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A block zero-padding method based on DCFT for L1 parameter estimations in weak signal and high dynamic environments

Key words: Threshold detection, Discrete chirp-Fourier transform (DCFT), Block zero-padding, High-dynamic, Weak L1 signal acquisition

Contact: Chao Wu
E-mail: wuchaoid@126.com
ORCID: http://orcid.org/0000-0001-7769-6155

Introduction

- The weak L1 signal acquisition in the high dynamic environment faces a challenge: the integration peak is negatively influenced by the possible bit sign reversal every 20 ms and the frequency error.

- The block accumulating semi-coherent integration of correlations (BASIC) is a state-of-the-art method. This method converts the nonlinear problem into a linear one. This is achieved by calculating the inter-block conjugate products. Moreover, to alleviate the influence of bit sign reversal on the integration peak, the block zero-padding is used. However, it brings new noise terms which are not good for acquisition under the low signal-to-noise ratio (SNR).

Introduction (Con’d)

- This paper has proposed a novel acquisition method for parameter estimations in weak signal and high dynamic environments. Due to the influence of the bit sign reversal and frequency error on the integration peak, the post-correlation signal in the high dynamic environment cannot be directly used for integration. So, the signal is processed by the block zero-padding method based on DCFT in this paper.

Methodology

Based on the analysis by Yang *et al*. (2008), the baseband L1 signal of a specific satellite vehicle (SV) through the 1 ms correlation process can be written as:

$$\begin{aligned} x_n &= b_n A \exp\{\mathrm{j}[2\pi(f_0 n T_\mathrm{s} + \alpha n^2 T_\mathrm{s}^2) + \phi_0]\} + w_n \\ &= s_n + w_n \end{aligned}$$

