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Full Length Research Paper

Nyquist Folding Receiver for the Interception of Frequency Agile Radar Signal

Deguo Zeng*, Xiaodong Zeng and Bin Tang

School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China.

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This work was carried out to improve the probability of interception of frequency sweep and lower the system complexity of non-sweep mode of the electronic intelligence system for frequency agile radar signal. A low complexity receiver structure and its associated demodulation algorithm with high probability of intercept are also presented. Moreover, the applicability of this structure for the wideband radar signal is demonstrated. First, the received signal is modulated by analog signal and treated as the local oscillator to move the local signal with different Nyquist zone into the baseband to extract the zone information. Then, the digital local oscillator synchronized with the analog modulation is used to reconstruct the demodulated sub-sampling signal. Finally, the zone and sub-sampling signal could be used to estimate signal parameters by the classical signal processing methods. Simulation results show that when the signal to noise ratio is more than -16 dB, the probability of correct decision for the Nyquist zone is better than 90%.

Key words: Frequency agile, sub-sampling, synchronous Nyquist folding receiver, Nyquist zone.

INTRODUCTION

Frequency agility (FA) signal is also known as frequency hopping (FH), which is widely used in communications, radar, sonar and other fields because of its good performance in anti-interference, and low possibility for intercept (Fan et al., 2008). In the field of radar, FA has been widely researched. Chen (2008) used the FA waveform in multiple-input and multiple-output (MIMO). Maric et al. (1994) applied Costas arrays in spread sequence (SS)/FH multi-user radar and sonar systems. Scholand et al. (2005) proposed the idea of FA combined with orthogonal frequency-division multiplexing (OFDM), and showed its good performance. Cupido et al. (2006) reported that Homodyne sweep system can cover the 18 to 100 GHz, and the hop size could be as wide as GHz in the new millimeter-wave frequency agile system. Hunt (2009) realized FA radar in 0.5 to 2 GHz, and the performance is fine.

In electronic countermeasures, the intercept and analysis of FA signal have always been a hot topic. Current researches are mainly focused on the digital signal processing after direct sampling or sub-sampling. The common ways of intercept are channelized receiver (Li et al., 2009) and time-frequency analysis (Hao and Papandreou-Suppappola, 2006). Meanwhile, many scholars did the researches on the parameter estimation of FA (Angelosante et al., 2010; Aziz et al., 2006; Barbarossa et al., 1997; Chung et al., 1995; Gui et al., 2011; Lam et al., 1990). However, the carrier frequencies of FA are generally controlled by the pseudo-random code, and the hop size may be several GHz. The frequency is constantly hopping which makes the interception difficult. If we cannot intercept FA properly, it would be meaningless for the following signal processing. Assuming the frequencies of radar are hopping in the range of several hundreds of MHz to 18 GHz, we would need more than 10 channels for the whole probability reconnaissance according to the current speed of ADC. If we adopt the way of frequency sweep, the complexity of the equipments could be reduced, while the probability of interception cannot be guaranteed. It is a difficult problem in the electronic countermeasures on how to realize the high probability of interception of a wideband or ultra wideband FA signal with low system complexity.

Driven by the idea of compressed sensing (CS), Fudge proposed Nyquist folding receiver (NYFR) and

*Corresponding author. E-mail: zedg@sina.com. Tel: +86-18602802078. Fax: +86-028-61830432.

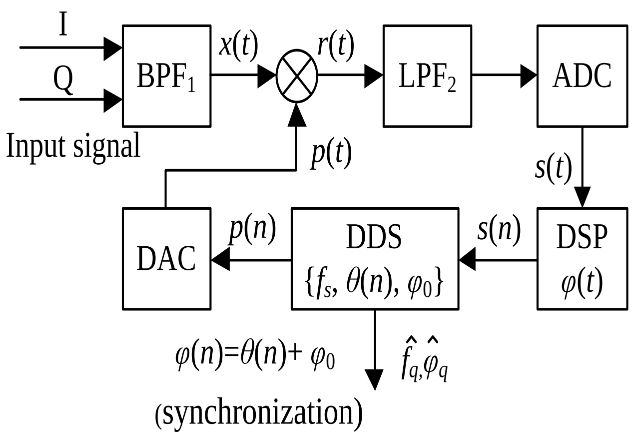

Figure 1. Block diagram of SNYFR.

