A Novel Three-Point Modulation Technique for Fractional-*N* Frequency Synthesizer Applications

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Abstract. *This paper presents a novel three-point modulation technique for fractional-N frequency synthesizer applications. Convention modulated fractional-N frequency synthesizers suffer from quantization noise, which degrades not only the phase noise performance but also the modulation quality. To solve this problem, this work proposes a three-point modulation technique, which not only cancels the quantization noise, but also markedly boosts the channel switching speed. Measurements reveal that the implemented 2.4 ~ 2.6 GHz fractional-N frequency synthesizer using three-point modulation can achieve a 2.5 Mbps GFSK data rate with an FSK error rate of only 1.4 %. The phase noise is approximately -98 dBc/Hz at a frequency offset of 100 kHz. The channel switching time is only 1.1 μs with a frequency step of 80 MHz. Comparing with conventional two-point modulation, the proposed three-point modulation greatly improves the FSK error rate, phase noise and channel switching time by about 10 %, 30 dB and 126 μs, respectively.*

Keywords

Fractional-*N* frequency synthesizer, delta-sigma, three-point modulation, phase-locked loop, GFSK.

1. Introduction

In recent years, wireless technologies have been developed to eliminate the need for wire-links between consumer products, such as computers, digital cameras, video cameras and digital TVs. For such applications, low power consumption, high integration, high efficiency and a moderate system throughput are always the dominant design considerations [1]. Numerous modulator architectures are utilized to satisfy these requirements.

Although quadrature modulation is the most popular method of constant envelope modulation, some more attractive approaches are available [2]. Since constant envelope modulations, such as GMSK and GFSK, contain baseband information in the frequency or phase of the carrier signal, a frequency synthesizer can be utilized to modulate the signal directly without the use of mixers. Based on this idea, an offset phase-locked loop (OPLL) modulation technique was developed [3], [4]. The baseband signal modulates the reference signal of an OPLL-based synthesizer for up-conversion. The synthesizer acts as a low-pass filter to filter out the image signals and spurious noise. Therefore, the RF band-pass filter at the output can be eliminated, not only reducing the cost of implementation, but also making the system more integrable. The main drawback of this architecture is that it utilizes two RF voltage-controlled oscillators (VCO) and consequently consumes more power than the single-VCO architecture. Moreover, the loop bandwidth limits the data rate of OPLL modulation.

To solve the problem of the high power consumed OPLL modulation, a closed-loop modulation technique is developed [5], [6]. This architecture utilizes a delta-sigma modulation (DSM) based fractional-*N* frequency synthesizer to provide sufficiently high frequency resolution that the baseband signals can directly modulate the synthesizer. However, the data rate is limited by the loop bandwidth in a similar way to the OPLL modulation. To increase the data rate, a two-point modulation technique was developed [7], [8]. The two-point modulation has one more modulation point than the closed-loop modulation. This modulation point is at the VCO of the fractional-*N* frequency synthesizer. Since a VCO is inherently a frequency or phase modulator, it can be modulated directly [9]. Accordingly, the modulated frequency synthesizer ceases to be a closed loop for the baseband signal, and consequently it has an unlimited modulation bandwidth. Such two-point modulated synthesizers have been widely adopted in GSM, DECT, and Bluetooth applications [7], [8].

The main problem of the two-point modulated fractional-*N* frequency synthesizer is suppression of the quantization noise [7], [8]. Since a first-order DSM results in many fractional spurs in the output spectrum, a higher-order DSM is utilized in a two-point modulated fractional-*N* frequency synthesizer. Although a higher-order DSM consumes more power, it can randomize the quantization noise and push it to a higher offset frequency [10]-[13].

The loop bandwidth of the synthesizer must be small enough to suppress effectively this shaped quantization noise. However, a lower loop bandwidth results in a slower channel switching speed and a higher in-band phase noise [14]. Fig. 1 presents suppression of the quantization noise and the locking process of a two-point modulated fractional-*N* frequency synthesizer. Both of the channel switching speed and the DSM quantization noise increase with the loop bandwidth. The increased DSM quantization noise substantially degrades the modulation quality. This tradeoff makes the conventional two-point modulated fractional-*N* frequency synthesizer difficult to optimize for wireless systems. This paper proposes a novel three-point modulation technique to solve this problem.

