Low-Noise Synthesizer Design Examples

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Introduction

This is the 5th and concluding article in our series on ultra-low noise synthesizers. Article 1 (Dec. 2018) introduced higher order phase locked loop design, article 2 (Feb. 2019) reviewed noise sources, article 3 (March 2019) analyzed noise shaping in the loop, and article 4 (Oct. 2019) presented commercially available parts for the low noise PLL designer. This is the longer and more detailed version of this article available for download at www.longwingtech.com. This concluding article is devoted to showing the noise performance results and trade-offs in design examples using the low noise techniques and parts presented earlier. It shall contrast the best performance available with fully integrated synthesizers with that possible with discrete VCO's and external active filters.

In general, it may be stated that modern delta-sigma synthesizers with integrated VCO's can generally match the phase noise of discrete VCO solutions at offset frequencies well within their loop bandwidths. In fact, since fully integrated synthesizers sometimes feature the lowest charge pump noise their manufacturers offer, they may be several dB better. But, the best octave bandwidth VCO's below 4GHz can currently outperform on-die narrowband emulations of wideband VCO's by about 2 to 8dB, while the best narrowband VCO's can exceed on-die performance by 10 to 30dB. Thus, the narrowband external VCO case can allow significant superiority past the loop bandwidth, for the applications where this matters. This will be shown in the examples here.

Example 1: Fully Integrated High Performance Synthesizer

An outstanding example of a state of the art device of this type is the Texas Instruments LMX2594/95 (the 95 is basically the same performance but with a frequency doubler for higher frequency). The performance of this part will be shown both here and in the phase noise graphs of several other solutions for comparison. If a fully integrated part of this performance level does not meet requirements, it would typically be necessary to go to a discrete VCO solution. Its noise set up for 8 GHz is shown in the below graph taken from its datasheet. Design and phase noise prediction may be quickly performed using the "PLLatinumSim" program provided on the Texas Instruments website, which allows selection of loop filter form and inputting of crystal reference phase noise. In this highly integrated case only a simple RC loop filter is needed. For more detailed control of the design than the assumptions in this program, the author recommends the methods developed earlier in this series, using an analysis program such as Mathcad.