reconfigurable direct RF bandpass sampling receiver (RDRFBSR) (Fudge et al.; 2008a; Fudge et al., 2008b). The two types of receiver are similar and overcome the disadvantages of the traditional sub-sampling technique that can only aim at a particular Nyquist sampling zone. The main idea of Fudge is that the Nyquist zone could be mapped to a parameter of the signal by performing extra analog modulation on the received signals, and then we can sample the received signal with added Nyquist zone information. By changing the mode of analog modulation and the channel number, we can achieve the whole probability interception of a wideband or ultra-wideband signal in one channel without using frequency sweep. However, the structures of NYFR and RDRFBSR are easily affected by noise at the zero crossing rising (ZCR) time when controlling the clock of shape pulse by using a full analog structure for wideband modulation. Besides, there is no structure for synchronization in NYFR or RDRFBSR, and the initial phase of the signal is lost. In addition, the efficient demodulation of the output of NYFR and the applicability of the structure for other kinds of radar signal interception need further study.

This paper presents an improved structure marked as synchronous NYFR (SNYFR) to realize the interception of FA signal and shows the algorithm for the estimation of Nyquist zone. We provide a new way of the interception of FA and demonstrate the general applicability of SNYFR on the other wideband radar signals.

SYNCHRONOUS NYQUIST FOLDING RECEIVER

Structure for SNYFR

The structure of SNYFR is shown in Figure 1. The input signal is FA, and the agile range is from several hundreds of MHz to 18 GHz. To facilitate the follow-up derivation rigorously, we assume the input analog signal has been preprocessed into I/Q signals and the interesting frequency band is from 0 to 18 GHz. First, the input signal is filtered by a ultra wideband (UWB) filter (LPF$_1$) whose passband is [0, 18 GHz] to remove the out-of-band noise to get the complex signal $x(t)$. Then, $x(t)$ is mixed by the UWB complex local oscillator (LO) $p(t)$ to obtain the modulated signal $r(t)=x(t)p^*(t)$ where the mark * stands for complex conjugation, and $r(t)$ is filtered by the second complex low-pass filter (LPF$_2$) with the passband $[-f_s/2 \quad f_s/2]$ to get the signal $s(t)$, where f_s is the sampling rate for digital signal processing. Finally, sample $s(t)$ by the rate of f_s to obtain $s(n)$. The $p(t)$ is generated by the digital analog converter (DAC) and direct digital synthesizer (DDS), where DDS is synthesized by the digital signal $p(n)$ and constitutes of f_s, the phase $\theta(n)$ and the initial phase φ_0. The instantaneous phase $\varphi(n)=\theta(n)+\varphi_0$ of the component corresponding to center frequency f_s of $p(n)$ is also sent to DSP for synchronization.

Theoretical analysis

Assume that $x(t)$ is frequency agile, which is given by

$$x(t)=\sum_{q=0}^{Q-1} e^{j(2\pi f_q t+\varphi_q)} \mu(t-qT_r) \tag{1}$$

where $\mu(t)=\begin{cases}1, 0\le t<T_P\\ 0, otherwise\end{cases}$, T_P is the pulse width, T_r is the pulse repetition interval (PRI), $T_r>T_P$; f_q and φ_q are the agile frequency and initial phase for the qth sub-pulse and Q is the number of pulses, respectively. The NYFR in Fudge et al. (2008a,b) used the ZCR voltage of sinusoidal frequency modulation (SFM) to control the shaping pulse to get the UWB LO. While, the basic idea of NYFR is to move the corresponding local UWB with different Nyquist zone into the baseband to extract the zone information by exchanging the location of the traditional position of the LO and the received signal. As long as the LO has different band in each Nyquist zone, we can get the same result in NYFR. The LO could be simplified as

