FPGA-based Real-time Generator of Combination Chaotic Frequency-modulated Signal for Noise Radar

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Abstract— This paper proposes a design scheme for generating the Combination chaotic frequency-modulated (CCFM) signal for noise radar in real-time based on FPGA. The CCFM signal is real-time generated by instant calculation in FPGA, and it keeps good chaotic property even with short quantization length. The experiment demonstrates that the generated CCFM signal has very low sidelobe of auto-correlation and excellent orthogonality.

1. INTRODUCTION

Noise radars use random waveforms, which are of thumbtack ambiguity and efficient spectrum utilization, so they can improve the electronic counter-countermeasure (ECCM) capability and low probability of detection and intercept (LPD/LPI) characteristics [1–3].

As a kind of pseudo-noise signal, chaotic signal is generated from deterministic system. Compared with general noise signal, chaotic signal is easy to produce and control, also the cost is small [4]. However, some chaotic signal has high peak sidelobe ratio (PSLR) of auto-correlation function, which may result in weak targets being masked by surrounding strong scatter targets [5, 6].

Some papers have proposed a few methods to reduce sidelobe [7, 8], but they do not consider the feasibility of digital realization. The short quantization length will destroy the chaotic property of chaotic signal. In order to keep good chaotic property with limited quantization length, we propose to adopt the combination chaotic map for frequency-modulation, so as to obtain the combination chaotic frequency-modulated (CCFM) signal [9]. In this paper, we further propose a scheme to generate the CCFM signal in real-time based on FPGA.

The rest of the paper is organized as follows. In Section 2, we introduce the CCFM signal model. In Section 3, we present the real-time generation of CCFM signal based on FPGA. In Section 4, we conduct experiment to demonstrate the performance of generated CCFM signal. Finally in Section 5, we conclude the paper.

2. CCFM SIGNAL MODEL

The maximum period of one-dimensional chaotic map is limited by the quantization length. If the quantization length is M, then their repetition periods will not exceed 2^M. In order to keep the chaotic characteristic in case of short quantization length, we propose the combination chaotic map by embedding the Logistic map into Bernoulli map, i.e., the Logistic map is used to produce the parameters for Bernoulli map, and then Bernoulli maps under diverse parameters are combined to obtain the combination map sequence [9]. The form of combination map is shown as follows:

$$\begin{cases} x_{m+1} = u \cdot x_m \cdot (1 - x_m) & 0 < x_m < 1 \\ B_m = 1.4 + 0.6 \cdot x_m & 0 \le m \le M \\ y_{m,n+1} = g(y_{m,n}) = \begin{cases} B_m y_{m,n} + 0.5, & y_{m,n} < 0 \\ B_m y_{m,n} - 0.5, & y_{m,n} \ge 0 \end{cases} & 0 \le n \le N \\ \phi = \left\{ \{y_{0,0}, y_{0,1}, \ldots, y_{0,N}\}, \{y_{1,0}, y_{1,1} \ldots, y_{1,N}\}, \ldots, \{y_{M,0}, y_{M,1}, \ldots, y_{M,N}\} \right\} & \end{cases} \tag{1}$$

where $\{x_n\}$ is the Logistic sequence and its parameter should satisfy $3.569945 < u \le 4$. In view of the fact that the boundary of Logistic sequence is $0 < x_n < 1$, and the range of Bernoulli map parameter is $1.4 < B < 2$, one can let $B_m = 1.4 + 0.6 \cdot x_m$. Then the combination map is used for frequency-modulation to finally get the CCFM signal.

$$s(n) = A \exp\left\{ j2\pi \sum_{i=0}^{n} \phi_i \right\} \tag{2}$$

3. DESIGN OF THE FPGA-BASED REAL-TIME GENERATOR OF CCFM SIGNAL

The hardware is composed of FPGA, digital-to-analog converter (DAC), low-pass filter (LPF) and intermediate-frequency (IF) modulator. The FPGA generates the digital inphase and quadrature (I/Q) components of the baseband CCFM signal, the DAC converts the digital signal into analog signal, and the IF modulator transforms the I/Q components of baseband signal into IF signal.

The FPGA software includes four functional modules: 1) Trigger module produces the trigger signal, which determines the duration and interval of each pulse. 2) The logistic map module generates the parameters for Bernoulli map. The Logistic map is realized by multiplexer and adder. 3) The Bernoulli map module generates the combination map sequence by combining Bernoulli map sequences under diverse parameters. The Bernoulli map is also realized by multiplexer and adder. 4) The chaotic FM module generates the I/Q components of the CCFM signal. In view of the Sine and Cosine function are complicated in FPGA calculation, we use two lookup tables instead of direct calculation, one is for Cosine function and the other is for Sine function. The lookup table is stored in the ROM.