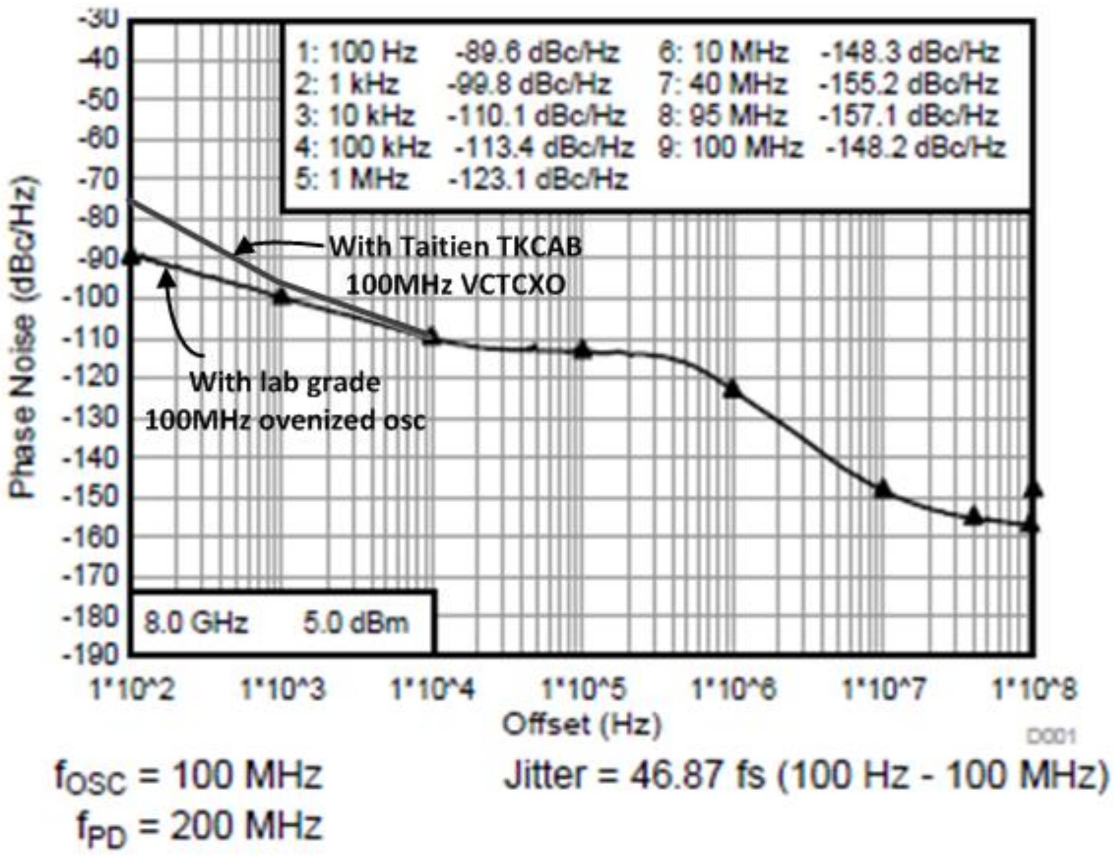


Figure 1: LMX2594 phase noise, Fout at 8 GHz, loop BW ~300KHz. Getting this performance in an integrated VCO synthesizer requires power, in this case 3.3V at 340mA. An ovenized reference, as used here in this data sheet graph, will typically require about 150mA at 12V, and typically cost at least several hundred dollars. The close in increase in noise with a lower cost but still excellent Taitien 100MHz TKCAB VCTCXO is also shown, which consumes a maximum of 40mA at 5V, and cost about $30 in volume (see part 4).

The LMX2594 on-die VCO at 8 GHz has open loop phase noise of approximately -80dBc/Hz at 10kHz. This is a good but not great noise level. It is good enough that effective suppression in the loop towards its industry leading Pn1Hz of -235 (fractional mode) can occur. However, it cannot suppress all the way down to the limit implied by this floor, as the VCO noise and 1/f noise in the synthesizer are too high to allow that with the maximum loop bandwidth on the order of 300kHz. These other two noise sources are why the suppression is nearly flat from the loop bandwidth down to the 1/f corner, instead of going down as frequency goes down as theory predicts.

Despite this internal noise limit that does not take full advantage of the PLL divider and charge pump noise floor, the LMX2594 does deliver quite excellent performance that is a challenge for discrete VCO synthesizers to beat. With discrete VCO's not delivering their best normalized performance at the higher frequencies (>~4GHz) that allow making full use of high Fpd for max noise suppression, and with the best synthesizers for external VCO usage having noise floors of Pn1Hz in the -231 range (Analog Devices ADF41513), discrete VCO's face an uphill battle in keeping up with integrated competition for noise within the loop BW. Beyond the loop BW the best discrete VCO's have a significant noise advantage, but there is a limited set of such VCO's available.

However, because most of the integrated noise is contained in the band of the two decades of frequency centered at the loop bandwidth, and the integrated VCO synthesizer bandwidth is usually about an order of magnitude larger, the integrated VCO synthesizer often has the better integrated phase noise. The integrated noise of the LMX2594 at a representative frequency of 10GHz is shown below.

Table 1: Integrated noise of the LMX2594 integrated VCO synthesizer with 10GHz output and 250kHz bandwidth, over bandwidths suitable for evaluating QAM usage. QAM is one of the applications demanding outstanding phase noise.

Integrated Noise Freq Range	**Integrated Noise**	**Comment**
25kHz to 2.5MHz	50.6fs, 0.182deg	
2.5kHz to 25MHz	53.1fs, 0.192deg	
1kHz to 100MHz	54.0fs, 0.194deg	
10kHz to 10MHz	51.8fs, 0.186deg	A common noise bandwidth for M-QAM radio system specification.
1024-QAM (popular) req = 1.83 deg rms, above shows approx 20dB safety margin. 2048-QAM (advanced) req = 1.3 deg rms, above shows approx 17dB safety margin. 4096-QAM (leading edge) req = 0.91 deg rms, above shows approx 14dB safety margin.		

The LMX2594 is seen above to be up to task of high order QAM, though possibly with questionable phase margin at the state of the art level of 4096-QAM.

Another important application for low noise synthesizers is cellular base stations. Recall that the equations evaluating the effect of phase noise on adjacent channel rejection were given earlier. These allow the table below giving reciprocal mixing blocking (adjacent channel rejection) as a function of modern channel bandwidths and resulting frequency ranges for phase noise integration.

Table 2: Modern cellular adjacent channel rejection performance of the LMX2594 in the 2GHz frequency range.

