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Undersampling channelized receiver using principle of signal matched-phase

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Abstract: In the traditional digital channelized receiver, there is no simple algorithm to reconstruct the wideband cross-channel signal without distortion. Moreover, the analog-to-digital converter (ADC) limits the instantaneous bandwidth and dynamic range of the receiver. These problems restrict the applications of digital channelized receiver in radar and communication. Based on the principle of signal matched-phase, a novel channelized receiver structure is presented, where the sub-channels can be seamlessly combined. The presented structure uses the principle of signal matched-phase to solve the frequency ambiguity in the case of the multi-channel undersampling signals. It can reconstruct the wideband cross-channel signal with extremely low distortion, and that it avoids the use of high-speed and high-resolution ADC in wideband and high dynamic applications. Simulation results show the effectiveness of the structure.

Keywords: digital channelization, principle of signal matched-phase, cross-channel signal reconstruction

Classification: Electron devices, circuits, and systems

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1 Introduction

Digital channelization is widely used in the radar and communication interception receivers with high probability of interception [1]. As the traditional channelized receiver cannot match the bandwidth of unknown signal adaptively [2, 3], the signal will be distributed into multiple sub-channels when signal bandwidth is greater than the bandwidth of the channel. Thus, it requires complex synthesis filters to reconstruct the signal, and it cannot reconstruct the phase modulation signal exactly. A digital channelized receiver whose sub-channel bandwidth and position can be reconfigured is proposed in [4, 5]. However, in applications of the electronic countermeasures (ECM), bandwidth and frequency of the interception signals are unknown, then it is difficult to get the reconstruction parameters, and the sub-channel convergence problem still exists. The afore mentioned digital channelized receivers use the high speed ADCs as input front-end. In addition to the extremely high sampling frequency, the ADC must support a very large dynamic range to resolve the signal from the various electromagnetic radiation sources. Currently, since these ADCs are difficult to design and manufacture, the bandwidth and dynamic range of ECM receiver is greatly restricted. Channelized receiver based on hybrid filter banks avoids using high speed ADC [6]. Actually, it uses analog analysis filters to pre-process the input signal, then samples the signal by multiple ADC, and finally uses the synthesis filters to reconstruct the wideband signal. However, this method needs to design a very complex analog analysis filter.

Signal matched-phase principle (SPMP) is a signal estimation method in recent years for wideband and low signal-to-noise power ratio (SNR) conditions [7, 8]. It suppresses noise and interference using multi-channel by assuming that the phase of the desired signal in each channel can match with each other, while the phase of noise and interference cannot match. It has been proven that the method has the high sensitivity and can effectively eliminate the noise and strong coherent interference. Based on the princi-

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ple of signal matched-phase, a novel digital channelized receiver structure is presented. Firstly, the presented receiver structure uses low speed ADCs to sample multi-channel delay signals with undersampling frequency. Secondly, it aligns the phase of sub-band frequency components by phase correction network. Consequently, it gets the sub-band signals from multi-channel undersampling signals with the signal matched-phase algorithm. The presented structure has better amplitude-frequency characteristics than the traditional one, and the sub-channels can be seamlessly combined. It can reconstruct the wideband cross-channel signal with extremely low distortion. Moreover, it only uses accessible low-speed, high-resolution ADC, and avoids the use of high-speed, high-resolution ADC in wideband and high dynamic applications.

2 Signal model and the implementation block diagram

Fig. 1 shows the block diagram of the channelized receiver based on the principle of signal matched-phase. It is assumed that the input signal is

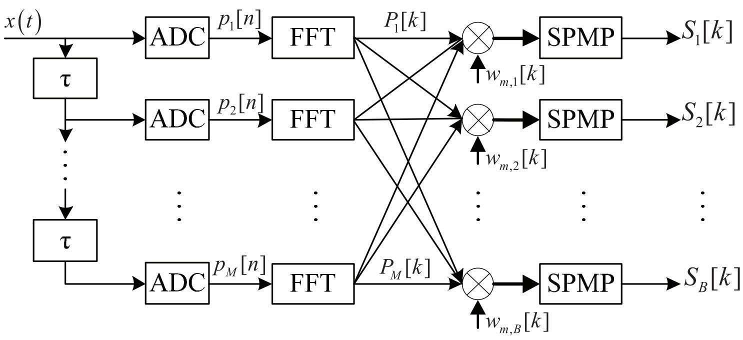

Fig. 1. Block diagram of the channelized receiver based on SPMP.