$$p(t)=\sum_{k=0}^{K} e^{jk(2\pi f_s t+\theta(t)+\varphi_0)} \tag{2}$$

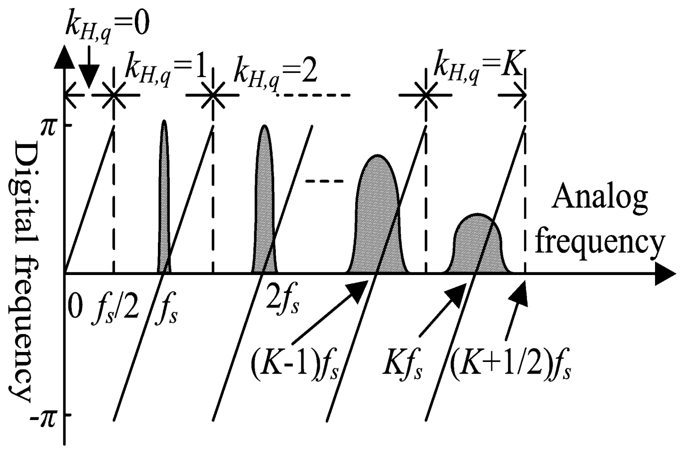

Figure 2. The distribution of $k_{H,q}$ and the spectrum of $p(t)$.

where $e^{j(2\pi f_s t+\theta(t)+\varphi_0)}$ is the continuous wave frequency modulation, such as SFM; φ_0 is the initial phase, $\theta(t)$ is the modulation phase corresponding to $\varphi_0=0$, K is determined by the interception bandwidth B_I. The spectrum diagram of $p(t)$ is shown at the shaded area in Figure 2, where the vertical axis is the spectrum amplitude and the Figure is not marked. When K is fixed, the maximum interception bandwidth can be expressed as

$$B_I=(K+1/2)f_s \tag{3}$$

After mixing and filtering by LPF1, the output should be

$$s(t)=\sum_{q=0}^{Q-1} e^{j\left[\left(2\pi f_q-2\pi f_s k_{H,q}\right)t+\varphi_q-k_{H,q}\theta(t)-k\varphi_0\right]}\mu(t-qT_r) \tag{4}$$

where $k_{H,q}=round(\omega_q/2\pi f_s)$, $k_{H,q}\in\{0,1,\ldots,K\}$ is the Nyquist zone of sub-sampling and the distribution of $k_{H,q}$ is shown in Figure 2. Sample $s(t)$ can present as

$$s(n)=\sum_{q=0}^{Q-1} e^{j\left[\left(2\pi f_q-2\pi f_s k_{H,q}\right)nT_s-k_{H,q}\theta(n)+\varphi_q-k_{H,q}\varphi_0\right]}\mu(nT_s-qT_r) \tag{5}$$

where $T_s=1/f_s$ is the sampling interval. From (5), we know that the output of the qth sub-pulse is a wideband signal where the center frequency, bandwidth and initial phase are $f_q-f_s k_{H,q}$, $k_{H,q}B_\theta$ and $\varphi_q-k\varphi_0$ respectively. If the signal is just within one Nyquist zone, known by the Nyquist sampling theorem, the condition of sampling without aliasing is

$$k_{H,q}B_\theta \le KB_\theta=\left(\frac{B_I}{f_s}-\frac{1}{2}\right)B_\theta \le f_s \tag{6}$$

where B_I is the minimum of the bandwidths which satisfy (3) and are greater than the interception bandwidth. Equation 6 could be rewritten as

$$(2B_I-f_s)B_\theta \le 2f_s^2 \tag{7}$$

We can recover the signal without distortion when (7) is satisfied. For electronic reconnaissance, the interception frequency range is 18 GHz, and if the sampling rate is 2 GHz, we have $B_I=19$GHz according to Equation 3, then $B_\theta \le 222.2$ MHz from (7).

Situation of different Nyquist zone to get the same center frequency

The NYFR and SNYFR solve the problem that, the traditional sub-sampling could only sample one Nyquist per time. When the interception bandwidth is $(K+1/2)f_s$, there is one mixed signal $x(t)=A_1e^{j(2\pi f_1 t+\varphi_1)}+A_2e^{j(2\pi f_2 t+\varphi_2)}$ containing two frequencies, namely: $f_1=f_0+k_1f_s$ and $f_2=f_0+k_2f_s$, $-f_s/2<f_0<f_s/2$, $k_1,k_2\in\{0,1,\ldots,K\}$, where A_1 and A_2 are the amplitudes corresponding to f_1 and f_2, φ_1 and φ_2 are the initial phases corresponding to f_1 and f_2, respectively.