Channel BW	**Integration Range**	**Integrated noise (deg rms)**	**Phase noise limited reciprocal blocking**
1.4MHz	0.7-2.1MHz	0.009	69dB
5MHz	2.5-7.5MHz	0.005	74.2dB
10MHz	5-15MHz	0.005	74.2dB
20MHz	10-30MHz	0.007	71.3dB

It is noted in the long version of part 3 that while the modern cellular blocking requirements are a complicated set, about 80% of such requirements are between 44dB and 86dB. The LMX2594 appears capable of meeting many of these requirements. It will be shown that a discrete solution can do moderately better, and would be the superior solution in some conditions.

For land mobile use this 8GHz carrier would be divided down to about 500MHz. This reduces the noise profile in the above figure by about 24dB. The flat part of the spectrum from about 10kHz to 500kHz would be reduced from about -112dBc/Hz to about -136. This easily passes the land mobile requirement derived in the long version of part 3 of -125dBc/Hz. The LMX2594 would appear to be a good synthesizer choice in a vehicular or basestation land mobile radio. However, the power consumed by the LMX2594 would be a strong negative in a portable radio.

Example 2: Discrete Land Mobile Synthesizer

Land mobile radio is an application requiring low phase noise due to its closely spaced channels of 12.5kHz (see long form of part 3). Let us compare the somewhat brute force but effective approach of the LMX2594 with the more classic approach of a low noise discrete VCO. What we will find is that the LMX2594 will prove moderately lower noise out to about 100kHz, and only above this offset will the discrete solution provide superior noise.

VCO: For this relatively narrowband application we select the Synergy Microwave DCRO178205-10 VCO covering 1785 to 2060MHz. This VCO shows -109dBc/Hz at 10kHz, and requires 10V at 35mA. Divide by 4 to cover 446.25 to 515MHz and reduces this noise by 12dB.

Synthesizer: Analog Devices ADF41513, Pn1Hz = -231 in fractional mode. This part requires 3.3 V at about 75mA. Though this part covers to 26.5GHz, it is cost effective for a higher performance part at about $30 in 1k volume. Using this synthesizer, we will perform basic analysis and simulation with the convenient Analog Devices program “SimPLL”.

Crystal Reference: Taitien TKCAB 100MHz VCTCXO.

Loop Filter: Custom Longwing active providing 0 to 12V.

Loop: Bandwidth of 50kHz and phase margin of 60 degrees.