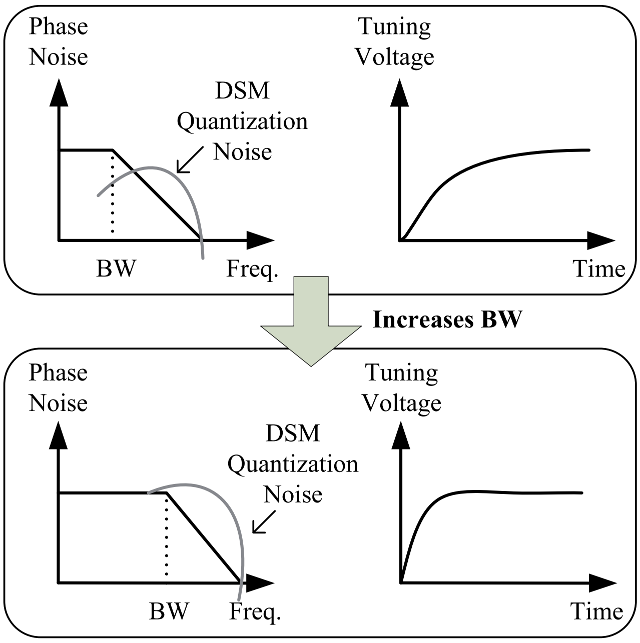


Fig. 1. Phase noise suppression and locking process of two-point modulated fractional-*N* frequency synthesizer.

2. Proposed Architecture

Fig. 2 shows the proposed fractional-*N* frequency synthesizer using three-point modulation. The third modulation point that is not present in conventional two-point modulation is at the end of the loop filter (LPF) of the synthesizer. The quantization noise is extracted from the modified first-order DSM. Both the channel selection information and the extracted quantization noise are then injected into the fractional-*N* frequency synthesizer via the third modulation point. Therefore, both the frequency switching speed and the phase noise of the synthesizer can be improved. In contrast with a traditional three-point modulation technique that only uses phase-interpolation in a fractional-*N* synthesizer to reduce quantization noise [15], the proposed synthesizer resembles a traditional three-point modulated synthesizer except that its frequency switching speed is also greatly boosted while cancelling the quantization noise.

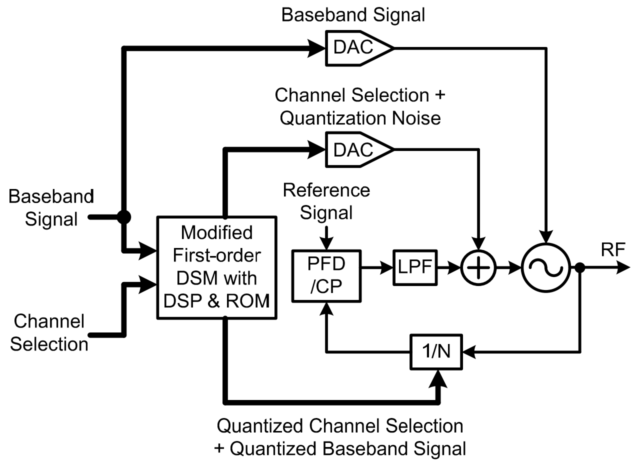


Fig. 2. Modulated fractional-*N* frequency synthesizer using three-point modulation.

In the proposed architecture, the DSM is the core of the three-point modulation because the signal that is applied to the third modulation point originates from the DSM. Accordingly, a conventional DSM should be modified to provide additional signal to the third modulation point. Fig. 3 shows a modified first-order DSM as an example; the quantization output can be derived as

$$M_1[n] = .f[n] + d[n] + \left(1 - Z^{-1}\right) Q_e[n] \qquad (1)$$

where $.f\,[n]$ denotes channel selection information; $d[n]$ denotes the baseband signal; $Q_e[n]$ denotes the original quantization noise of the DSM, and $(1 - Z^{-1})Q_e[n]$ denotes the shaped quantization noise of the DSM. The extracted quantization noise can then be derived as

$$M_{1\_e}[n] = \left(1 - Z^{-1}\right) Q_e[n]\,, \qquad (2)$$

which is exactly the quantization noise of the DSM. For an m^{th}-order DSM, equations (1) and (2) can be modified as

$$M_m[n] = .f[n] + d[n] + \left(1 - Z^{-1}\right)^m Q_e[n], \qquad (3)$$

and

$$M_{m\_e}[n] = \left(1 - Z^{-1}\right)^m Q_e[n]\,, \qquad (4)$$

respectively. These output signals are injected into the frac-

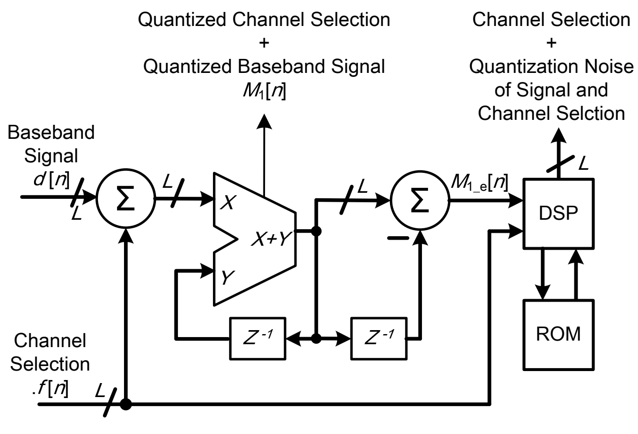


Fig. 3. Modified first-order DSM for three-point modulation.