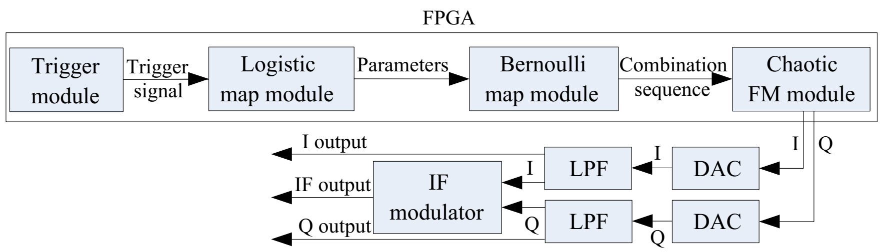

Figure 1: Block diagram of the FPGA-based real-time generator of CCFM signal.

4. EXPERIMENT RESULTS

In the experiment, we generate 20 pulses of CCFM signal corresponding to different initial values, and the signal parameters are listed in Table 1. Then the I/Q waveforms are sampled and restored by Tektronix MSO70404 oscilloscope with 8 bit sampling accuracy and 125 MHz sampling rate. The sampled waveforms are shown in Fig. 2.

Auto-correlation function (ACF) can describe the range resolution of a radar signal [10] and low sidelobe of ACF is preferred because it helps to avoid weak targets being masked by around strong targets. The ACF of sampled CCFM signal is shown in Fig. 3, where the peak-sidelobe-ratio (PSLR) is -22.72 dB.

When two or more radar systems operate at the same frequency band simultaneously, then mutual inference is usually unavoidable if without taking some specific measure. The orthogonality of signals is a good measure for anti-mutual inference capability [11], and better orthogonality means less mutual inference. The orthogonality can be described by the cross-correlation coefficient

Table 1: Parameters of generated CCFM signal.

Duration	Interval	Bandwidth	Quantization length
10 µs	5 µs	62.5 MHz	16 bit

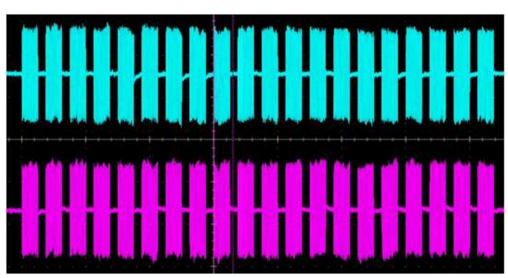

Figure 2: The I/Q components of sampled CCFM signal, where the upper is the inphase component, and the lower is the quadrature component.

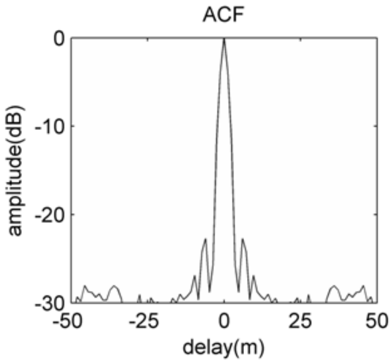

Figure 3: The ACF of sampled CCFM signal.

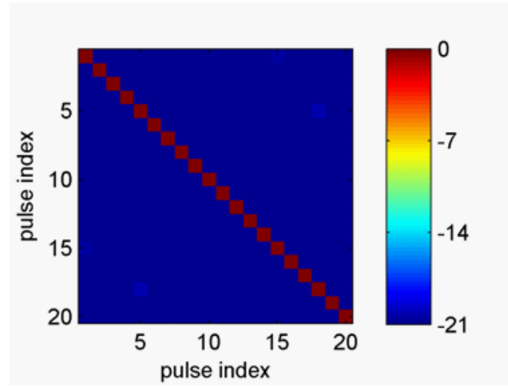

Figure 4: The cross-correlation coefficient of sampled CCFM signal.

between signals. The cross-correlation coefficients of sampled CCFM signals are presented in Fig. 4. The diagonal line is the auto-cross coefficients,which are normalized to 0 dB. The off diagonal line values are cross-correlation coefficients, and the maximum of them is −20.24 dB. The excellent orthogonality of the generated CCFM is demonstrated.

5. CONCLUSION

This paper proposes a design scheme for real-time generation of the CCFM signal for noise radar based on FPGA. The realized CCFM signals are of good chaotic property even with short quantization length. The combination map is generated by embedding the Logistic map into Bernoulli map, i.e., Logistic map produces the parameters for Bernoulli map, and then Bernoulli sequence under diverse parameters are combined to obtain the combination map sequence.

In the generator, the CCFM signal is generated by instant calculation iteratively in FPGA, so it does not need large memory space to store the whole waveform, and it is suit for generating long time signals. The experiment demonstrates that the generated CCFM signal has low sidelobe of auto-correlation and excellent orthogonality.

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