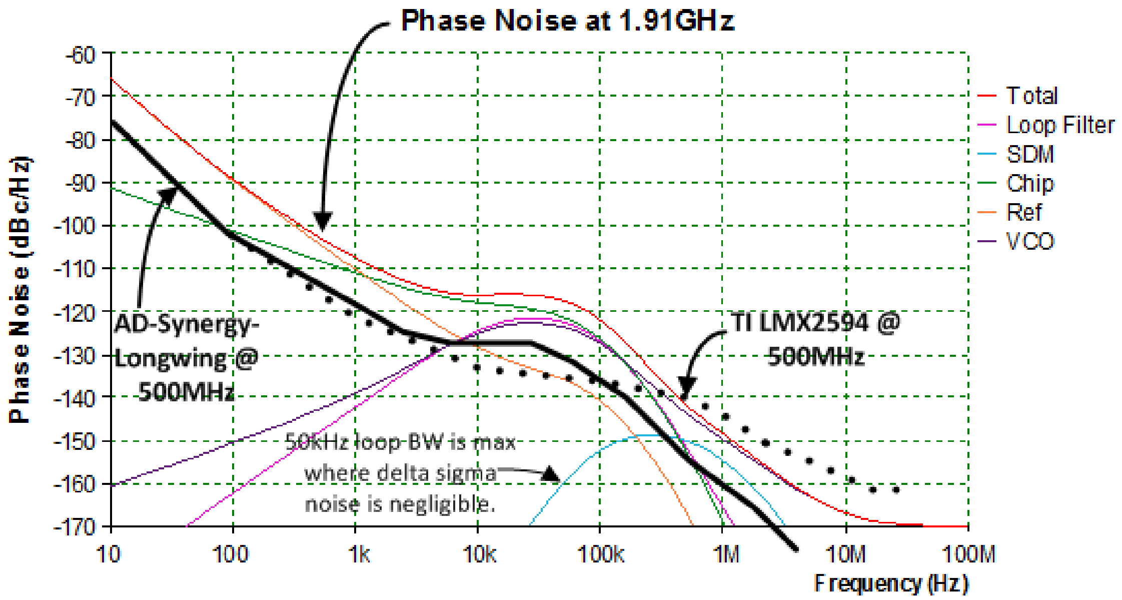


Figure 2: High quality discrete land mobile synthesizer with 50kHz BW compared to Texas Instruments LMX2594 with 300kHz BW. The 50kHz BW is the most that the discrete synthesizer with 50MHz Fpd can use without delta-sigma noise becoming prominent. This graph is generated using the CAD program “ADIsimPLL” available on the Analog Devices website.

We see in the above that the Synergy-Analog solution is similar to the LMX2594 out to about 3kHz, inferior from 3kHz to 100kHz by as much as 8dB, and then superior above 100kHz.

The superiority of the Synergy-Analog solution with a custom Longwing active filter at 200kHz is about 6dB, growing to about 16dB at 1MHz.

The Synergy DCRO178205-10 2GHz band VCO has normalized phase noise that is 17dB superior to the on-die VCO of the LMX2595, but this is overcome by the noise suppression allowed by the 200MHz phase detector frequency of the LMX2594 (a 6 dB benefit to the LMX2594), the higher loop bandwidth of 300kHz compared to 50kHz (as much as delta-sigma noise will allow with only a 50MHz phase detector frequency), and by the 5 dB better noise floor of the LMX2595. Of these factors favoring the LMX, the higher loop bandwidth is the most important. The lower loop bandwidth was forced for the ADF41513 by the lower phase detector frequency of 50MHz, which was in turn forced by the lower VCO frequency around 2GHz and lower limits of the N divider. The suppression in the loop bandwidth is second order (40dB per decade, 12 dB per octave), so 300kHz compared to 50kHz is a major difference. The net result is that the 17dB superiority of the Synergy DCRO178205-10 turns into an inferiority of up to 8 dB inside the loop bandwidth.

As discussed in the long form of article 3, the land mobile requirements were dominated by the challenging European receive adjacent channel requirements. These were approximately an average LdB(f) over a 12.5kHz bandwidth of -125dBc/Hz for the dominantly used 12.5kHz channel spacing.

From the above figure this discrete synthesizer divided down to about 500MHz would achieve a LdB(flat) of about -129dBc Hz. It meets the 12.5kHz adjacent channel noise requirement derived in Part 3 with margin of 4dB on top of the 10dB built into that requirement. But, while this approach satisfies noise requirements, it is less flexible and moderately more expensive than a fully integrated synthesizer such as the LMX2594 could deliver. While the sum of the synthesizer plus VCO cost is similar to the highly integrated VCO, the discrete VCO system must bear the cost of the very low noise active filter and higher voltage, low noise power supplies for the VCO and its steering. So, it is really only justified if its moderately lower power consumption and better far out noise are required.

Example 3: Handheld Land Mobile Synthesizers with Integrated VCO's (LMX2572 and LMX2571)

The above land mobile examples are suitable for vehicle or base station radios, but the higher current of the integrated VCO LMX2594 (~340mA), and higher tune voltage of the DCRO178205-10 VCO (12V) are not as suitable for handheld transceivers.

A candidate fully integrated solution with generous safety margin on noise performance is the Texas Instruments LMX2572. This part is intended for battery powered applications. Its supply requirement is 3.3V at 75 to 86mA, while still providing Pn1Hz of -232 (likely -231 fractional), max output to 6.4GHz, and divided output as low as 12.5MHz. Phase detector maximum frequencies range from 120MHz (4th order delta-sigma) to 200MHz (1st and 2nd order delta-sigma). It accepts reference inputs to 125MHz, and has an internal reference doubler.

The phase noise is shown below set up for a 6GHz VCO divided by 12 to 500MHz for land mobile use. The reference is a 100MHz Taitien TKCAB VCTCXO.