tional-N frequency via three modulation points. The first modulation point is the divider of the synthesizer. The quantization output $M_m[n]$ is injected into the fractional-N frequency synthesizer by controlling the modulus of the divider. The second modulation point is the VCO of the synthesizer. The baseband signal $d[n]$ is converted from digital to analog and then injected into the synthesizer by directly modulating the VCO. The third modulation point is the LPF of the synthesizer. The extracted quantization noise $M_{m\_e}[n]$ is processed using the digital signal processor (DSP) and a read-only memory (ROM). The DSP not only inverts the phase of the quantization noise but also adjusts its magnitude. The DSP also predicts the frequency tuning voltage of the VCO by using a lookup-table which is stored in the ROM. The DSP combines the predicted tuning information with the processed quantization noise, and then applies it to the end of the LPF.

Fig. 4 shows the circuit design of the third modulation point. The processed signals are injected into the synthesizer using a two-stage voltage adder behind the LPF. Since the first stage adds and inverts the signals simultaneously, the second stage inverts the added signal to a proper phase. Therefore, the three-point modulation technique not only cancels out the DSM quantization noise but also increases the channel switching speed, making the proposed synthesizer more attractive for use in advanced wireless systems.

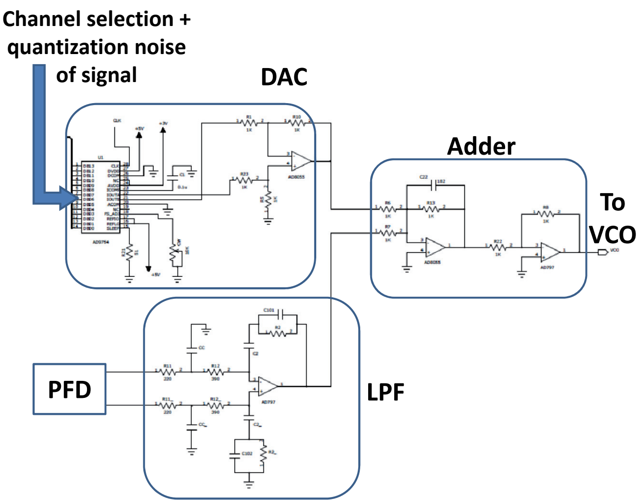


Fig. 4. Circuit design of the third modulation point.

3. System Analysis

Fig. 5 presents the phase noise model of the three-point modulated fractional-N frequency synthesizer that is shown in Fig. 2. $F(s)$ represents the transfer function of the LPF. K_d denotes the combined gain of PFD and CP, and K_v denotes the sensitivity of VCO. The baseband signal is denoted $\Phi_{sig}(s)$. The phase noise from the VCO and reference signal is denoted $\Phi_{n,VCO}(s)$ and $\Phi_{n,ref}(s)$, respectively. The term $\Phi_{n,DSM}(s)$, which denotes the DSM quantization noise in the frequency domain can be obtained from (4) as

$$\phi_{n,DSM}(s) = \frac{j\pi f_{ref}}{\sqrt{3}Ns}\left(2\sin\frac{s}{j2f_{ref}}\right)^m \tag{5}$$

where f_{ref} represents the reference frequency, and N denotes the division ratio [7], [8]. The output phase of the modulated frequency synthesizer can be derived as

$$\phi_{RF}(s) = \left[\frac{1}{N}H(s) + H_e(s)\right]\phi_{sig}(s) + \phi_{n,ref}(s)H(s) + \phi_{n,vco}(s)H_e(s) \tag{6}$$

where

$$H(s) = \frac{NK_vK_dF(s)}{Ns + K_vK_dF(s)}, \tag{7}$$

$$H_e(s) = \frac{Ns}{Ns + K_vK_dF(s)}. \tag{8}$$

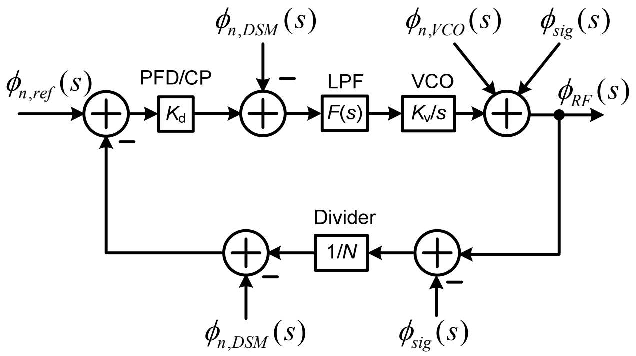


Fig. 5. Phase noise model of fractional-N frequency synthesizer using three-modulation.

