=2cos((\omega_C +\Delta\omega_C)t+\theta)$$
$$= e^{-j[(\omega_C+\Delta\omega_C)t+\theta]} + e^{j[(\omega_C+\Delta\omega_C)t+\theta]} \qquad (4)$$

where $\Delta\omega_C$ and θ are the amount of CFO and the phase offset.

After the first mixer, the signals are downconverted to IF stage. Then Bandpass Filters (BPF's) with the center frequency of ω_I is employed to select the channel and suppress the high frequency components. The output of the BPF's is:

$$r_{IF,k}(t) = s(t)f_{sk} e^{j[(\omega_I-\Delta\omega_C)t-\theta]}$$
$$+ s^*(t)f^*_{sk} e^{-j[(\omega_I-\Delta\omega_C)t-\theta]} + i(t)f_{ik} e^{-j[(\omega_I+\Delta\omega_C)t+\theta]}$$
$$+ i^*(t)f^*_{ik} e^{j[(\omega_I+\Delta\omega_C)t+\theta]} \qquad (5)$$

Finally, the IF signals are further downconverted to baseband and processed by lowpass filters. At this point, A/D conversion is performed. The signal observation corresponding to the kth antenna $X_k(n)$ is given by:

$$X_k(n) = \text{Re}\{s(n)f_{sk} e^{-j(\Delta\omega_C n+\theta)} +i^*(n)f^*_{ik} e^{j(\Delta\omega_C n+\theta)} \} \qquad (6)$$

where n represents the discrete time index.

For BPSK signals, since $s(t)$ and $i(t)$ are real-valued, so (6) can be written as:

$$X_k(n) = a_k s(n) + b_k i(n) \qquad (7)$$

Where $a_k = \text{Re}\{ f_{sk} e^{-j(\Delta\omega_C n+\theta)} \}$ and $b_k = \text{Re}\{ f^*_{ik} e^{j(\Delta\omega_C n+\theta)} \}$

The signals $s(n)$, $i(n)$ and $X_k(n)$ are each processed in frames of length N. Thus, while $s(n)$, $i(n)$ and $X_k(n)$ in (7) represent one sample signals, s_N, i_N and $X_{N,k}$ are used to denote blocks of signals, each containing N successive samples. Hence,

$$X_{N,k} = a_k s_N + b_k i_N \qquad (8)$$

Therefore, the signal observation matrix is expressed as:

$$\mathbf{X} = \begin{bmatrix} X_{N,1} \\ X_{N,2} \end{bmatrix} = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix} \begin{bmatrix} s_N \\ i_N \end{bmatrix} = \mathbf{AS} \qquad (9)$$

In system model (9), $\mathbf{X}$ is the 2 by N observation matrix, $\mathbf{A}$ is the unknown 2 by 2 mixing matrix, and $\mathbf{S}$ is the 2 by N source signal matrix to be recovered by ICA techniques. The separation of the source signals depends on the assumption that the signals are statistically independent.

Since ICA is a blind algorithm, no estimation of the channel parameters is required. This represents a significant advantage for wireless receiver design.

The successful ICA separation depends on the non-singularity of the mixing matrix. This is guaranteed by the randomness of the channel's fading coefficients. There is no requirement concerning the relative strength of the source signals. Thus, the operating range for input Signal to Interference Ratio (SIR) is quite large.

It is worth mentioning that there is practical limitation on the amount of CFO that the proposed technique is able to correct. The CFO should be smaller than the guard band between adjacent channels. Therefore, if the frequency offset is too large, coarse frequency synchronization should be implemented before ICA processing [5].

The inherent order ambiguity of ICA processing is an important problem to be addressed. To properly identify the desired signal, reference sequences are required in source signal frames. In most communication standards, the reference sequences are available.

3 Block ICA Algorithms for Signal Separation

A description of the kurtosis-based Fast-ICA algorithm [6] is given below. The purpose is to extract two components from two observations $X_{N,1}$ and $X_{N,2}$. The procedure finds a 2 by 2 separation matrix $\mathbf{W}$, so that s_N and i_N can be obtained when $\mathbf{W}$ is applied to the 2 by N observation matrix $\mathbf{X}$ given by (9).

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

Step 2. Initialize the 1st row of the separation matrix $\underline{w}$ to a random vector of unity length. Also, set iteration index $j = 0$.

Step 3. Set

$$w(j+1) = \frac{1}{N}\sum_{n=1}^{N}\{[w(j)\,X_1(n)]^3 X_1(n)\} - 3w(j);$$

Step 4. Normalize $w(j+1)$ to unity length;

Step 5. Check the convergence of $w(j+1)$. If it is not reached, set $j = j+1$ and go back to **Step 3**, otherwise proceed;

Step 6. Set the second row of the separation matrix to $\begin{bmatrix} w[2] & -w[1] \end{bmatrix}^T$.

