Low-noise hybrid frequency synthesizers for 5G technology

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Abstract. This paper presents the results of structural design and analysis of the noise characteristics of a low-noise hybrid frequency synthesizer based on direct digital and indirect synthesis methods for using as a shaper of harmonic signals for fifth generation telecommunication systems transceivers. The hybrid synthesizer is based on a phase-locked loop (PLL) with DDS operating on fundamental frequency images. Due to this, the hybrid synthesizer generates a wide range of output frequencies with high frequency resolution, as well as a low level of phase noise and discrete side components of the spectrum of the output signal.

1. Introduction

The increasing trend of informatization of contemporary society leads to increased demand for access to uninterrupted mobile communications and high-speed Internet. The current fourth-generation mobile networks (LTE) already in many respects do not satisfy all the needs for high-quality communication indicators. In this regard, the concept of the transition to the fifth generation mobile communication technology (5G) was formulated. The main advantages of 5G technology in comparison with technologies of previous generations are improved quality of mobile communications, high data transfer speed (over 1 Gb/s), reduced delay time (up to 1 ms), increased number of simultaneous connections to the base station (up to 1 million per 1 km²) [1].

Currently, the works of implementation 5G systems are actively conducted in the physical layer. To achieve the parameters specified in the 5G concept, it is planned to use specialized multi-element digital antenna arrays Massive MIMO as part of the base stations, as well as to apply digital modulation technology OFDM with a channel width of 100 MHz [2]. However, since all modulation systems based on frequency compression are extremely sensitive to phase fluctuations of the signal, in order to increase the spectral efficiency of this type of modulation, it is necessary to reduce the level of intrinsic phase noise of the harmonic signal generator of the base station, which is a frequency synthesizer. A frequency synthesizer is an essential element of any radio system, forming a series of periodic signals in a given frequency range with a fixed frequency tuning step. The tactical and technical characteristics of the radio system as a whole largely depend on the own parameters and characteristics of the synthesizer.

Most of the benefits of 5G technology are achieved through the use of a very wide frequency band (up to 1 GHz). For the development of 5G, the Federal Communications Commission (FCC) preliminary allocated a bandwidth 3.85 GHz for licensed use in the range 28 GHz (27.5–28.35 GHz), 37 GHz (37–38.6 GHz), 39 GHz (38.6–40 GHz). It should be noted that the final frequency ranges will be approved at the international conference WRC-19. Nevertheless, it seems currently relevant to
conduct a research on the possibility of forming harmonic signals in given frequency ranges with a low level of intrinsic phase noise.

The aim of this work is to develop a hybrid frequency synthesizer architecture based on direct digital and indirect methods that generates a harmonic signal in a wide frequency band with a reduced level of phase noise for 5G technology.

2. Architecture and phase noise of hybrid frequency synthesizers based on direct digital and indirect synthesis methods

The generalized structural diagram of the frequency synthesizer is shown in figure 1. The reference-frequency generator REF generates a signal with a frequency \( f_{\text{REF}} \), which is a clock for the frequency synthesizer FS. The synthesizer itself, in turn, generates a signal with a frequency \( f_{\text{OUT}} \) belonging to the frequency range from \( f_{\text{OUT}_{\text{min}}} \) to \( f_{\text{OUT}_{\text{max}}} \) with a tuning step \( \Delta f \). The frequency spectrum of the output signal of the synthesizer is shown in figure 1 (b).

![Figure 1](image)

**Figure 1.** Block diagram (a), spectrum (b) and power spectral density of phase noise (c) of the frequency synthesizer

The phase noise level of the output signal of the frequency synthesizers is estimated by power spectral density (PSD) \( L(F) \) of the phase noise in a single sideband depending on an offset frequency \( F \) from the carrier frequency. Figure 1 (c) shows a graph of the distribution of the phase noise PSD of the output signal of the frequency synthesizer near the carrier frequency.

At present, two methods of frequency synthesis are the most common: direct and indirect. The output of the synthesizers of the direct synthesis method is obtained from the reference signal by addition, multiplication, mixing or division. However, such shortcomings as complexity of architecture and high energy consumption, significantly limit the use of direct synthesis method synthesizers in modern radio systems. The development of digital circuitry has led to the isolation and active dissemination of direct digital synthesizers (DDS) [3]. The advantages of DDS include high frequency resolution, the possibility of various types of modulation. However, DDS is characterized by disadvantages typical for any digital system: the need for clocking with a signal with a frequency of at least twice as high as the required output frequency, as well as the spectrum of the output signal contaminated with discrete spurs.