Equation (6) shows that the proposed three-point modulation successfully cancels out the DSM quantization noise $\Phi_{n,DSM}(s)$ regardless of the variation of the synthesizer's parameters which include the synthesis frequency, division ratio, loop bandwidth and the order of the synthesizer. Therefore, the loop bandwidth of the synthesizer can be optimized to suppress the phase noise from the VCO and that from the reference signal. Since a frequency synthesizer inherently has the characteristic:

$$\frac{1}{N}H(s) + H_e(s) = 1. \tag{9}$$

Equation (6) can be simplified as

$$\phi_{RF}(s) = \phi_{sig}(s) + \phi_{n,ref}(s)H(s) + \phi_{n,vco}(s)H_e(s). \tag{10}$$

In (10), the coefficient of the signal phase is exactly unity. Hence, the system acts like an all-pass filter, which modulates the input signal without any limitation on the bandwidth.

Fig. 6 shows the signal modulation and noise suppression of the three-point modulated fractional-N frequency synthesizer. Three-point modulation cancels out the DSM quantization. The system transfer function $H(s)$ acts like a low-pass filter that can filter out the reference phase noise.

The error transfer function $H_e(s)$ acts like a high-pass filter that can filter out the VCO phase noise. Therefore, the three-point modulated fractional-N frequency synthesizer can output a modulation signal with optimized phase noise.

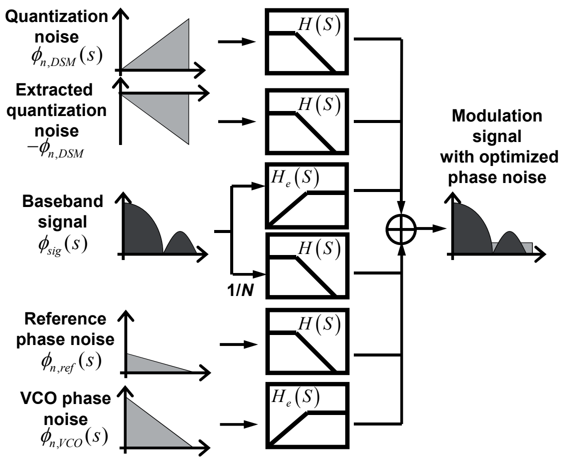


Fig. 6. Signal modulation and noise suppression of the fractional-N frequency synthesizer using three-point modulation.

4. Experimental Results

To confirm the effectiveness of the proposed technique, a three-point modulated fractional-N frequency synthesizer is implemented, as presented in Fig. 7. The synthesizer is designed to operate at 2.4 ~ 2.6 GHz with GFSK modulation. The reference frequency and the loop bandwidth are set as 20 MHz and 100 kHz, respectively. The division ratio and the frequency resolution of the fractional-N frequency synthesizer can then be found as 120 ~ 130 and 305 Hz, respectively. The data rate of the GFSK modulation reaches 2.5 Mbps, where the bandwidth-time (BT) product of Gaussian filter and modulation index is set at 0.5 and 0.312, respectively. Both three-point modulation and two-point modulation techniques are applied to the implemented fractional-N frequency synthesizer for comparison.

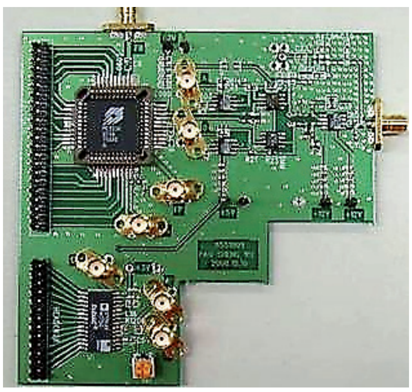


Fig. 7. Implementation of fractional-N frequency synthesizer using three-point modulation.

Fig. 8 (a) and (b) shows the simulated output spectrum of the implemented fractional-N frequency synthesizer, obtained using a first-order DSM and a second-order DSM, respectively. The simulator of these simulations is the Agilent Advanced Design System (ADS). The simulation results show that the three-point modulation technique improves the phase noise by approximately 20 dB over those obtained using two-point modulation. It also eliminates over 45 dB of fractional spurs which appear when the conventional two-point modulation is used.