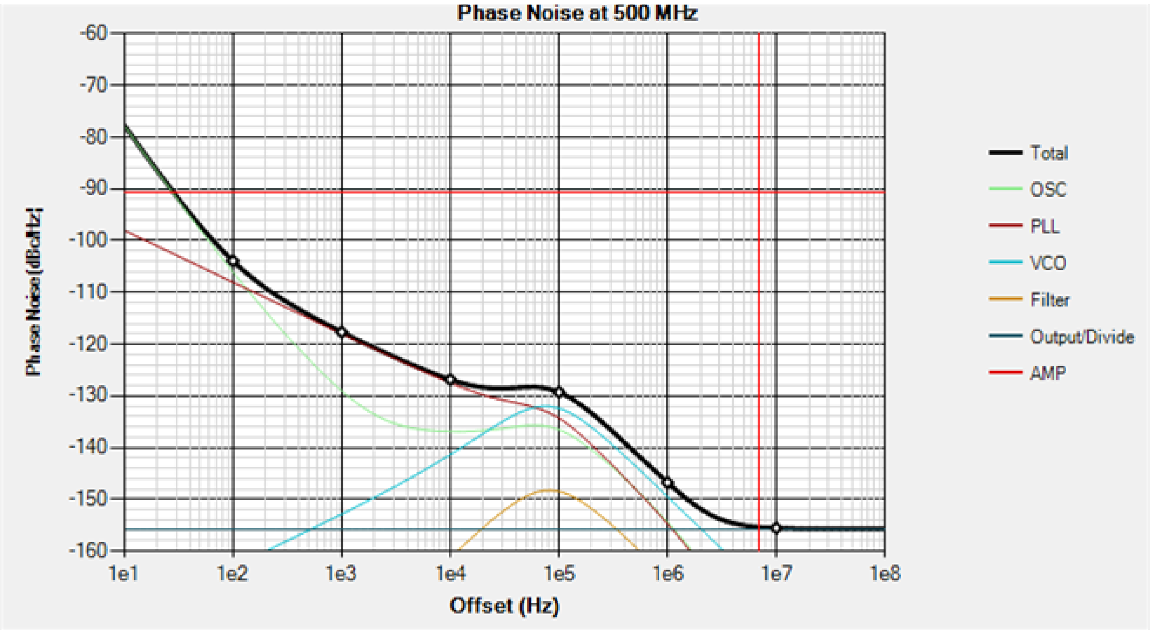


Figure 3: LMX2572 phase noise at 500MHz output with Taitien TKCAB 100MHz reference and loop bandwidth of 155kHz.

This device meets the land mobile requirement of average LdB of -125dBc/Hz from 6.25kHz to 18.75kHz land mobile with about 3dB to spare. As the requirement has a 10dB to 12dB safety margin built in, this is generous safety margin that likely approaches 15dB over statutory requirements.

The LMX2571 is a still lower power Texas Instruments delta-sigma synthesizer designed for battery powered applications. This synthesizer has integrated VCO's, but can also accept external VCO's. In internal-VCO mode its power requirements are 3.3V at 39mA. It has 3 internal VCO cores covering 4200 to 5520MHz. The internal VCO noise referred to 480MHz is -92dBc/Hz at 10kHz (implying -72 at 4800MHz). In external VCO mode its power requirements are as low as 9mA, and it features a 5V charge pump for external VCO's needing that much tune range. It can come within about 5dB of the adjacent channel noise of the LMX2572 shown above, which is generally sufficient for portable radios.

Example 4: 1-2 GHz Discrete Broadband Synthesizer (cellular base station)

The cellular base station application is one that may need superior far out noise to what an integrated VCO can provide, and which can afford the moderately higher price of a low noise active loop filter and low noise higher voltage power supplies to provide for that.

VCO: For this wider band application we select the Synergy DCYS100200-12 1 to 2 GHz VCO, which is among the lowest normalized noise of Synergy's octave range VCO's. It does require 12V for power and 28V for tuning. The noise shown below is for 1.15GHz to 2GHz, as 1.15GHz is the lowest frequency allowing Fpd of 50MHz. For 1 to 1.15GHz, an Fpd of 25MHz would be needed if still using a 100MHz reference, and this lower Fpd would result in less noise suppression in the loop BW.

Synthesizer: Analog Devices ADF41513, Pn1Hz = -231 in fractional mode. This part requires 3.3 V at about 75mA. Though this part covers to 26.5GHz, it is cost effective for a higher performance part at about $30 in 1k volume. Using this synthesizer, we will perform basic analysis and simulation with the Analog Devices program "SimPLL".

Crystal Reference: Taitien TKCAB 100MHz VCTCXO.
Loop Filter: Custom Longwing active providing 0 to 28V.
Loop: Bandwidth of 55kHz and phase margin of 60 degrees.