If there was an ADC that supports the spectrum as wide as $(K+1/2)f_s$ with sampling rate f_s, sample $x(t)$ with sub-sampling and the digital signal should be

$$\begin{aligned} s_1(n) &= A_1e^{j[(2\pi f_1-2\pi f_s k_1)nT_s+\varphi_1]} + A_2e^{j[(2\pi f_2-2\pi f_s k_2)nT_s+\varphi_2]} \\ &= A_1e^{j(2\pi f_0 nT_s+\varphi_1)} + A_2e^{j(2\pi f_0 nT_s+\varphi_2)} \end{aligned} \tag{8}$$

It was found that from (8), the two frequencies are both transformed into f_0, and there is no extra information to decide the original Nyquist zone, that is, we cannot estimate f_1 and f_2 from (8).

Corresponding to (8), the output signal of SNYFR is

$$\begin{aligned} s_2(n) &= A_1 e^{j[(2\pi f_1 - 2\pi f_s k_1)nT_s - k_1\theta(n) + \varphi_1 - k_1\varphi_0]} + A_2 e^{j[(2\pi f_2 - 2\pi f_s k_2)nT_s - k_2\theta(n) + \varphi_2 - k_2\varphi_0]} \\ &= A_1 e^{j[2\pi f_0 nT_s - k_1\theta(n) + \varphi_1 - k_1\varphi_0]} + A_2 e^{j[2\pi f_0 nT_s - k_2\theta(n) + \varphi_2 - k_2\varphi_0]} \end{aligned} \tag{9}$$

Equation 9 shows that the output signal of SNYFR is different from the one of sub-sampling. Compared with the latter, the former has extra wideband frequency modulations $e^{j[-k_1\theta(n) - k_1\varphi_0]}$ and $e^{j[-k_2\theta(n) - k_2\varphi_0]}$ on the corresponding frequency f_1 and f_2. These extra modulations contain information about the Nyquist zone, which could be estimated by the bandwidth as an example. If we know the zone information k_1 and k_2, we could reconstruct the sub-sampling signal from (9) to estimate the frequency f_0 and the corresponding amplitudes and initial phases using different zone. With the combination of k_1, k_2 and f_0, we can estimate the absolute frequency of the signal, namely, f_1 and f_2. In conclusion, the sampling range of sub-sampling is just one Nyquist zone, while SNYFR extend the range to the entire interception bandwidth. In addition, Equation 9 shows that there is no cross terms of different frequencies, therefore, the SNYFR is "linear" in nature and easy to the follow-up signal processing.

APPLICABILITY OF SNYFR FOR THE WIDE BAND RADAR SIGNAL

Besides FA, the common radar signals are phase shift keying (PSK), linear frequency modulation (LFM) and nonlinear LFM (NLFM), etc., and they can be modeled as wideband signals. Let $x(t)$ be the wideband radar signal, according to Fourier transform (FT) theory, we obtain

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi f t} df \tag{10}$$

where $X(f)$ is the FT of the signal $x(t)$.

Equation 10 shows that $x(t)$ consists of infinite frequency components. Then, according to the property of (9), the output should be

$$s(n) = \int_{-\infty}^{\infty} X(f - f_s k_f) e^{j[(2\pi f - 2\pi f_s k_f)nT_s - k_f\theta(n) - k_f\varphi_0]} df \tag{11}$$

where $k_f = round(f / f_s)$.