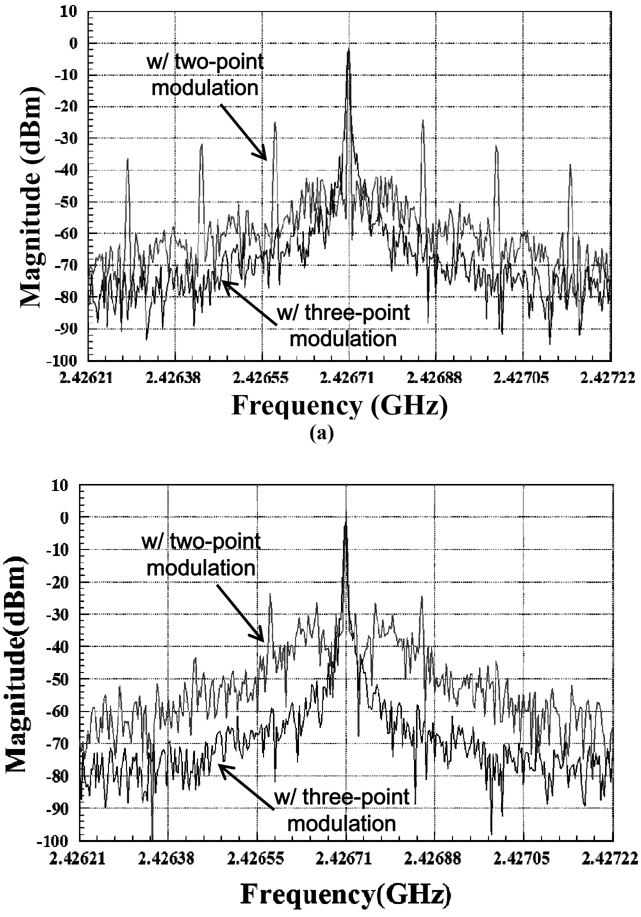
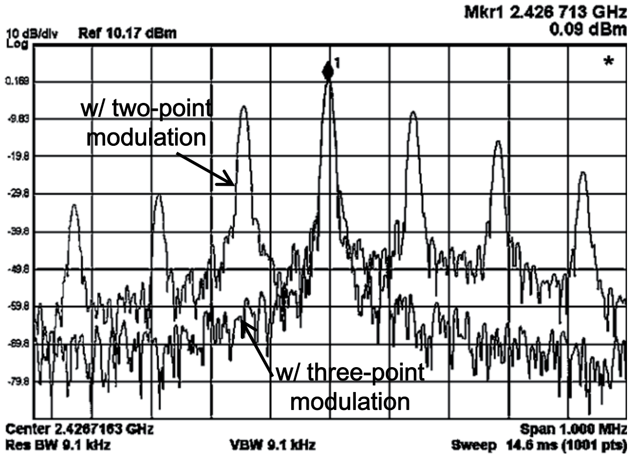


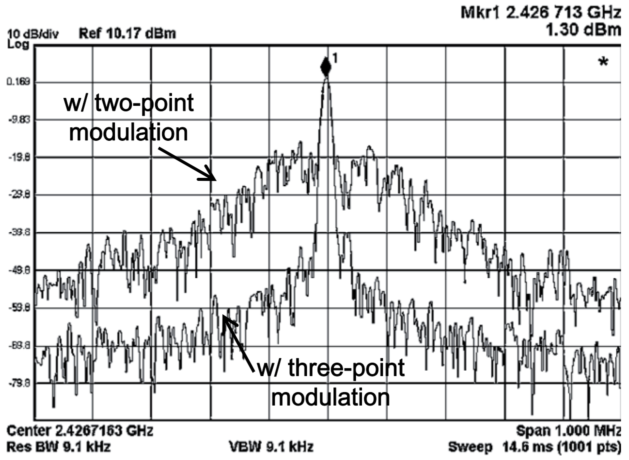
Fig. 8. Simulated output spectrum of modulated fractional-N frequency synthesizer using **(a)** first-order DSM, and **(b)** second-order DSM.

Fig. 9 (a) and (b) present the measured output spectrum of the three-point modulated frequency synthesizer using a first-order DSM and a second-order DSM, respectively. The instrument of these measurements is the Agilent N9020A MXA Spectrum Analyzer. The measured output spectra match the simulated results in Fig. 8. The proposed three-point modulation technique effectively cancels out the DSM quantization noise and therefore yields a purer output spectrum than the conventional two-point modulation.

Fig. 10 (a) and (b) present the measured phase noise of the three-point modulated frequency synthesizer using first-order DSM and second-order DSM, respectively. Both Fig. 9 and 10 demonstrate that the three-point modulation approach perfectly eliminates the quantization noise and fractional spurs. When a first-order DSM is utilized, the measured phase noise is -98 dBc/Hz at a frequency offset of 100 kHz. The proposed three-point modulation approach improves the fractional spurs by more than 55 dB. When a second-order DSM is utilized, the measured phase noise is -97 dBc/Hz at an offset frequency of 100 kHz. The in-band and out-band phase noise is improved by more than 30 dB and 20 dB, respectively.