$x(t)$. Firstly, the input signal is delayed by the multi-stage delay line to get M signals $x(t-(m-1)\tau)$, $m = 1, 2, \ldots, M$, where the delay unit is $\tau = 1/f_s M$. Secondly, we get the sample sequence $p_m[n]$, if the M signals are sampled by low speed ADCs where sampling frequency is f_s. Thirdly, we obtain the transformation sequence $P_m[k]$, $m = 1, 2, \ldots, M$, by N-point fast Fourier transform (FFT) on $p_m[n]$, where $k = 1, 2, \ldots, N$ is frequency index. We can see that signal in each undersampling branch is aliasing distortion, according to the Nyquist sampling theorem when the bandwidth of input signal is greater than twice of the sampling frequency. In order to get the sub-bands of interest from aliasing signals, we need to study and use the differences of characteristics between sub-bands, and take a certain method to separate them. We can find that the phase-shift characteristics of each sub-band signal are inconsistent in delayed undersampling sequence. Hence, we can use the phase-shift characteristics to distinguish different sub-bands. The SPMP suppresses noise and interference using multi-channel by assuming that the phase of the desired signal in each channel can match with each other while the phase of noise and interference cannot match. Here, according

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to the phase-shift characteristics of the desired sub-band, we correct the phase of each undersampling sequence to make sure the phase of sub-band signal components is aligned. Finally, we extract desired sub-band signal by the signal matched-phase algorithm. Meanwhile, the other sub-band signal components which cannot meet the phase alignment are greatly inhibited by the signal matched-phase algorithm.

Here, the input bandwidth $f_s M/2$ is divided into $B = M/2$ sub-bands. Each sub-band is corresponding to an aliasing band in undersampling signal, where the bandwidth of a sub-band is f_s.

According to the position of sub-band $b = 1, 2, \ldots, B$, we take phase correction on the transformation sequence $P_m[k]$ in the frequency domain to get $X_m[k] = P_m[k] \cdot w_m[k]$. The calibration weight is

$$\begin{aligned} w_{m,b}[k] &= \exp\left(-j2\pi\left(f_s \cdot (b-1) + f_s \cdot \frac{k}{N}\right) \cdot \frac{m-1}{f_s} \cdot \frac{1}{M}\right) \\ &= \exp\left(-j2\pi\left((b-1) + \frac{k}{N}\right) \cdot \frac{m-1}{M}\right), \end{aligned} \tag{1}$$

where f_s is the sampling frequency of ADC, N the size of FFT, b the sub-band position number, m the sampling channel number, k the frequency index, and M the total number of sampling channels. We correct the phase of the signal in each undersampling branch. Consequently, we extract the desired sub-band signal by the signal matched-phase algorithm.

3 The signal-matched-phase algorithm for sub-band reconstruction

The presented channelized receiver uses the signal matched-phase algorithm based on least squares. When extracting the b-th sub-band, the FFT of M signals after phase correction can be written as

$$X_m[k] = S_b[k] + \overline{N}_m[k], m = 1, 2, \ldots, M, \tag{2}$$

where $S_b[k]$ is the phase-aligned signal components of b-th sub-band, $\overline{N}_m[k]$ the other sub-band signal components and noise. The symbol $X_m[k]$, $S_b[k]$ and $\overline{N}_m[k]$ can be abbreviated as X_m, S_b and $\overline{N}_m]$ respectively. By left moving the $S_b[k]$ item and taking modulo on both sides of (2), we get

$$|X_m|^2 + |S|^2 - 2\mathrm{Re}(X_m)\mathrm{Re}(S) - 2\mathrm{Im}(X_m)\mathrm{Im}(S) = \left|\overline{N}_m\right|^2, \tag{3}$$

where $m = 1, 2, \ldots, M$. Taking subtraction on adjacent equations one by one in Eq. (3), we get

$$\begin{aligned} &2\mathrm{Re}(X_m - X_{m-1})\mathrm{Re}(S) + 2\mathrm{Im}(X_m - X_{m-1})\mathrm{Im}(S) \\ &= (|X_m|^2 - |X_{m-1}|^2) - (\left|\overline{N}_m\right|^2 - \left|\overline{N}_{m-1}\right|^2), m = 2, \ldots, M. \end{aligned} \tag{4}$$

