Radar hybrid signal generators based on high-speed digital-to-analog converters

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Abstract. Wideband frequency synthesizers are used in many different applications, such as radars, telecommunications and others. Radar parameters are dependent on the synthesizers phase noise. A general flow-chart of a hybrid frequency synthesizer based on direct digital and direct analog synthesis methods that uses a high-speed digital-to-analog converter (DAC) in special operating modes to increase the operating frequency is presented in this paper. The noise characteristics of a hybrid synthesizer with a DAC operating in two modes are simulated.

1. Introduction

Synthesizers of the direct digital synthesis — direct digital synthesizers (DDS) are used as generators of harmonic signals of radar stations [1–5]. The advantages of these synthesizers are high speed frequency tuning and small step of frequency tuning, good phase noise level, and support for various types of modulation. Also direct digital synthesizers have some disadvantages, namely: relatively low output frequencies, a significant number of discrete side components of the spectrum.

The hybrid method of frequency synthesis (based on combinations of several synthesis methods) allows combining the advantages and reducing the impact of the disadvantages of other synthesis methods. In radio systems where high spectral purity is required from signal generators (for example, in control and measuring equipment), hybrid synthesizers based on direct digital and indirect methods of frequency synthesis are usually used [6, 7]. In radar stations and telecommunications systems, where the main requirement for shapers is a high speed of tuning, hybrid synthesizers based on direct analog and direct digital synthesis methods are often used. At the same time, the signal generator of any radio system must have a low level of phase noise, since this directly affects the main tactical and technical characteristics of the radio system: sensitivity, range, noise immunity.

The purpose of this work is research of methods for improving the spectral and noise characteristics of hybrid frequency synthesizers based on direct analog and direct digital synthesis methods when using them as radar signal generators.

2. Special operating modes of high-speed digital-to-analog converters

Frequency multipliers are used to increase the output frequency of direct digital synthesizers, but the use of multipliers leads to an increasing of the phase noise level and discrete side spectrum components. Another way to increase the output frequency of the DAC is to use copies of the spectrum of the output signal of the DAC — images of the fundamental frequency. The disadvantage of using images is their relatively low amplitude, which decreases with increasing image number. It is proposed in the
literature [8–11] to use a digital-to-analog converter (DAC) in special operating modes for increasing the amplitude of images. DAC is the main part of a direct digital synthesizer. The modes of operation of high-speed DACs are distinguished:

1. Normal operation (non-return-to-zero — NRZ). The image with the maximum level is located in the first Nyquist zone. The amplitudes of images with higher numbers decrease with increasing Nyquist zones according to the sin(x)/x law.

2. 2xNRZ — mode. DAC works at twice the clock speed if new data samples are recorded in the DAC core on both the leading and trailing edges.

3. Return-to-zero (RZ) mode. In this mode, the duration of the clock pulses decreases. A feature of the RZ mode is an increase in the amplitude of the image with the number \( n = -1 \) in the second Nyquist zone.

4. Radio frequency mode (RF). Each clock pulse of the NRZ mode is represented by two different-polar pulses of duration \( \tau = T/2 \). The images with the maximum amplitude are located in the second and third Nyquist zones.

5. RFZ mode (radio frequency return-to-zero mode). The duration of the multipolar pulses of the RF mode decreases with respect to the moment \( t = 0 \).

6. The mode, conventionally called RFZ2. The duration of the multipolar pulses, as well as in the RFZ mode, is \( \tau < T/2 \), however, the change in their duration is carried out relative to the moments of time \( t = 0 \) and \( t = T/2 \).

According to the research results, the use of high-speed DACs in special operating modes allows increasing the amplitude of images by 6-8 dB. Thanks to it, you don’t need to use multi-stage amplifiers that introduce additional phase noise.

3. Block diagram of a hybrid frequency synthesizer based on high-speed digital-to-analog converters

The principle of operation of hybrid synthesizers based on direct analog and direct digital synthesis methods is that the frequency grid with a small tuning step generated by the DDS is transferred to a higher frequency range by mixing with the frequency of the signal formed by an additional reference frequency generator (Ref). However, in many areas of radio engineering, the use of a single Ref is relevant in order to ensure the coherence of the phases of the reference and output signals. The generalized block diagram of a hybrid synthesizer based on direct analog and direct digital synthesis methods is presented in the figure 1.

![Figure 1. Generalized block diagram of a hybrid synthesizer](image-url)
fundamental frequency of the DDS $f_{DDS}$. At the output of the mixer, there is a signal with the values of the sum and difference of the input frequencies. Bandpass filter (BPF) transmits the required frequency $f_{out}$. The range of the output frequency in this case is determined by the range of the output frequency of the DDS and the filter elements, because, it is more difficult to separate the total frequency from the difference frequency at the mixer output if the DDS transmission coefficient ($k_{DDS} = f_{DDS} / f_{ref}$) is very small.