In the below we see that this synthesizer has noise superior to the LMX2594 both below about 5kHz and above about 200kHz.

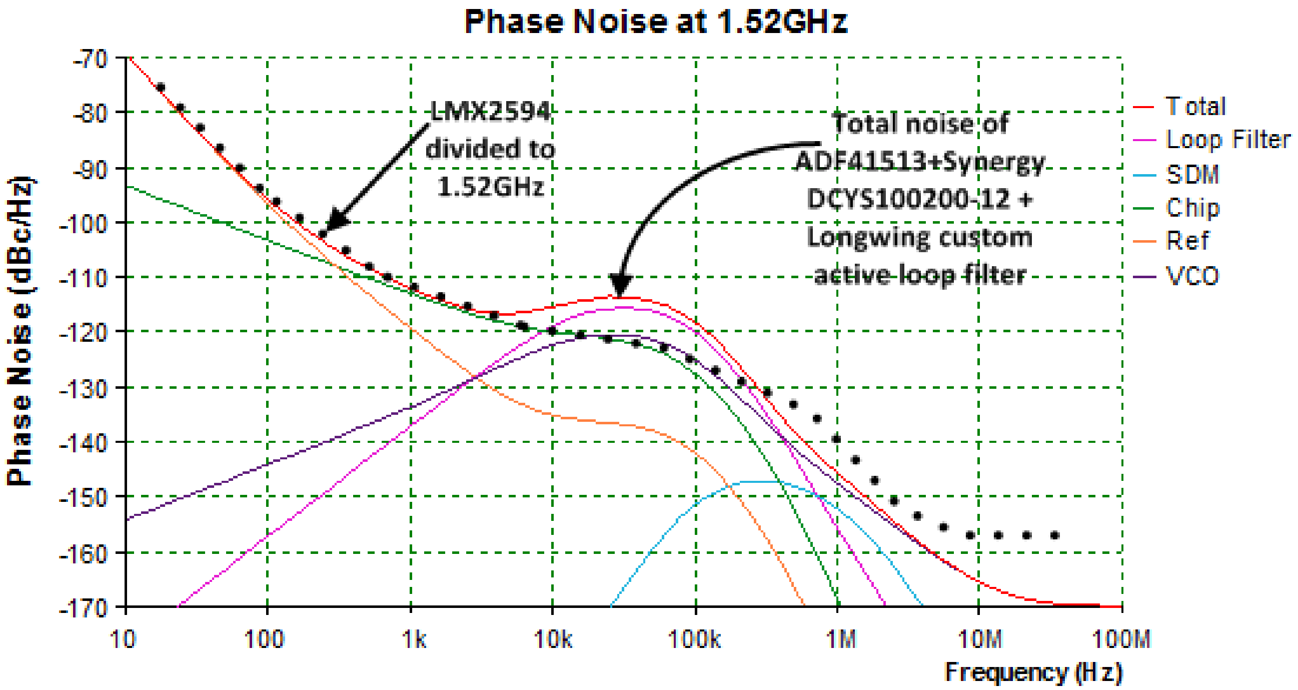


Figure 4: 1.15 to 2 GHz noise using the Synergy DCYS100200-12 VCO, the Analog Devices ADF41513 synthesizer chip, the Taitien TKCAB 100MHz VCTCXO, and the Longwing active loop filter. Fpd may be 50MHz above 1.15GHz. In comparison, the fully integrated LMX2594 range of better noise extends to about 2X loop BW. This simulation uses the custom Longwing active filter for the discrete synthesizer, which in this case is a 2.5dB improvement over the standard active filter.

Here we note that this discrete solution is nearly identical to the integrated LMX2594 close-in, inferior from 50kHz to 200kHz, and then superior beyond about 200kHz. The superior far-out performance would be the main reason to select this design over the moderately more cost effective fully integrated solution. The equations evaluating the effect of phase noise on adjacent channel rejection were given in the long form of Part 3. These allow the table below giving reciprocal mixing blocking (adjacent channel rejection) as a function of modern channel bandwidths and resulting frequency ranges for phase noise integration.

Table 3: Modern cellular adjacent channel rejection performance of the 1-2GHz synthesizer using the Synergy DCYS100200-12 VCO. Here the noise is integrated from the phase noise profile instead of using the deg rms noise function the CAD program SimPLL, as the noise is below the numerical limits of that program.