Methodology

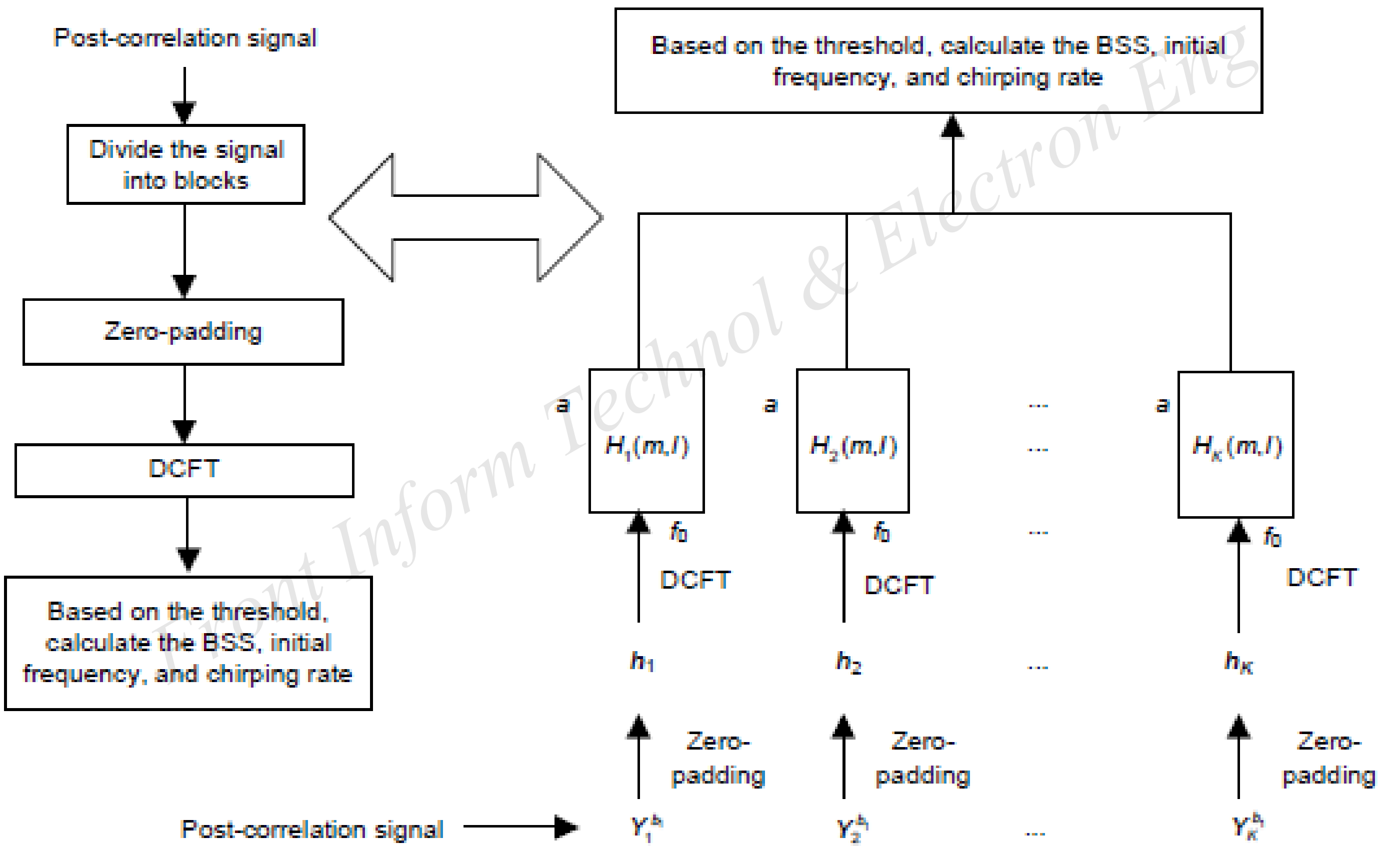


Fig. 3 Diagram of the block zero-padding method based on DCFT

Methodology

Step 1: Divide x_n into several blocks:

$$\begin{aligned} &Y_k^b = [x_{20(k-1)+i+b-1}],\ i = 1, 2, \ldots, M, \\ &k = 1, 2, \ldots, K,\ b = 1, 2, \ldots, M. \end{aligned} \tag{8}$$

It is assumed that bit synchronization is obtained when b is equal to b_1.

Step 2: Write the zero-padding block as

$$h_k = [0_{M(k-1)} \quad Y_k^{b_1} \quad 0_{N-kM}]. \tag{9}$$

Methodology

Step 3: Instead of calculating the inter-block conjugate products of x_n (Yang *et al.*, 2008), perform DCFT on h_k:

$$H_k(m,l) = \mathrm{DCFT}(h_k). \tag{10}$$

The kth bit sign can be solved as follows:

$$\begin{aligned}\delta_k^{b_1}(m,l) = \arg \max_{\delta_k^{b_1}(m,l)\in\{-1,1\}} \Big| & S_{k-1}^{b_1}(m,l) \\ & + \delta_k^{b_1}(m,l)\cdot \mathrm{real}\left(H_k^{b_1}(m,l)\right)\Big|,\end{aligned} \tag{11}$$

where real(·) represents the real part. The partial sum $S_k^{b_1}(m,l)$ and bit sign vector $\boldsymbol{B}_k^{b_1}(m,l)$ can be obtained as follows:

Methodology

$$S_k^{b_1}(m,l) = S_{k-1}^{b_1}(m,l) + \delta_k^{b_1}(m,l)\,\mathrm{real}(H_k^{b_1}(m,l)), \quad (12)$$

$$B_k^{b_1}(m,l) = [B_{k-1}^{b_1}(m,l) \quad \delta_k^{b_1}(m,l)], \quad (13)$$

where $S_0^{b_1}(m,l)$ is equal to 0 and $B_0^{b_1}(m,l)$ is an empty vector.

Step 4: Make detection based on the set threshold V_t. The threshold is set based on the false alarm probability. If J $\left(J = |S_K^{b_1}(m_0,l_0)|\right)$ is larger than V_t, the signal is acquired. Thus, the BSS is $B_K^{b_1}(m_0,l_0)$. Then based on Eqs. (6) and (7), the initial frequency f_0 and chirping rate α can be easily obtained. If not, the local code phase should be updated.