The matrix form is $\boldsymbol{A} \cdot \boldsymbol{S} = \boldsymbol{X}$, where

$$\boldsymbol{A} = 2 \times \begin{bmatrix} \mathrm{Re}(X_2 - X_1) & \mathrm{Im}(X_2 - X_1) \\ \mathrm{Re}(X_3 - X_2) & \mathrm{Im}(X_3 - X_2) \\ \cdots & \\ \mathrm{Re}(X_m - X_{m-1}) & \mathrm{Im}(X_m - X_{m-1}) \end{bmatrix}, \tag{5}$$

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$$\boldsymbol{S} = \begin{bmatrix} \mathrm{Re}(S) \\ \mathrm{Im}(S) \end{bmatrix}, \tag{6}$$

$$\boldsymbol{X} = \begin{bmatrix} |X_2|^2 - |X_1|^2 - |\overline{N}_2|^2 + |\overline{N}_1|^2 \\ |X_3|^2 - |X_2|^2 - |\overline{N}_3|^2 + |\overline{N}_2|^2 \\ \cdots \\ |X_m|^2 - |X_{m-1}|^2 - |\overline{N}_m|^2 + |\overline{N}_{m-1}|^2 \end{bmatrix}. \tag{7}$$

Based on the matched-phase principle, there is an assumption that fluctuation of the noise power spectrum in each channel is consistent, i.e.

$$|\overline{N}_1|^2 \approx |\overline{N}_2|^2 \approx \cdots \approx |\overline{N}_i|^2,\ i = 2, \ldots, M. \tag{8}$$

Solving equations using the least square criterion, we can obtain the desired signal $\boldsymbol{S} = \boldsymbol{A}^{\dagger}\boldsymbol{X}$, where $\mathbf{A}^{\dagger}$ expresses the Moore-Penrose generalized inverse. Finally, we extract the b-th sub-band signal, that is $\boldsymbol{S}_b = \{S_b[k]\}_{k=1}^{N}$, $b = 1, 2, \ldots, B$.

4 Wideband signal reconstruction

The signal components may be distributed to several sub-bands adjacent when the input signal bandwidth is greater than the bandwidth of the sub-band. The aliasing bands in undersampling signal can be seamlessly combined in the presented channelized receiver. Therefore, when the wideband signal covers the j sub-bands from i-th, we can reconstruct the wideband signal by combining the several adjacent sub-bands, i.e., $\left[\boldsymbol{S}_i^T, \boldsymbol{S}_{i+1}^T, \ldots, \boldsymbol{S}_{i+j-1}^T\right]^T$.

5 Simulation and analysis

In experiments, we assume that sample frequency of ADC for each branch is 15.625 MSPS, the ADC quantization bit is 12 bits, the total number of undersampling branch is 32, the number of output sub-band is 16, and the bandwidth of each sub-band is 15.625 MHz. There are three input signals. The first signal is single-tone where the center frequency is 8.5 MHz. The second one is linear frequency modulated signal where the center frequency is 100 MHz and bandwidth is 100 MHz. The third one is quadrature phase shift keying (QPSK) signal where the center frequency is 200 MHz and code rate is 10 MHz. Fig. 2 (a) shows the power spectral density (PSD) of the input signal. Combining all sub-band signals, we get the reconstruction signal and its PSD is shown in Fig. 2 (b). We can see that the presented channelized receiver completely restored the frequency characteristics of signal.

We verify the performance of the wideband cross-channel signal reconstructed by parameter estimating. Using the method in [9], we estimate the carrier frequency and code rate parameters from the original QPSK signal and the reconstructed signal. Then, we simulate in the case of the signal contaminated by noise. The result is the average of 1000 trials. Fig. 2 (c) shows the normalized root mean square error (NRMSE) of the carrier frequency and code rate parameters estimated from the original QPSK signal and the