(a)

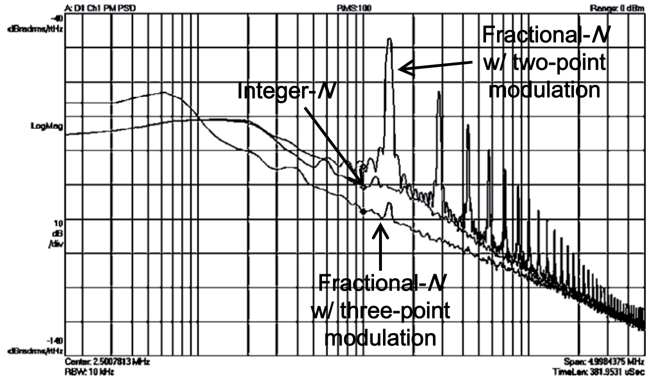


(b)

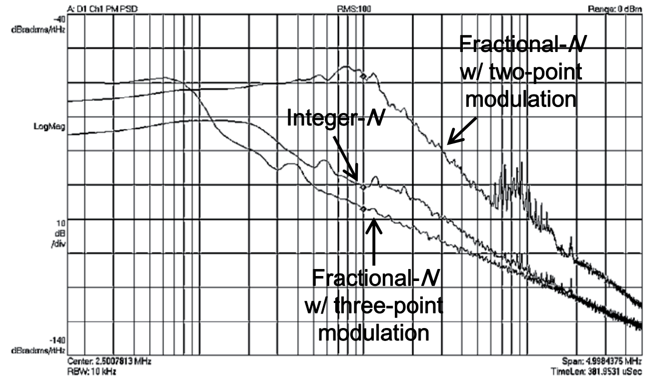
Fig. 9. Measured output spectrum of three-point modulated fractional-*N* frequency synthesizer using **(a)** first-order DSM, and **(b)** second-order DSM.

Fig. 11 (a) and (b) present the measured channel switching times using the conventional two-point modulation and the proposed three-point modulation, respectively. The instrument of these measurements is the Tektronix TDS2000 Oscilloscope. The frequency step of channel switching is set to 80 MHz. Since the three-point modulation blends modulation signal with the channel selection information in the third modulation point, Fig. 11 (b) presents a lock-in process rather than a pull-in progress, which is presented in Fig. 11 (a). The measured channel switching time is only 1.1 μs, so the switching speed is around 115 times faster than that of two-point modulation.

Fig. 12 (a) and (b) present the measured modulation quality of a first-order-DSM based fractional-*N* frequency synthesizer that is achieved using conventional two-point modulation and the proposed three-modulation, respectively.

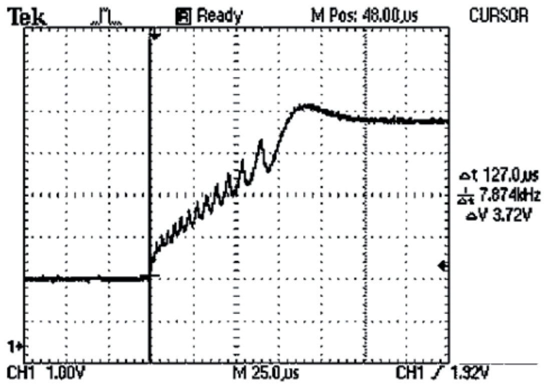


(a)

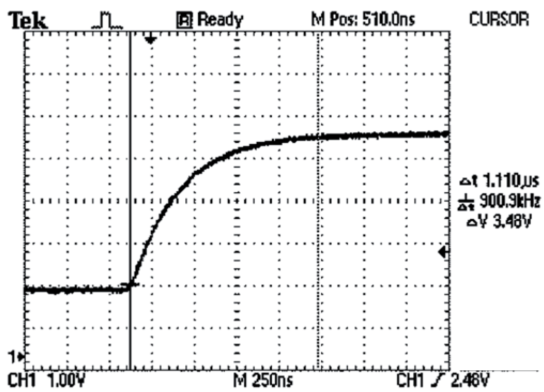


(b)

Fig. 10. Measured phase noise of three-point modulated fractional-*N* frequency synthesizer using **(a)** first-order DSM, and **(b)** second-order DSM.

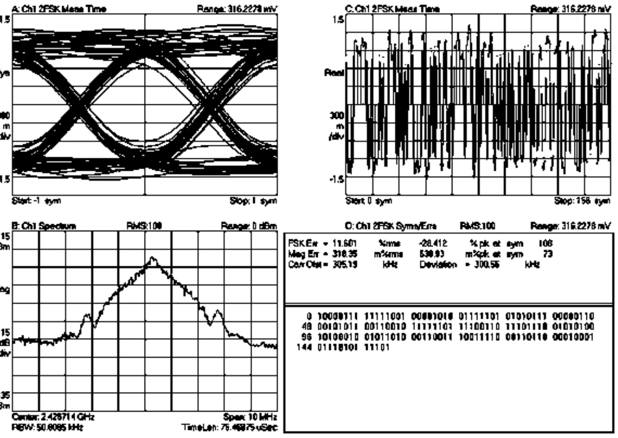


(a)