Channel BW	Integration Range	$\int L(f)df$	Phase noise limited reciprocal blocking
1.4MHz	0.7-2.1MHz	3.0E-9	75.2dB
5MHz	2.5-7.5MHz	8.43E-10	80.7dB
10MHz	5-15MHz	4.21E-10	83.8dB
20MHz	10-30MHz	4.1E-10	83.9dB

Recall from Part 3 that while the modern cellular blocking requirements are a complicated set, about 80% of such requirements are between 44dB and 86dB. The LMX2594 or 95 appears capable of meeting many of these requirements, but this discrete solution does better by amounts ranging from about 6 to 13dB. This could be important in some base station designs. Still, this example illustrates just how competitive the fully integrated solution has become, where here is a close call between integrated and discrete with the best parts used for each.

Example 5: 902-928 MHz Discrete VCO Synthesizer (RFID)

RFID is an application that calls for outstanding phase noise in the reader, and for this application a superb VCO is available.

VCO: Z-Comm ZRO0915, the lowest normalized noise VCO on the market that has significant tune range. Only very narrow SAW based oscillators have lower noise than this device.

Synthesizer: Analog Devices ADF41513, Pn1Hz = -231 in fractional mode.

Crystal Reference: Taitien 6800 ovenized.

Loop Filter: Custom Longwing active providing 0 to 12V.

Loop: Bandwidth of 12kHz and phase margin of 55 degrees.

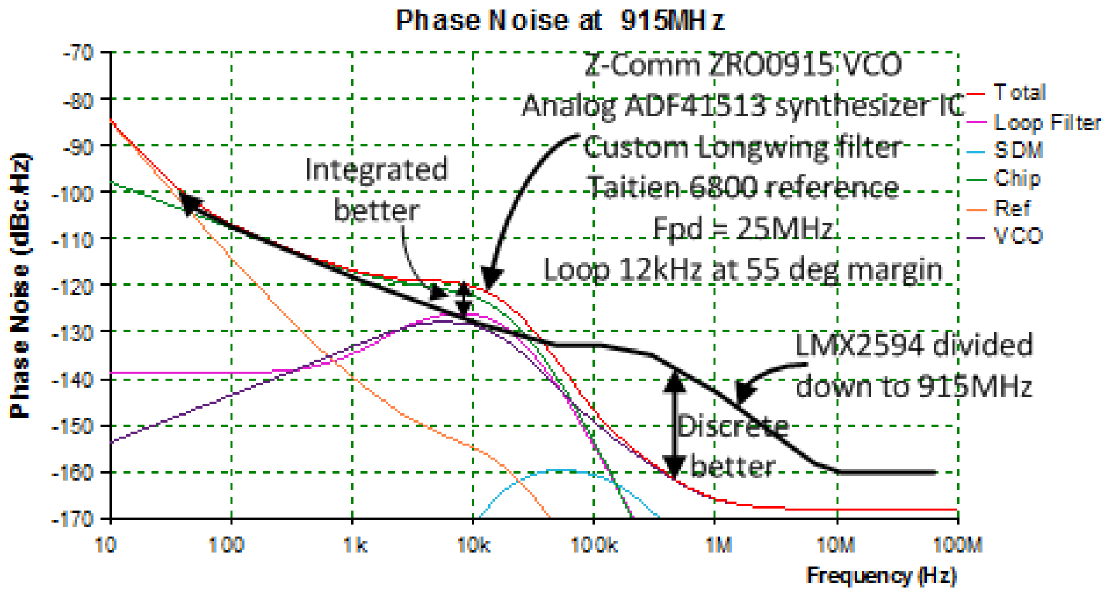


Figure 5: The Z-Comm ZRO0915 ultra-low noise VCO locked up by the ADF41513 synthesizer, with Taitien 6800 100MHz reference. The 12kHz loop bandwidth used here is a much as can be

used and keep the delta-sigma noise invisible. The Longwing ultra-low noise active filter is used here, and improves noise performance around the loop bandwidth by about 2 dB over a standard low noise active filter.