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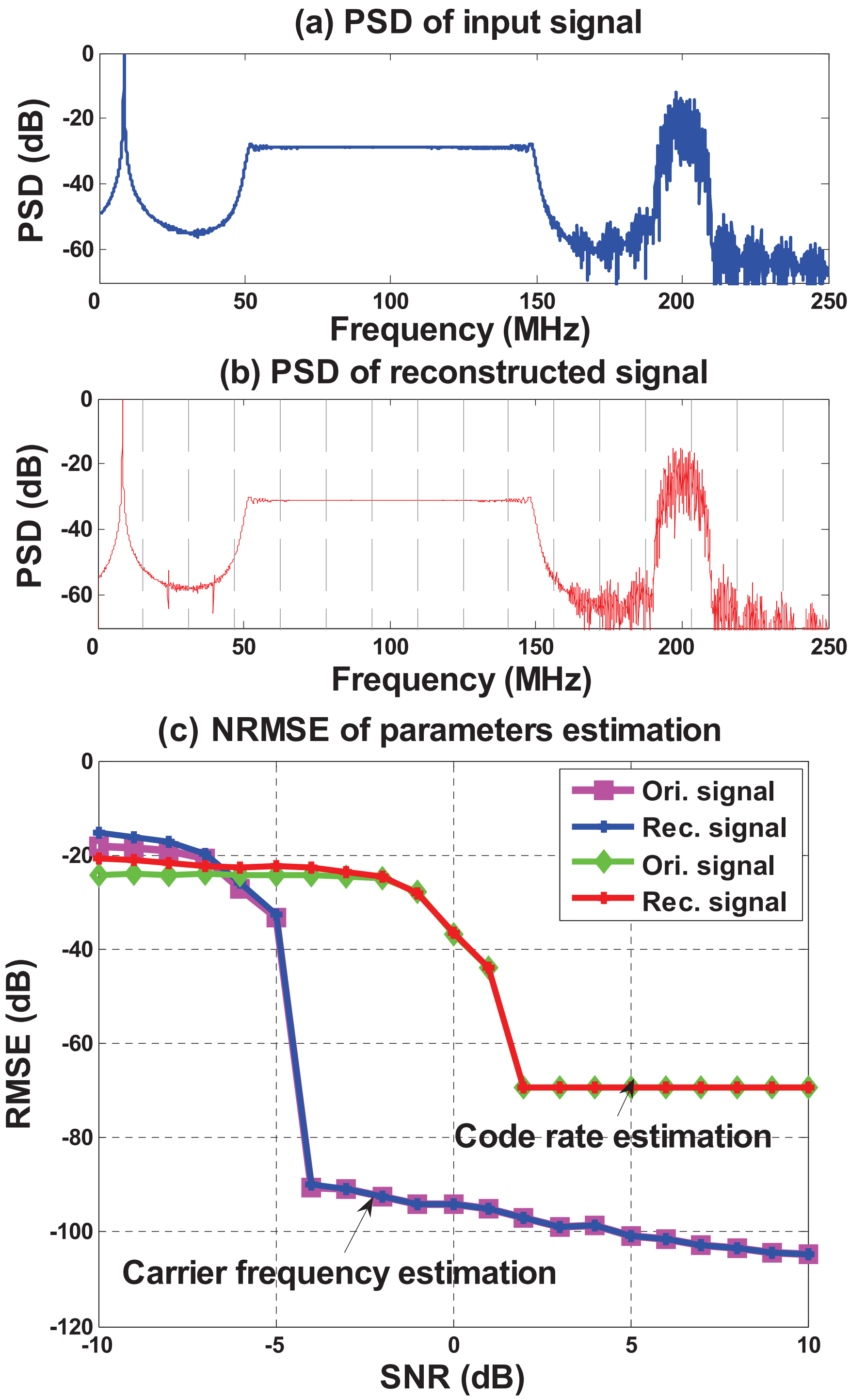

Fig. 2. Simulation results: (a) PSD of input signal, (b) PSD of reconstructed signal, (c) NRMSE of parameters estimation.

reconstructed one. It can be seen from Fig. 2 (c) that the estimation performance curves of the original signal and the reconstructed one are almost completely overlapped. It shows that the presented structure reconstruct the wideband cross-channel signal with extremely low distortion.

The effective number of bits (ENOB) is an important measure of ADC performance. We use the sine-wave fitting algorithms [10] to estimate the

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equivalent ENOB of presented structure. In simulations, the ADC bits used in presented receiver range from 5-bit to 10-bit. The equivalent ENOB of presented receiver structure is shown in Table I. We can see that there is basically no loss of the ENOB. In brief, the receiver avoids the use of high-speed and high-resolution ADC, and it also has the ability of sampling wideband signals with high-precision.

Table I. Equivalent ENOB.

ADC bits	5 bits	6 bits	7 bits	8 bits	9 bits	10 bits
Equivalent ENOB	4.8515	5.8902	6.8317	7.8602	8.8617	9.8692

6 Conclusion

This paper presents a channelized receiver structure based on the signal matched-phase principle. The simulation results show that the receiver structure has well amplitude-frequency characteristics, and it can reconstruct the cross-channel signal with extremely low distortions. Meanwhile, it only uses accessible low-speed and high-resolution ADC instead of high-speed one, and it also ensures a better precision in wideband and high dynamic applications. To sum up, the channelized receiver structure can be applied in the frequency domain panoramic monitor and rate conversion in radar or communication interception application.

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