Multipliers and frequency dividers with variable transmission coefficients are used to increase the range of the output frequency of a hybrid synthesizer. In [10] it is proposed to use a harmonic generator based on a diode with charge accumulation as a multiplier. The use of such generator will significantly increase the tuning range (up to several octaves), while maintaining a high frequency resolution. However, the use of frequency multipliers requires a large number of high-order filters to suppress discrete spectrum components. In this paper, it is proposed to use a digital code generator (DCG) and a high-speed digital-to-analog converter (DAC) in hybrid synthesizers instead of direct digital synthesizers.

A generalized block diagram of a hybrid synthesizer based on a DAC in special operating modes is shown in figure 2.

![Figure 2. Generalized block diagram of a hybrid synthesizer based on high-speed digital-to-analog converters](image)

The diagram in figure 2 differs from the previous one. A high-speed digital-to-analog converter (DAC) is used instead of the DAC. Special digital code from the digital code generator (DCG) is fed to the input of the DAC. The required special DAC operation mode is implemented depending on the digital code.

We will conduct a study of the noise characteristics of the presented scheme. The mathematical model of the power spectral density (PSD) of the phase noise [11–14] of a hybrid synthesizer is:

$$S_{HS}(F) = S_{DAC}(F) + S_{Ref}(F)K_{DAC}^2 + S_{Mix}(F) + S_{BPF}(F),$$

where $S_{DAC}(F)$, $S_{Ref}(F)$, $S_{Mix}(F)$, $S_{BPF}(F)$ — the phase noise mathematical models of a high-speed DAC, a reference frequency generator, a mixer, and filter elements, respectively; $K_{DAC} = f_{out} / f_{ref}$ — the DAC transmission coefficient (similar to the DDS transmission coefficient in (1)).

We will conduct a simulation of the phase noise PSD of a hybrid synthesizer when the DAC operates in two modes: NRZ and 2xNRZ. The initial parameters of the synthesizer for modeling: reference frequency $f_{ref} = 1$ GHz, output frequencies $f_{out1} = 1100$ MHz, $f_{out2} = 1400$ MHz. The results of simulation are presented in the figure 3.
The simulation results showed that the use of a special 2xNRZ operating mode makes it possible to significantly reduce the level of phase noise PSD at frequencies offset from the carrier frequency above 1 kHz (by 5–7 dB).

4. Conclusion
This paper describes the possibility of using special operating modes of high-speed digital-to-analog converters in hybrid frequency synthesizers based on direct analog and direct digital methods of frequency synthesis.

The simulation results showed that the use of a special 2xNRZ mode of operation allows for carrier detuning frequencies above 1 kHz to 5–7 dB reduce the level of phase noise PSD. In this regard, it is relevant to conduct comprehensive research on the development of a universal block diagram of a hybrid synthesizer based on high-speed DACs and the development of an algorithm for selecting the optimal mode based on the specified requirements for the synthesizer frequency band, its noise and spectral characteristics.

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References
[1] Kroupa V 1999 Direct Digital Frequency Synthesizers (New York: IEEE Press)
[2] Technical Tutorial on Digital Signal Synthesis 1999 Analog Devices, Inc.
[3] Vankka J 2000 Direct Digital Synthesizers: Theory, Design and Applications (Helsinki: Helsinki University of Technology)
[4] Chenakin A 2010 Frequency Synthesizers: From Concept to Product (New York: Artech House)
[5] Goldberg B-G 1999 Digital Frequency Synthesis Demystified DDS and Fractional-N PLLs (Eagle Rock, VA: LLH Technology Publishing)
[6] Sam B 1999 Applied Microwave & Wireless 76–84
[7] Romashov V, Romashova L, Yakimenko K and Doktorov A 2020 Journal of Physics:
[8] Romashov V, Doktorov A, Yakimenko K and Sochneva N 2020 Journal of Physics: Conference Series 1632 1–5
[9] Laperle C and O’Sullivan M 2014 Journal of Lightwave Technology 32 629-43
[10] Yoffe Y, Wohlgemuth E and Sadot D 2020 Journal of Lightwave Technology 38 3096-105
[11] Leeson D 1966 Proc. IEEE 54 329-30
[12] Rubiola E 2010 Phase Noise and Frequency Stability in Oscillators (Cambridge: Cambridge University Press)
[13] Kroupa V 2003 Phase Lock Loops and Frequency Synthesis (Chichester: John Wiley & Sons)
[14] Drucker E 1999 Microwaves & RF 1 69–84