The Nyquist zone k_f is one parameter of the wideband signal $s(n)$ and could be estimated from $s(n)$. Since $\theta(n)$) and φ_0 are known in SNYFR, if we have estimated k_f by time-frequency distribution or other algorithms, we could remove the item of $e^{j[-k_f\theta(n) - k_f\varphi_0]}$ to get

$$s'(n) = \int_{-\infty}^{\infty} X(f - f_s k_f) e^{j[(2\pi f - 2\pi f_s k_f)nT_s]} df \tag{12}$$

The $X(f - f_s k_f)$ in $s'(n)$ is completely retained and the difference between $X(f - f_s k_f)$ and $X(f)$ is only the index of frequency decided by k_f when f_s is fixed. Since we have estimated k_f, we can fully recover the spectrum $X(f)$, that is, we can recover the wideband signal $x(t)$ from $X(f)$ where the phase, frequency and modulation parameters are not lost. In conclusion, SNYFR is suitable for wideband radar signal in principle, and the limitation is defined by (7).

ESTIMATION OF NYQUIST ZONE

Before the estimation of Nyquist zone, we assume that the signal has been detected with the relevant algorithm. After the detection, we could estimate the Nyquist zone.

As mentioned previously, the output of the qth sub-pulse is a wideband signal where the center frequency, bandwidth and initial phase are $f_q - f_s k_{H,q}$, $k_{H,q} B_\theta$ and $\varphi_q - k\varphi_0$ respectively. We could estimate the Nyquist zone using the time-frequency distribution (TFD) (Hao, 2006) by dividing the amplitude of the ridge of TFD and the amplitude corresponding to the bandwidth B_θ. However, when B_θ and $k_{H,q}$ are too small, the peaks and valleys of the TFD to estimate the amplitude would be close and not easy to be recognized; when the signal to

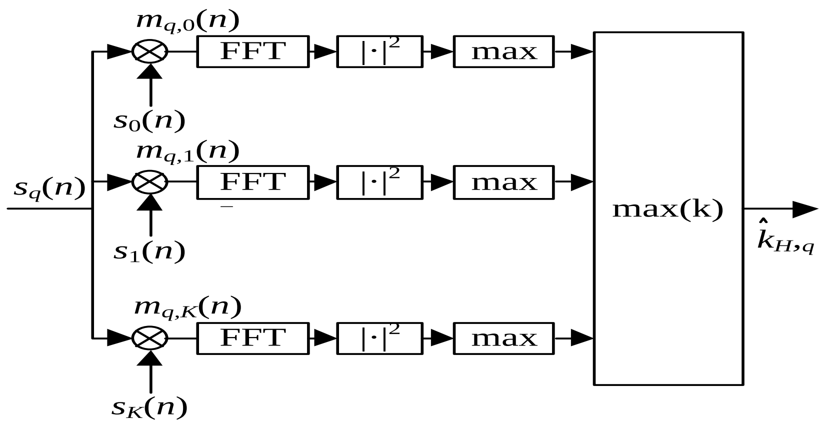

Figure 3. Estimator of $k_{H,q}$.

noise ratio (SNR) is low, the estimation of peaks and valleys would not be an easy work.

We have the synchronization between the DSP and DDS using $\varphi(n) = \theta(n) + \varphi_0$, then the synchronous LO group with the same amplitude and different bandwidth should be

$$s_k(n) = e^{-jk\varphi_n} = e^{-j[k\theta(n)+k\varphi_0]} \tag{13}$$

where $k \in \{0,1,\ldots,K\}$. Without loss of generality, we consider the output denoted as $s_q(n)$ of the qth sub-pulse,

$$s_q(n) = e^{j\left[\left(2\pi f_q - 2\pi f_s k_{H,q}\right)nT_s - k_{H,q}\theta(n) + \varphi_q - k_{H,q}\varphi_0\right]} \tag{14}$$

Then, $s_q(n)$ is multiplied by the conjugate $s_k(n)$, and we have

$$\begin{aligned} m_{q,k}(n) &= s_q(n)s_k^*(n) \\ &= e^{j\left[\left(2\pi f_q - 2\pi f_s k_{H,q}\right)nT_s - k_{H,q}\theta(n) + \varphi_q - k_{H,q}\varphi_0\right]} e^{j\left[k\theta(n)+k\varphi_0\right]} \end{aligned} \tag{15}$$

and

$$\begin{cases} m_{q,k_{H,q}}(n) = e^{j\left[\left(2\pi f_q - 2\pi f_s k_{H,q}\right)nT_s + \varphi_q\right]}, k = k_{H,q} \\ m_{q,k}(n) = e^{j\left[\left(2\pi f_q - 2\pi f_s k_{H,q}\right)nT_s + \varphi_q\right]} e^{j\left[\left(k-k_{H,q}\right)\theta(n) + \left(k-k_{H,q}\right)\varphi_0\right]}, k \neq k_{H,q} \end{cases} \tag{16}$$