Methodology

The overall false alarm probability can be written as

$$P_{\mathrm{FA}} = 1 - \prod_{m=1}^{M_0} \prod_{l=1}^{L} (1 - P_{\mathrm{fa},l,m}),$$

where $P_{\mathrm{fa},l,m}$ is the false alarm probability per detected cell. $M_0 \cdot L = N_{\mathrm{c}}$ (N_{c} is the number of detected cells). $P_{\mathrm{fa},l,m}$ can be written as

$$\begin{aligned} & P_{\mathrm{fa},l,m}(J \geq \max(\beta_1, \beta_2, \ldots, \beta_{2^{K-1}})) \\ & \quad = 1 - P\{|\eta_1| \leq \beta_1, |\eta_2| \leq \beta_2, \ldots, |\eta_{2^{K-1}}| \leq \beta_{2^{K-1}}\} \\ & \qquad \cdot (-1)^{\rho_m^1 + \rho_m^2 + \ldots + \rho_m^{2^{K-1}}} \\ & \quad = 1 - \sum_{m=1}^{2^{K-1}} F\left((-1)^{\rho_m^1} \beta_1, (-1)^{\rho_m^2} \beta_2, \ldots, (-1)^{\rho_m^{2^{K-1}}} \beta_{2^{K-1}}\right), \end{aligned} \qquad (16)$$

Methodology

where ρ_m^θ is 0 or 1, and $1 \le \theta \le 2^{K-1}$. $F(\cdot)$ is the cumulative distribution function (CDF) of the multi-normal distribution with covariance matrix $C_{l,m}$ and mean vector U. $C_{l,m}(\eta_i, \eta_j) = E[(\eta_i - E(\eta_i))(\eta_j - E(\eta_j))]$, and $1 \le i, j \le 2^{K-1}$. $\beta_1, \beta_2, \ldots, \beta_{2^{K-1}}$ are thresholds. It is assumed that $\beta_1 = \beta_2 = \ldots = \beta_{2^{K-1}} = V_t$. When $P_{\mathrm{fa},l,m}$ is set, V_t can be calculated using the numerical solution.

When the signal is aligned with the local code and the estimated parameters (including the chirping rate and initial frequency) are close to the parameters of the received signal, the detected cell can be assumed as (l_0, m_0), and the detection probability of the proposed method can be written as

$$\begin{aligned} & P_\mathrm{D}(J \ge V_t) \\ & = 1 - P\left\{ |\eta_1| \le V_t, |\eta_2| \le V_t, \ldots, |\eta_{2^{K-1}}| \le V_t \right\} \\ & = 1 - \sum_{m=1}^{2^{K-1}} \left[(-1)^{\rho_m^1 + \rho_m^2 + \ldots + \rho_m^{2^{K-1}}} \right. \\ & \quad \left. \cdot F\left((-1)^{\rho_m^1} V_t, (-1)^{\rho_m^2} V_t, \ldots, (-1)^{\rho_m^{2^{K-1}}} V_t \right) \right]. \end{aligned} \quad (17)$$