Fast-ICA typically converges within 10 iterations if the mixing matrix is stationary. Under dynamic channel conditions, convergence problem arises. Recently, a novel Optimum Block Adaptive ICA (OBA/ICA) algorithm was proposed [7]. OBA/ICA exhibits better convergence properties than Fast-ICA for time-varying mixing matrices. In OBA/ICA, **Step 3.** of the above described procedure is replaced by:

Step 3. Set $w(j+1) = w(j) - 0.25[R]_j^{-1} q(j)$

where the matrices $[R]_j$ and $q(j)$ are defined by the observation matrix $\mathbf{X}$ and $w(j)$. (See [7])

4 Simulation Results

To study the performance of the proposed technique, computer simulations are performed assuming Rayleigh fading channels. 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. As long as the mixing matrix $\mathbf{A}$ is full rank, the nature of its coefficients is not of great significance.

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

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

where *s(k)* is the *k*th sample of the desired signal, *y(k)* is the estimate of the *s(k)* obtained at the output of the demodulation stage. SIR represents the average ratio of the desired signal power to the power of the estimation error.

In our simulations, the block size is varied from 100 to 1000 samples. For each block size, 100 Monte Carlo simulations are performed to get the average performance. The phase offset in (4) is assumed uniform over $[0, 2\pi)$, and the frequency offset simulated is 0.0002π. If the sampling frequency is 100MHz, this represents a frequency offset of 10kHz. The resulting average SIR and the number of iterations required for convergence adopting Fast-ICA and OBA/ICA are shown in Figs. 2 and 3.

It is seen from Fig. 2 that both algorithms successfully achieve image rejection of 40~50dB, and there is no significant difference for different choices of block sizes. In Fig. 3, it is shown that OBA/ICA converges faster than Fast-ICA, especially for longer block sizes.

5. Conclusions

A novel technique performing image suppression and Carrier Frequency Offset (CFO) compensation simultaneously is proposed for diversity wireless receivers. Block ICA algorithms are employed. Simulation results confirm the effectiveness of the proposed technique. Also, it is shown that, due to the time variation in the mixing matrix introduced by CFO, the recently proposed OBA/ICA converges faster than the well known Fast-ICA.

References:
[1] Won Namgoong, Teresa H. Meng, Direct-Conversion RF Receiver Design, *IEEE Transactions on Communications*, vol.49, No. 3, Mar. 2001.

[2] Mikko Valkama, Markku Renfors, Visa Koivunen, Advanced methods for I/Q imbalance compensation in communication receivers, *IEEE Transactions On Signal Processing*, vol. 49, no. 10, Oct. 2001.

[3] Jan Crols, Michiel S. J. Steyaert, A single-chip 900 MHz CMOS receiver front-end with a high performance Low-IF topology, *IEEE Journal on Solid-State Circuits*, vol. 30, no. 12, Dec. 1995.

[4] E. A. Lee, D.G. Messerschmitt, *Digital Communication*, Kluwer Academic, Norwell, Mass., USA, 1998.

[5] Mikko Valkama, Markku Renfors, Visa Koivunen, Blind I/Q signal separation-based solutions for receiver signal processing, *EURASIP Journal On Applied Signal Processing*, vol. 16, pp. 2708-2718, 2001.

[6] A. Hyvärinen and E. Oja, A fast fixed-point algorithm for independent component analysis, *Neural Computation*, 9(7): 1483-1492, 1997.

[7] W. Mikhael, T. Yang, Optimum Block Adaptive Algorithm for Gradient Based Independent Component Analysis (OBA/ICA) for Time Varying Wireless Channels, *Proceedings of The 62nd IEEE Vehicular Technology Conference*, Dallas, Texas, Sept. 2005.
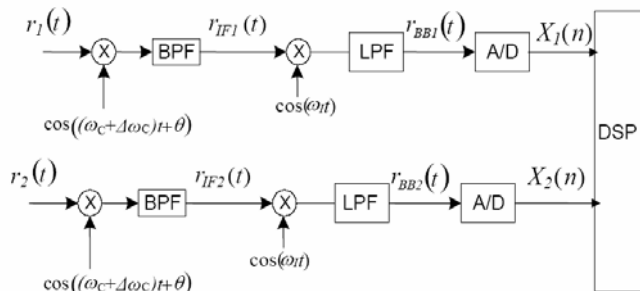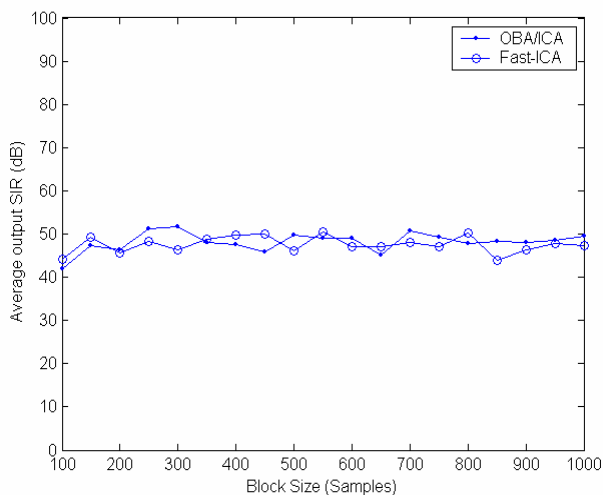
Fig. 1 Diversity BPSK receiver structure

Fig. 3 Average number of iteration to convergence by OBA/ICA and Fast-ICA

Fig. 2 Average SIR achieved by OBA/ICA and Fast-ICA