Where $k = k_{H,q}$, $m_{q,k}(n)$ is a single tone whose carrier frequency is $f_{SNYFR} = f_q - f_s k_{H,q}$. While $k \neq k_{H,q}$, $m_{q,k}(n)$ is a wideband signal whose bandwidth is $\left|k - k_{H,q}\right| B_\theta$. We can perform the automatic modulation classification (AMC) on each $m_{q,k}(n)$ for different k (Zeng et al., 2010), and the output of AMC corresponding to $\hat{k}_{H,q}$ is monopulse. The algorithm of AMC is difficult, and we will find out an easy way. The FT could accumulate the energy with the same frequency, and if the signals have the same amplitudes and lengths, the maximum amplitude of FT of the signal whose bandwidth is the minimum would be the maximum. In conclusion, we could estimate the spectrum of $m_{q,k}(n)$ at first, and then get $\hat{k}_{H,q}$ by choosing the k whose maximum spectrum is the maximum. The architecture of the algorithm is shown in Figure 3.

The classical algorithm, such as maximum likelihood (ML) (Kay, 1993), for the estimation of the frequency denoted as $\hat{f}_{SNYFR}$ and the initial phase $\hat{\varphi}_q$ of (16) could be used after the estimation of $\hat{k}_{H,q}$, and the estimation of $\hat{f}_q$ is given by

$$\hat{f}_q = \hat{f}_{SNYFR} + f_s \hat{k}_{H,q} \tag{17}$$

PERFORMANCE ANALYSIS

Advantages of SNYFR over NYFR

The proposed SNYFR has advantages over NYFR in the following aspects: the structure of NYFR used the ZCR of SFM to control the shaping pulse to get the UWB LO;

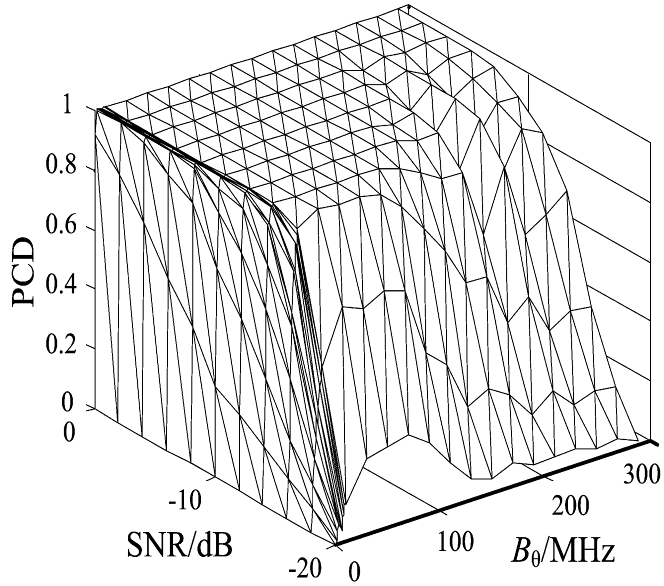

Figure 4. The PCD vs. SNR and B_θ.