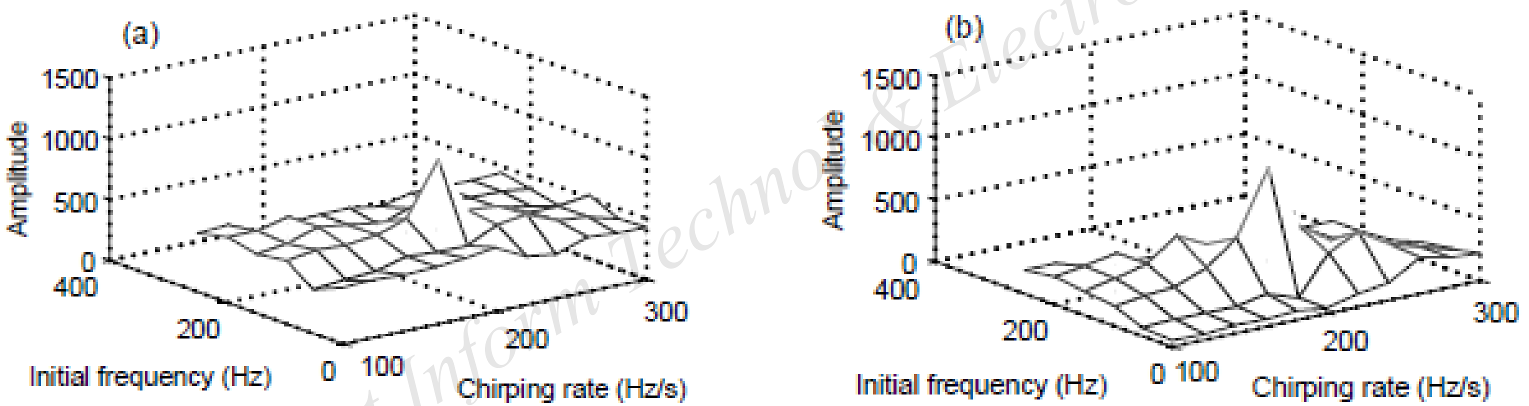
Methodology

The mean vector $\boldsymbol{U}'$ can be written as

$$\boldsymbol{U}'(\eta_m) = \sum_{k=1}^{K} \Bigg\{ (-1)^{n_k} b_k \cdot \sum_{n=0}^{M-1} \exp\left[2\pi \mathrm{j} \left(\Delta f (n + kM) + \Delta\alpha (n + kM)^2 \right) \right] \Bigg\}, \tag{18}$$

where $1 \le m \le 2^{K-1}$, $\Delta f = f_0 T_s - m_0 / N$, and $\Delta\alpha = \alpha T_s^{\,2} - l_0 / N^2$.

Simulation results



(a) The partial sum under -40 dB

(b) The partial sum under -20 dB

Fig. 5 Amplitude of the partial sums

Simulation results (Con’d)

