

Nyquist folding digital receiver for signal interception

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Abstract: A new architecture, denoted as the Nyquist folding digital receiver (NYFDR), to compress the data for signal interception is presented. The NYFDR is a digital version of the Nyquist folding receiver (NYFR). Simulation results show that the NYFDR has advantages over NYFR in the detection of Nyquist zone. Moreover, the data rate and resource consumption of the NYFDR are less than those of the digital channelized receiver (DCR).

Keywords: electronic countermeasures, synchronous Nyquist folding receiver, digital channelized receiver

Classification: Microwave and millimeter wave devices, circuits, and systems

References

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1 Introduction

For signal interception, one of the most famous architectures is the digital channelized receiver (DCR) [1, 2]. The DCR consists of two parts. The first part is to channelize the interception bandwidth using a filter bank, and it is often implemented in field programmable gate array (FPGA) because of its huge data throughput. The second part is to analyze the detailed information of the received signal, which is often implemented by digital signal processor (DSP) for its flexibility. Between the two parts, there is a detection mechanism to transmit the effective channel data from the first part to the second one. The DCR is a classic architecture for signal interception.

However, the output data rate of FPGA would increase as the number of effective channels augments, and we want to reduce and fix the data rate of the output to facilitate the data transmission from FPGA to DSP.

The Nyquist Folding receiver (NYFR) and the reconfigurable direct radio frequency bandpass sampling receiver (RDRFBRSR) were invented by Fudge [3, 4] who showed that the entire analog bandwidth could be folded into one Nyquist zone using one analog-to-digital converter (ADC) by marking the different frequency zones with dependent frequency modulations. This approach reduces the number of ADCs considerably, and we can recover the signal from the output of the NYFR in a sparse environment. However, the structures of the NYFR and the RDRFBRSR are easily affected by noise at the zero crossing rising (ZCR) time when controlling the clocks of shaped pulses by using a full analog structure for wideband modulation. Besides, there is no structure for synchronization in the NYFR or the RDRFBRSR, and the initial phase of the signal is lost.

This letter proposes the digital version of the NYFR, namely the Nyquist folding digital receiver (NYFDR). We use different noise sequences with fixed bandwidth to represent different zones to improve the processing bandwidth of signal for the NYFR. Further, the NYFDR could get similar functions and less data rate than the DCR.

2 NYFDR

The structure of the NYFDR is shown in Fig. 1. First, quadrature sampling is used to receive the signal by the rate f_s , and the complex sampled signal is $x(n)$. Then, $x(n)$ is multiplied by the conjugation of a complex wideband modulated signal denoted as $p(n)$, which is the local oscillator signal (LOS), and we can get the modulated signal $s(n)$. Finally, $s(n)$ is filtered by a complex filter $h(n)$ whose passband is $[-\omega_{s2}/2, \omega_{s2}/2]$ and the output is $y(n)$,

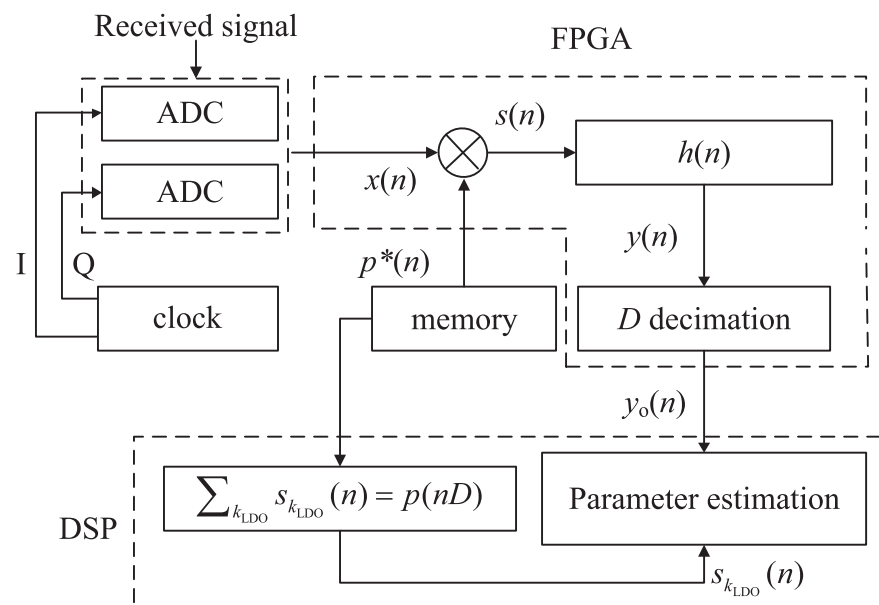


Fig. 1. Structure of NYFDR.