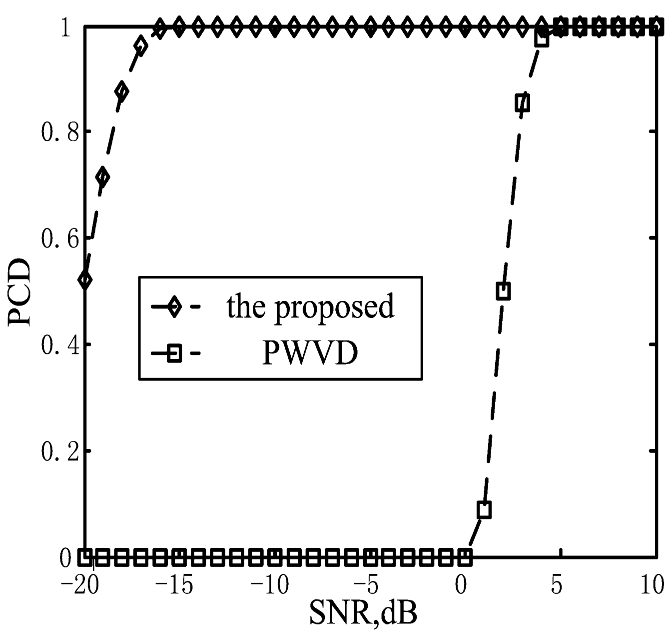

Figure 5. The PCD of zone versus SNR.

however, the theoretical analysis is too complex and there are lots of approximate equivalent; while, the expressing of SNYFR for LO showed in (2) is easy to understand, and the output expression in (5) is strictly equivalent. The detection of ZCR in NYFR by analog circuits is not an easy work, and the ZCR is sensitive to noise while the wideband modulation of SNYFR is controlled by the DAC which is not sensitive to noise. The LO and DSP of NYFR are not synchronous, and we cannot estimate the initial phase of the received signal, but when the SNYFR is synchronous, we can estimate the initial phase easily.

Simulations for the estimation of Nyquist zone

Simulations have been done to verify the performances of the estimation of Nyquist zone. The frequencies of the received signal are assumed to be 0.8, 1.3, 3.4, 5.6, 7.8GHz, 9.3, 11.5, 13.2, 15.7 and 17.4 GHz. The wideband modulation is SFM and the bandwidth range is from 0 to 300 MHz. The pulse width is 0.5 μs. The SNRs are from -20 to 10 dB, where the noise is Gaussian and white. Each signal was run 500 times. When the entire zones are estimated correctly, we just think the estimation is right and the performance is evaluated by the probability of correct decision (PCD). The results are shown in Figure 4. Figure 4 shows that, when the modulation bandwidth is 0, SNYFR is just the sub-sampling and we cannot distinguish the Nyquist zone, that is, the PCD is 0, in the absence of a prior. When the modulation bandwidth is less than 10 MHz, the PCD increases with the increase of bandwidth for fixed SNR. When the modulation bandwidth increases to 10 MHz or so, the PCD is stable. When the modulation bandwidth is greater than 222 MHz, modulation bandwidth is greater than the sampling rate, and then the condition determined by (7) cannot be satisfied, making the zone detection maybe wrong. In conclusion, the preferred bandwidth should be from 10 to 100 MHz, and the PCD would be greater than 90% when SNR is above -16 dB.

The performance comparison between the proposed and the way using pseudo Wigner Ville distribution (PWVD) is presented as $f_q = 10.4\text{GHz}$, $B_\theta = 100\text{MHz}$, $f_s = 2\text{GHz}$. Each signal was run 500 times. Figure 5 shows the PCD of zone versus SNR. When SNR is greater than -16 dB, the PCD of the proposed is above 90%, while the PWVD method needs 4 dB to achieve the same PCD. The proposed algorithm is much better than the one of PWVD, and the reason is that, PWVD does not use synchronization information, but the ridge in the time-frequency plane is sensitive to noise, while the proposed makes full use of the synchronization demodulation method to get better noise immunity.

CONCLUSIONS

Based on the structure of synchronous Nyquist folding receiver for the interception of frequency agile radar signal, the down-conversion of the received signal is realized with a wideband frequency modulated LO which contains the information of Nyquist zone, then, we adopt the synchronous demodulation to estimate the zone. As a result of the synchronization technology, SNYFR can estimate the initial phase of the received signal and improve the reliability of the structure NYFR whose UWB

LO is all implemented by analog circuits. Moreover, we show that this structure is also suitable for the wideband radar signal, indicating SNYFR can be applied to other kinds of radar signal. Simulation results show that when the SNR is greater than -16 dB, the probability of correct decision of Nyquist region is above 90%. SNYFR could realize the full interception with low complexity in theory.

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