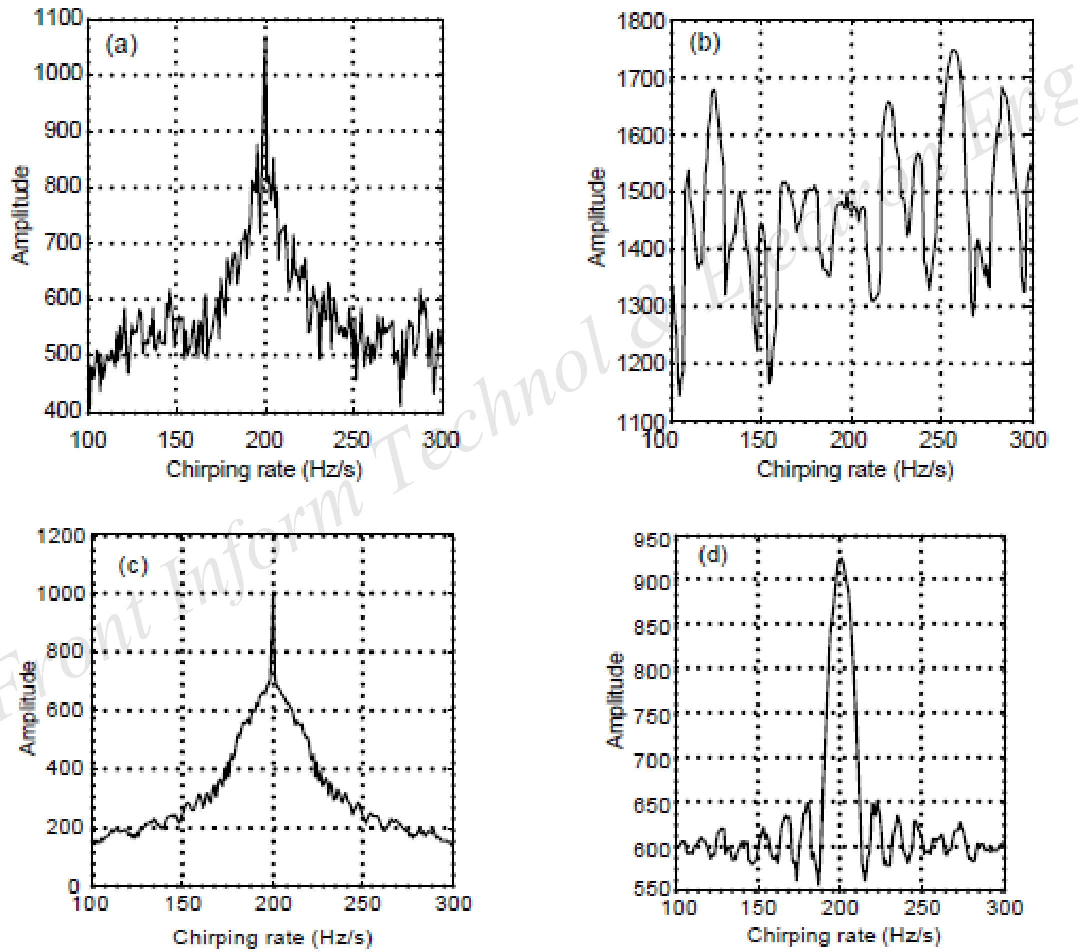


Fig. 6 Chirping rate comparison

(a) Proposed method under −40 dB; (b) BASIC under −40 dB; (c) Proposed method under −20 dB; (d) BASIC under −20 dB

Simulation results (Con’d)

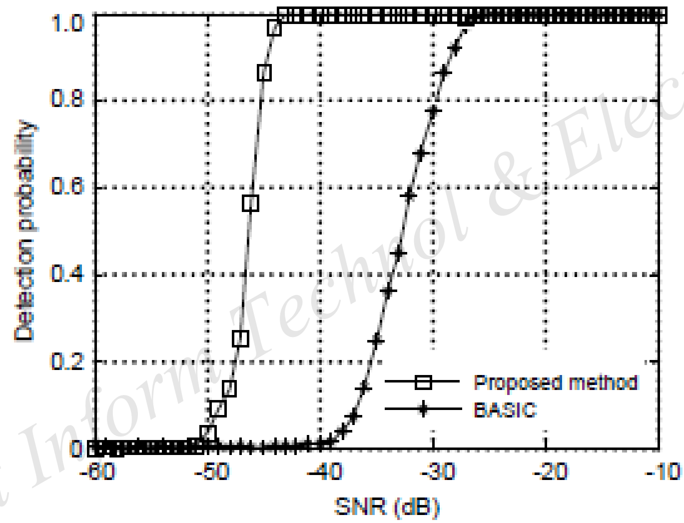


Fig. 7 Detection probability comparison between the proposed method and BASIC

Simulation results (Con’d)

Table 2 Bit sign sequence (BSS) determination (SNR=−20 dB)

Item	Bit sign																			
	k=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Original	1	1	−1	1	1	−1	−1	1	1	1	−1	1	1	−1	1	−1	−1	1	1	1
Proposed method	1	1	−1	1	1	−1	−1	1	1	1	−1	1	1	−1	1	−1	−1	1	1	1
BASIC																				
δ_k	−	1	−1	−1	1	−1	1	−1	1	1	−1	−1	1	−1	−1	−1	1	−1	1	1
b_k^p	1	1	−1	1	1	−1	−1	1	1	1	−1	1	1	−1	1	−1	−1	1	1	1
b_k^n	−1	−1	1	−1	−1	1	1	−1	−1	−1	1	−1	−1	1	−1	1	1	−1	−1	−1

Table 3 Bit sign sequence (BSS) determination (SNR=−40 dB)

Item	Bit sign																			
	k=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Original	1	1	−1	1	1	−1	−1	1	1	1	−1	1	1	−1	1	−1	−1	1	1	1
Proposed method	1	1	−1	1	1	−1	−1	1	1	1	−1	1	1	−1	1	−1	−1	1	1	1
BASIC																				
δ_k	−	1	1	1	−1	1	1	1	−1	−1	1	−1	−1	−1	−1	−1	1	1	1	−1
b_k^p	1	1	1	1	−1	−1	−1	−1	1	−1	−1	1	−1	1	−1	1	1	1	1	−1
b_k^n	−1	−1	−1	−1	1	1	1	1	−1	1	1	−1	1	−1	1	−1	−1	−1	−1	1

Conclusions

- This paper combines DCFT and the block zero-padding process, and proposes the block zero-padding method based on DCFT for parameter estimations in weak signal and high dynamic environments .
- The simulation shows that the proposed method can estimate the high dynamic parameters under a lower SNR than BASIC. This method is the open-loop acquisition method compared with the conventional receiver architecture using the closed-loop acquisition and tracking method, which is particularly suitable for software radio receivers with snapshot solutions.