which is decimated with $D \leq 2\pi/\omega_{s2}$. $p(n)$ and its related phase data are stored in memory. $s_{k_{\text{LDO}}}(n)$ is the local demodulation oscillation (LDO) signal and $\sum_{k_{\text{LDO}}} s_{k_{\text{LDO}}}(n) = p(nD)$, $k_{\text{LDO}} \in [0, K]$, where $K + 1$ is the number of Nyquist zones. The LDO signal is dependent of LOS, then we have established a synchronization mechanism between the LOS and LDO signal. The conjugation multiplication and decimation are implemented in FPGA, and the parameter estimations of the received signal could be implemented in DSP.

Assuming $x(n)$ is a multicomponent signal, which is given by

$$x(n) = \sum_{q=0}^{Q-1} \exp[j(\omega_q n + \varphi_q)] \quad (1)$$

where ω_q and φ_q are the angular frequency and initial phase for the q th component, respectively. Q is the number of frequencies and assumed to be a prior in this paper. Define the LOS as

$$p(n) = \sum_{k=0}^K \exp\{j[\omega_{s2}n/2 + k\omega_{s2}n + w_k(n)]\} \quad (2)$$

where $w_k(n)$ is zone dependent white Gaussian noise sequence with fixed bandwidth B , and noise sequences for different zones are independent. Then, the bandwidth of $\exp\{j[\omega_{s2}n/2 + k\omega_{s2}n + w_k(n)]\}$ is always equal to B for different k . K is determined by

$$K \leq (2\pi - B/2)/\omega_{s2} \quad (3)$$

The LOS in (2) is different with those in NYFR [3, 4]. The bandwidth of each LOS of the NYFR is proportional to the index of the Nyquist zone, and the maximum bandwidth is KB . When B is fixed, KB would be greater than ω_{s2} with the increase of K . However, for NYFDR, the maximum bandwidth of each LOS is B and independent of K . In conclusion, the bandwidth of LOS of the NYFDR is less than the one of the NYFR, and the LOS in (2) expands the processing bandwidth of the received signals.

Let $k_q = \text{round}((\omega_q - \omega_{s2}/2)/\omega_{s2})$, where $\text{round}(A)$ means the nearest integer to A . In order to facilitate the derivation, we just assume that the frequency ω_q is far away from an integer multiple of ω_{s2} , i.e., $B/2 < \omega_q - k_q\omega_{s2} < \omega_{s2} - B/2$. Then,

$$y(n) = s(n) \otimes h(n) = \sum_{q=0}^{Q-1} \exp\{j[(\omega_q - \omega_{s2}/2 - k_q\omega_{s2})n + \varphi_q - w_{k_q}(n)]\} \quad (4)$$

where \otimes denotes linear convolution.

After decimation, we have

$$y_o(n) = y(nD) = \sum_{q=0}^{Q-1} \exp\{j[(\omega_q - \omega_{s2}/2 - k_q\omega_{s2})nD + \varphi_q - w_{k_q}(nD)]\} \quad (5)$$

$y_o(n)$ is a multi-wideband signal. Simply, let $\omega_p \in [k_p\omega_{s2}, (k_p + 1)\omega_{s2})$, $\omega_q \in [k_q\omega_{s2}, (k_q + 1)\omega_{s2})$, and we assume that $k_q = k_p$ if and only if $p \equiv q$. The k_{LDO} th LDO signal is

$$s_{k_{\text{LDO}}}(n) = \exp\{j[(\omega_{s2}/2 + k_{\text{LDO}}\omega_{s2})nD + w_{k_{\text{LDO}}}(nD)]\} \quad (6)$$

Then, the demodulation is

$$\begin{aligned} y_{k_{\text{LDO}}}(n) &= y_o(n)s_{k_{\text{LDO}}}(n) \\ &= \sum_{q=0}^{Q-1} \exp\{j[(\omega_q + (k_{\text{LDO}} - k_q)\omega_{s2})nD + \varphi_q + w_{k_{\text{LDO}}}(nD) - w_{k_q}(nD)]\} \end{aligned} \quad (7)$$