Synthesizers of the indirect synthesis method are based on phase-locked loop (PLL) systems [4]. The output of these synthesizers is generated by a voltage controlled oscillator (VCO). The phase-frequency detector (PFD) compares the phase of the reference signal with the phase of the output and, in case of a mismatch, adjusts the frequency of the output signal of the voltage-controlled generator. The advantages of indirect synthesizers include a wide range of output frequencies and a small number of discrete side components of the spectrum of the output signal.
Currently, hybrid frequency synthesizers are actively used in the form of combinations of synthesizer elements of other synthesis methods. Synthesizers based on direct digital and indirect methods of frequency synthesis are the most promising. Such synthesizers provide a low level of phase noise and discrete side components of the spectrum of the output signal, and are also able to form a wide frequency range with a small tuning step. Figure 2 (a) – (c) shows the structural diagrams of the main types of hybrid frequency synthesizers based on direct digital and indirect synthesis methods [5, 6]. In fact, these circuits differ in the location of the DDS in the PLL system structure. The following notation is introduced in figure 2: REF – reference frequency generator, DIV – frequency divider, PFD – phase-frequency detector, VCO – voltage-controlled generator, MIX – frequency mixer.

![Diagram of Hybrid Frequency Synthesizers](image)

**Figure 2.** Block diagrams of hybrid frequency synthesizers (a)–(c) and a comparison of their phase noise level at $f_{OUT} = 3$ GHz (d): 1 – a hybrid synthesizer (a), 2 – a hybrid synthesizer (b), 3 – a hybrid synthesizer (c).

In accordance with the theory of radio automation, the PSD level of phase noise of PLL-based synthesizers is directly proportional to the square of the division coefficient $N$ in the feedback loop. Therefore, to reduce the phase noise level, it is necessary to reduce the value of the division coefficient in the feedback loop. Figure 2 (d) presents the dependences of the phase noise PSD of hybrid synthesizers at $f_{OUT} = 3$ GHz. It can be seen that the hybrid synthesizer with offset frequency generated by a DDS has the lowest phase noise level, since the division coefficient in this case is the smallest. Thus, to minimize the phase noise level of hybrid frequency synthesizers, it is necessary to achieve the lowest value of the division coefficient in the feedback loop.

### 3. Hybrid synthesizer with reduced phase noise

To achieve the smallest value of the division coefficient in the feedback loop of a hybrid frequency synthesizer, the output frequency of the DDS may be increased. However, the use of frequency multipliers for this is impractical, since it leads to a significant increase in phase noise and an increase in energy consumption. To increase the DDS output frequency, the authors of [6] propose using copies...
of the spectrum – images of the DDS fundamental frequency that appear in the spectrum as a result of digital-to-analog sinusoid conversion. The distribution of patterns in the DDS spectrum is shown schematically in figure 2 (a).

\[
\begin{align*}
    f_{DDS} &= f_{REF} \\
    f_{REF} &= f_{REF} \\
    2f_{REF} &= f_{REF}
\end{align*}
\]

Figure 2. Distribution of patterns in the spectrum of the DDS output signal (a) and block diagram of a hybrid synthesizer using DDS fundamental frequency images (b)

The frequencies of the DDS images are determined by the formula

\[
f_{IMG} = f_{REF} \left( |K_{DDS} + n| \right),
\]

where \(K_{DDS} = f_{DDS} / f_{REF} –\) DDS transmission coefficient, \(f_{DDS}\) – main output frequency of DDS; \(n = \pm 1, \pm 2, \ldots\) image number.

The DDS tuning step when working on images is equivalent to the DDS tuning step when working on the main frequency and is

\[
\Delta f_{DDS} = f_{REF} / 2^{NPA},
\]

where \(NPA\) – length of the DDS phase accumulator.

The amplitude of the images changes with increasing frequency in accordance with the law \(\sin(x)/x\). To select the desired image, it is necessary to use a band-pass filter BF, the amplitude of the image, if necessary, can be amplified using a power amplifier. The block diagram of a hybrid synthesizer using DDS fundamental frequency images is shown in figure 2 (b). The output frequency of the hybrid synthesizer, taking into account (1), is defined as

\[
f_{OUT} = N \cdot f_{REF} \cdot \left( |K_{DDS} + n| + 1/R \right).
\]

Define the main frequency relationships in the structure of the hybrid synthesizer to form the frequency ranges required for 5G technology. As a reference frequency generator, it is necessary to use a generator with a resonator on surface acoustic waves (SAW). Such generators form a signal with a high frequency (up to 4 GHz) and due to the high Q factor of the resonator have a low level of intrinsic phase noise. The main frequency relationships in the reference path will be: reference frequency \(f_{REF} = 3.5 \text{ GHz}\), the comparison frequency in PFD \(f_{PFD} = 350 \text{ MHz}\), the division ratio \(R = 10\).