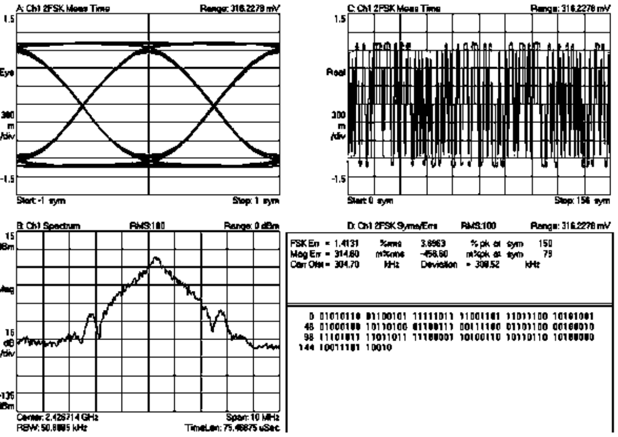


(b)

Fig. 11. Measured channel switching time using **(a)** conventional two-point modulation, and **(b)** proposed three-point modulation.

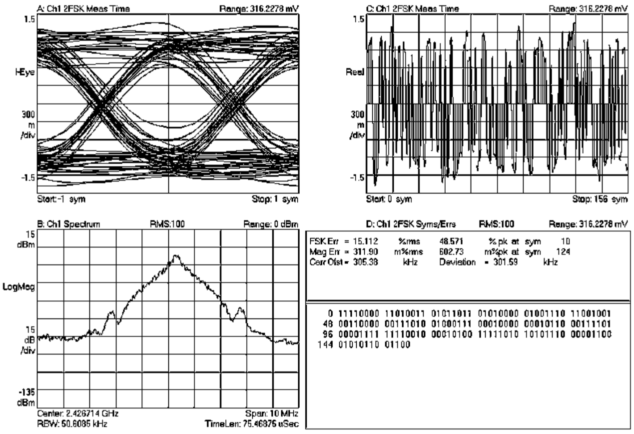


(a)

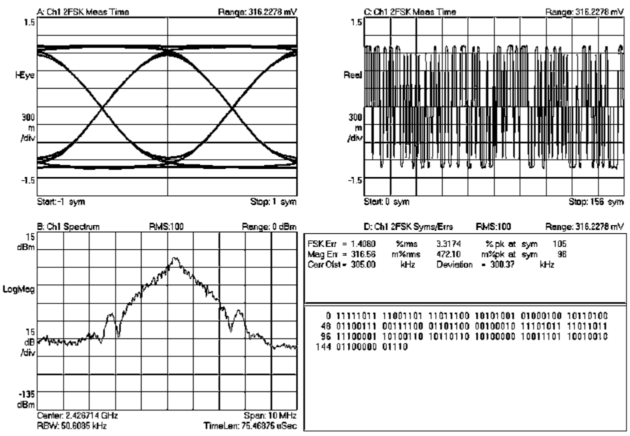


(b)

Fig. 12. Measured modulation quality of first-order-DSM based fractional-*N* frequency synthesizer using **(a)** conventional two-point modulation, and **(b)** proposed three-point modulation.



(a)



(b)

Fig. 13. Measured modulation quality of second-order-DSM based fractional-*N* frequency synthesizer using **(a)** conventional two-point modulation, and **(b)** proposed three-point modulation.

Fig. 13 (a) and (b) present the measured modulation quality of a second-order-DSM based fractional-*N* frequency synthesizer that is achieved using the conventional two-point modulation and the proposed three-modulation, respectively. The modulation quality achieved by three-point modulation is much better than that achieved by conventional two-point modulation, since the phase noise of the system is markedly better, as presented in Fig. 10. When a first-order DSM is utilized, three-point modulation improves the FSK error rate by about 10 %. When a second-order DSM is utilized, three-point modulation improves the FSK error rate by about 14 %. Both achieve a very low FSK error rate of only 1.4 % when the proposed three-point modulation is used.

These comparisons reveal that the three-point modulated fractional-*N* frequency exhibits remarkable performance, regardless of whether a first-order DSM or a second-order DSM is utilized. Therefore, a simple first-order DSM can be utilized instead of a higher-order DSM in the proposed three-point architecture to reduce both cost and power consumption. Tab. 1 compares the performance achieved using the proposed three-point modulation with that achieved using the conventional two-point modulation. It can be found that the proposed three-point modulation

Modulation scheme		Proposed three-point modulation	Conventional two-point modulation
Operating frequency (GHz)		2.4 ~ 2.6	2.4 ~ 2.6
Reference frequency (MHz)		20	20
Loop bandwidth		100 kHz	100 kHz
Frequency resolution		305 Hz	305 Hz
Modulation type		GFSK	GFSK
Data rate (Mbps)		2.5	2.5
DSM type		First-order DSM	Second-order DSM
Phase noise (dBc/Hz)	@100kHz	-98	-58
	@3MHz	-131	-125
Channel switching time (μs)		1.1	127
FSK error rate (%)		1.4	15

Tab. 1. Comparison between performance of proposed three-point modulation and conventional two-point modulation.

achieves a much better performance than that achieved using conventional two-point modulation.