For a detailed description of $y_{k_{\text{LDO}}}(n)$ for different k_{LDO} , we take $k_{\text{LDO}} = k_0$ for instance, then $y_{k_0}(n) = \exp\{j(\omega_0 nD + \varphi_0)\} + \sum_{q=1}^{Q-1} \{\exp\{j[(\omega_q + (k_0 - k_q)\omega_{s2})nD + \varphi_q + w_{k_0}(nD) - w_{k_q}(nD)]\}\}$. Obviously, $\exp\{j(\omega_0 nD + \varphi_0)\}$ is a tone. $w_{k_0}(nD) - w_{k_q}(nD)$, $q \neq 0$, is the linear combination of two independent wideband Gaussian noise sequences, and is still a wideband Gaussian noise sequence, then $\exp\{j[(\omega_q + (k_0 - k_q)\omega_{s2})nD + \varphi_q + w_{k_0}(nD) - w_{k_q}(nD)]\}$, $q \neq 0$, is also a wideband signal whose carrier frequency is $(\omega_q + (k_0 - k_q)\omega_{s2})D$. In conclusion, if $k_{\text{LDO}} \in \{k_q, q = 0, \dots, Q-1\}$, the output of $y_{k_{\text{LDO}}}(n)$ should contain a tone and $Q-1$ wideband signals, else the output just contains Q wideband signals.

Due to the accumulation properties of tone in frequency, we could do the fast Fourier transform (FFT) to $y_{k_{\text{LDO}}}(n)$, $k_{\text{LDO}} \in [0, K]$, and treat the indexes of zones corresponding to the maximum Q outputs as the estimation of Nyquist zones, which is shown in Fig. 2. If we have estimated all the zones, the parameter estimations of $x(n)$ turn into the parameter estimations of Q tones of $y_{k_{\text{LDO}}}(n)$, $k_{\text{LDO}} \in \{k_q, q = 0, \dots, Q-1\}$. In conclusion, we could estimate the parameters of the multicomponent signal from the output.

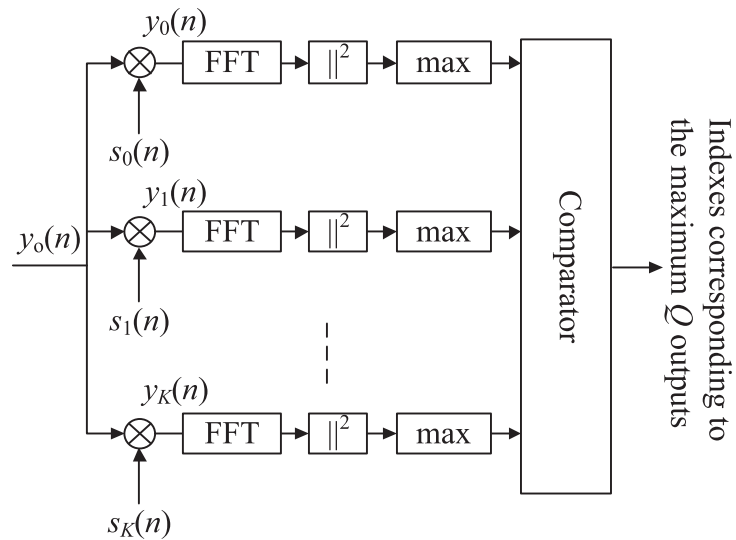


Fig. 2. Estimator of Nyquist zones.

3 Comparison

3.1 Comparison between NYFR and NYFDR

We evaluate the proposed NYFDR in the estimation of Nyquist zone context by simulations. In simulations, $f_s = 2.6 \text{ GHz}$, $\omega_{s2} = 325 \text{ MHz}/2.6 \text{ GHz} \times$

2π . The bandwidths, namely B , of LOS are 20 MHz, 60 MHz and 100 MHz for NYFR and NYFDR, respectively. The number of samples is $2.6 \text{ GHz} \times 1 \mu\text{s} = 2600$. The frequencies of $x(n)$ are 0.1 GHz, 1.1 GHz and 2.5 GHz. When all the zones are estimated correctly, we just consider the estimation is succeeded and the performance is evaluated by the probability of correct decision (PCD).

It can be seen from Fig. 3 that the proposed NYFDR can obtain over 90% PCD in a wide range of bandwidths when the signal-to-noise ratio (SNR) is greater than -5 dB , and the PCD of NYFR is limited by the bandwidth. The simulation shows that, the performance of NYFDR is not limited by the modulation bandwidth as the NYFR.