To ensure good filtering of the desired image, the transmission coefficient \(K_{DDS}\) is limited to values from 0.15 to 0.35. Thus, when using the first positive image (\(n = 1\)) taking into account (1), the DDS will generate frequencies \(f_{IMG} = 4025 \ldots 4725 \text{ MHz}\) with a tuning step \(\Delta f_{DDS} = 0.81 \text{ Hz}\) (at \(NPA = 32\)). In accordance with expression (3), when using a DIV divider with a division ratio of \(N = 6\), the hybrid synthesizer will form the frequency range \(f_{OUT} = 26.25 \ldots 30.45 \text{ GHz}\) with a tuning step...
not exceeding 10 Hz. Thus, the presented hybrid synthesizer is capable of generating a harmonic signal in the frequency ranges used in 5G technologies with a small frequency tuning step.

4. Analysis of the noise characteristics of hybrid synthesizers

To analyze the noise characteristics of hybrid frequency synthesizers, mathematical models of the phase noise PSD of synthesizers based on the Leeson model in the form of power polynomials will be used [4, 5, 7]. The mathematical model of the phase noise PSD of the synthesizer shown in figure 2 (b) has the form:

\[
L_{\text{HFS}}(F) = \left[ \frac{L_{\text{REF}}(F)}{R^2} + L_{\text{PFD}}(F) + L_{\text{LoopFilter}}(F) + L_{\text{MIX}}(F) + L_{\text{OFFSET}}(F) \right] \cdot |H_1(j2\pi F)|^2 + \nonumber
\]

\[+L_{\text{VCO}}(F) \cdot |H_2(j2\pi F)|^2, \tag{4}\]

where \( L_{\text{REF}}(F), L_{\text{PFD}}(F), L_{\text{LoopFilter}}(F), L_{\text{MIX}}(F), L_{\text{VCO}}(F) \) – mathematical models of the phase noise PSD of the corresponding blocks of the hybrid synthesizer; \( L_{\text{OFFSET}}(F) \) – contribution to the resulting level of phase noise of DDS operating on images of the fundamental frequency:

\[
L_{\text{OFFSET}}(F) = L_{\text{REF}}(F) \cdot n + K_{\text{DDS}} \nonumber
\]

\[+L_{\text{DDS img}}(F), \tag{5}\]

where \( L_{\text{DDS img}}(F) \) – mathematical model of the phase noise of DDS operating on images of the fundamental frequency.

Formulas for defining transfer functions for expression (4):

\[
H_1(j2\pi F) = \frac{H_1(j2\pi F) \cdot N}{1 + H_3(j2\pi F)} \quad \text{PLL external noise transfer function;}
\]

\[
H_2(j2\pi F) = \left(1 + H_3(j2\pi F)\right)^{-1} \quad \text{PLL internal noise transfer function;}
\]

\[
H_3(j2\pi F) = \frac{F_{\text{LoopFilter}}(j2\pi F) \cdot s_{\text{PFD}} \cdot s_{\text{VCO}}}{j2\pi F \cdot N} \quad \text{PLL open loop transfer function;}
\]

\[
F_{\text{LoopFilter}}(j2\pi F) \quad \text{transfer characteristic of the loop filter LPF; } s_{\text{PFD}} \quad \text{slope of discrimination curve PFD; } s_{\text{VCO}} \quad \text{slope of regulation curve VCO; } j = \sqrt{-1}.
\]

According to expression (4), mathematical modeling of the spectral power density of phase noise of a hybrid frequency synthesizer was carried out for the output frequency \( f_{\text{OUT}} = 28 \text{ GHz} \). Figure 4 (a) shows the noise contributions of the hybrid synthesizer blocks to the resulting PSD level of phase noise. Figure 4 (b) shows the results of comparing the PSD of the phase noise of a hybrid synthesizer with the noise characteristics of the signal conditioners from [8, 9].

5. Conclusion

This paper presents a variant of a hybrid frequency synthesizer based on direct digital and indirect synthesis methods. Thanks to the use of a phase-locked loop, the hybrid synthesizer has practically no discrete side components of the output signal spectrum. DDS provides high frequency resolution. The hybrid synthesizer generates frequency ranges from 26.25 to 30.45 GHz and from 35 to 40.6 GHz with a tuning step not exceeding 10 Hz. The use of DDS fundamental frequency images makes it possible to reduce the division coefficient in the PLL feedback loop, which leads to a significant decrease in the level of intrinsic phase noise. With \( f_{\text{OUT}} = 28 \text{ GHz} \), the hybrid synthesizer provides a PSD level of phase noise \( L = -109 \text{ dBC / Hz} \) (at a detuning frequency of 100 kHz) and has a gain in phase noise in front of synthesizers oriented to use in 5G technology.
Figure 4. Contributions of hybrid synthesizer blocks to the resulting phase noise level (a) and comparison of synthesizer noise characteristics (b) at $f_{\text{OUT}} = 28$ GHz.

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