5. Conclusion

A modulated fractional-*N* frequency synthesizer that is based on the proposed three-point modulation technique was implemented. This approach increases not only the channel switching speed but also the modulation quality over those achieved using the conventional two-point modulation technique. The experimental results demonstrate that the channel switching speed and FSK error rate are improved by approximately 115 times and 10 %, respectively. The phase noise is improved by more than 30 dB. These remarkable improvements make the three-point modulated fractional-*N* frequency synthesizer highly suited to use in advanced wireless systems.

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References

[1] WU, J. M., YEH, C. H., CHUANG, C. J. High dynamic range RF front end with noise cancellation and linearization for WiMAX receivers. *Radioengineering*, 2012, vol. 21, no. 2, p. 704 – 711.

[2] BAUDOIN, G., VILLEGAS, M., SUAREZ, M., DIET, A., ROBERT, F. Performance analysis of multiradio transmitter with polar or cartesian architectures associated with high efficiency switched-mode power amplifiers. *Radioengineering*, 2010, vol. 19, no. 4, p. 470-478.

[3] SU, P. U., HSU, C. M. A 0.25 um CMOS OPLL transmitter IC for GSM and DCS. In *Digest of the 2004 IEEE Radio Frequency Integrated Circuits Symposium*. 2004, p. 435-438.

[4] Silicon Laboratories Inc. Austin. TX. *SI4210 Aero II GSM/GPRS Transceiver (datasheet)*. 2 pages. [Online] Cited 2012-010-29. Available at: http://www.futurel.bg/datasheets/2/AeroII_PB.pdf.

[5] CAMINO, L., RAMET, S., BEGUERET, J. B., DEVAL, Y., FOUILLAT, P. Phase error determination in GMSK modulated fractional-*N* PLL. In *Digest of the 8th IEEE International Conference on Electronics, Circuits and Systems*, 2001, p. 47-50.

[6] WILKINS, B. Polaris total RadioTM, a highly integrated RF solution for GSM /GPRS and EDGE. In *Digest of the 2003 IEEE Radio Frequency Integrated Circuits Symposium*. 2003, p. 383-386.

[7] PENG, K. C., HUANG, C. H., PAN, C. N., HORNG, T. S. High performance frequency hopping transmitters using two-point delta-sigma modulation. In *Digest of the 2004 IEEE MTT-S International Microwave Symposium*, 2004, p. 2011-2014.

[8] PENG, K. C., HUANG, C. H., LI, C. J., HORNG, T. S. High performance frequency hopping transmitters using two-point delta-sigma modulation. *IEEE Transaction on Microwave Theory and Techniques*, 2004, vol. 52, no. 11, p. 2529-2535.

[9] PENG, K. C., HUANG, C. H., LI, C. J., HORNG, T. S., LEE, S. F. Design of a CMOS VCO with two tuning inputs applied for a wideband GFSK-modulated frequency synthesizer. In *Digest of the 2006 IEEE Radio and Wireless Symposium*, 2006, p. 443-446.

[10] LI, C. J., HUANG, C. H., HO, W. H., HORNG, T. S., PENG, K. C. Incorporating the single-loop delta-sigma modulator in fractional-*N* frequency synthesizer for phase-noise improvement. In *Proceedings of the 1st European Microwave Integrated Circuits Conference*, 2006, p. 183-186.

[11] PENG, K. C., WU, P. S. High performance fractional–*N* frequency synthesizer using a two-point channel selection technique. In *Digest of the 2009 IEEE Asia-Pacific Microwave Conference*, 2009, p. 1275-1278.

[12] CHRISTOFFERS, N., KOKOZINSKI, R., KOLNSBERG, S., HOSTICKA, B. J. High loop-filter-order sigma-delta fractional-*N* frequency synthesizers for use in frequency-hopping-spread-spectrum communication-systems. In *Proceeding of the 2003 IEEE International Symposium on Circuits and Systems*, 2003, p. 216 to 219.

[13] SHU, K., SANCHEZ-SINENCIO, E., MALOBERTI, F., EDURI, U. A comparative study of digital ΣΔ modulators for fractional-*N* synthesis. In *Digest of the 8th IEEE International Conference on Electronics, Circuits and Systems*, 2001, p. 1391-1394.

[14] VÁGNER, P., KUTÍN, P. X-band PLL synthesizer. *Radioengineering*, 2006, vol. 15, no. 1, p. 13 – 16.

[15] DENT, P. W. Frequency synthesizer systems and methods for three-point modulation with a DC response. *United States Patent* No. 5834987, 1998.

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