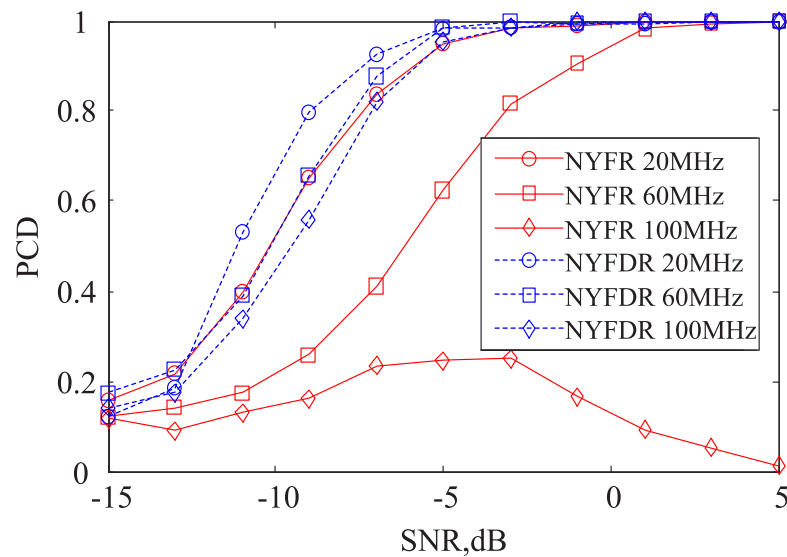


Fig. 3. The PCDs of different modulation bandwidths VS SNR.

3.2 Comparative analysis between the NYFDR and the DCR

We implement the DCR [2] and NYFDR in FPGA, respectively, and will compare the performance for NYFDR and DCR with the data rate where the format is clock frequency \times resolution \times number of buses (Mb/s). The frequency of the input complex signal ranges from 1.4 GHz to 2.6 GHz. The input complex signals are sampled by two ADCs of Analog Devices named ADC083000 at the rate of 2.6 Giga-samples per second (GSPS) with 8 bits resolution. The output data of DCR and NYFDR are expanded to 16 bits resolution as the accuracy requirement of the multiplication. The decimation factor and the order of filter, which corresponds to the $h(n)$ in NYFDR, for the DCR and the NYFDR are 8 and 80, respectively.

For DCR, we take the real part as an example to describe its data rate. The outputs for one ADC083000 are 4 buses double data rate (DDR) differential data, where the data rate is double $325 \times 8 \times 4 \text{ Mb/s}$ and the clock frequency is 325 MHz. We use the FPGA of XILINX named XC5VSX95T-2FF1136 to receive the DDR data, and convert the data to 8 buses pairs

single data rate (SDR) data, where the data rate is $325 \times 8 \times 8$ Mb/s. The number of channels for the DCR is 16, and the bandwidth of each channel is 162.5 MHz. Adjacent channels overlap 50% in frequency domain. The output signals are complex and distributed in 7 effective channels, and the data rate of each channel is $325 \times 16 \times 2$ Mb/s. Considering the image part, the maximum data rate is $325 \times 16 \times 14$ Mb/s. The output to input data rate ratio of the DCR is $(325 \times 16 \times 14 \text{ Mb/s}) / (325 \times 8 \times 16 \text{ Mb/s}) = 7/4$.

We implement the NYFDR on the same hardware platform. The output signal is complex and distributed in one zone, and the data rate is $325 \times 16 \times 2$ Mb/s. The output to input data rate ratio of the NYFDR is $(325 \times 16 \times 2 \text{ Mb/s}) / (325 \times 8 \times 16 \text{ Mb/s}) = 1/4$.

The slice registers and DSP48E slices are basic digital signal processing elements for XC5VSX95T-2FF1136, which are used to show the resource consumption. In the experiment, the NYFDR needs 923 slice registers and 206 DSP48E slices, and the maximum operating frequency is 371.032 MHz. However, the DCR needs 7082 slice registers and 210 DSP48E slices, and the maximum operating frequency is 368.053 MHz. The slice usage mainly depends on the complexity of the algorithm, so the algorithm of DCR is much more complex than the one of NYFDR. Then, the resource consumption of the NYFDR is almost the same as or less than that of the DCR. In conclusion, the data rate of the NYFDR is just 1/7 of the one of the DCR with less resource consumption.

4 Conclusion

The NYFDR introduces a synchronization mechanism between the LOS and DSP for parameter estimations, and expands the processing bandwidth of the NYFR by using a fixed bandwidth LOS. Moreover, the NYFDR has similar functions in data compression with the DCR in ultra-wideband applications. When the signal is distributed in multiple channels, the output data rate of the NYFDR is much less than that of the DCR with less resource consumption.

However, the parameter estimation algorithms of the NYFDR would be much more complex than the DCR, and the output SNR of the NYFDR would be less than that of the DCR. In conclusion, the NYFDR could be a better choice than the DCR for data compression for signal interception in a high SNR environment.

Acknowledgments

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