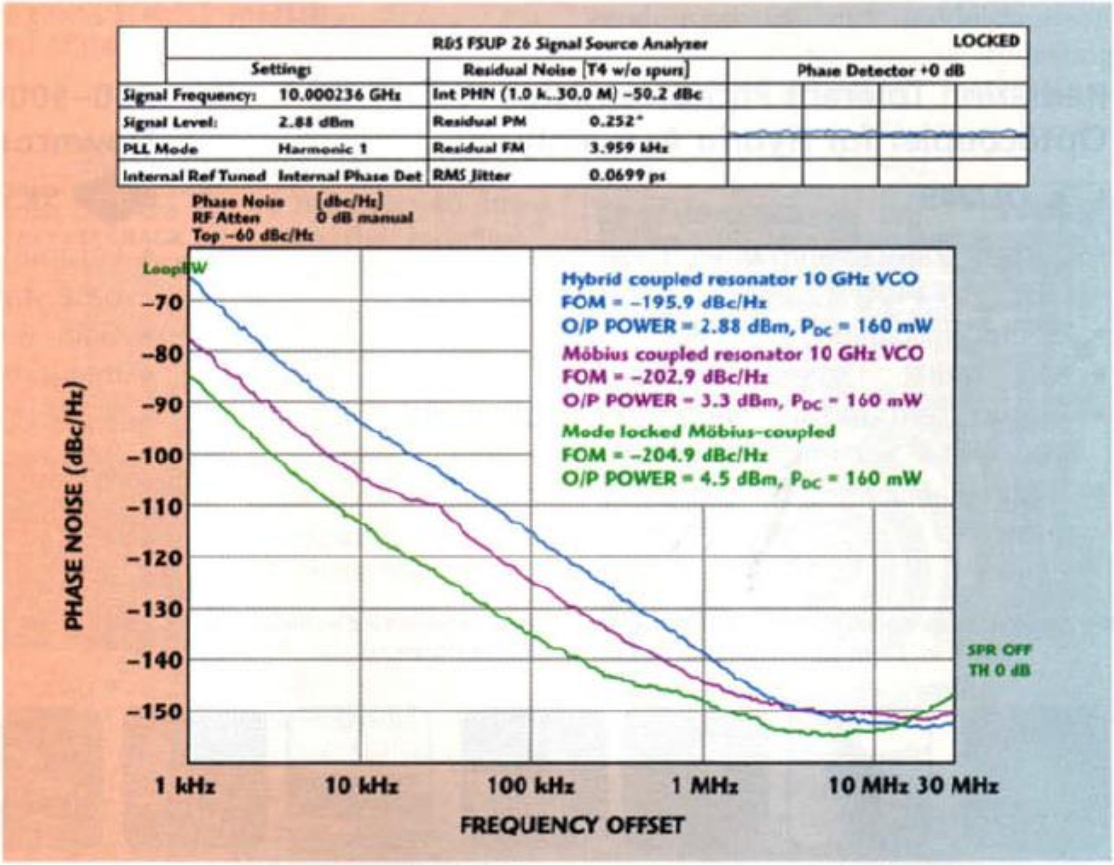
Despite the very low noise of the ZRO0915, the limit of 25MHz for Fpd when using a 100MHz reference oscillator still limits its noise performance around the loop bandwidth to be inferior to the LMX2594. The superiority of the LMX2594 extends from about 1kHz to 30kHz. However, the discrete synthesizer does match the LMX2594 from DC to 1kHz, and significantly improve upon the LMX for offsets above 30kHz. From 100kHz upward the discrete is superior by about 14 to 25dB. Simulations results for total jitter are 36fs and 0.01 deg for the discrete ZRO0915, and 55fs and 0.0157deg for the LMX2595. So, the ZRO0915 is about 3.7dB better for total integrated noise. If it had the benefit of a synthesizer IC with similar Pn1Hz, it would be about 7 dB better in total integrated noise.

Example 6: Future Mobius VCO and Improved Synthesizer (putting discrete VCO's ahead of fully integrated)

The discrete examples given so far have been limited by 2 issues:

1. Higher frequency VCO's that could take full advantage of synthesizer noise suppression with high Fpd do not typically exhibit as good a normalized phase noise as lower frequency VCO's.
2. Synthesizer IC's that accept external VCO's do not have as good a normalized noise floor (~-231dBc) as the best current synthesizers with internal VCO's (~ -235dBc).

It is of course possible for the external VCO synthesizer chip noise floor (charge pump and divider noise) to be improved to match that of internal VCO synthesizers. The VCO improvement is more challenging, but also possible. In "Microwave Journal", Nov. 2103, Synergy Microwave published an article entitled "Printed Resonators: Mobius Strip Theory and Applications". The Mobius Resonator is a high Q printed resonator depending on a surface propagation mode that can serve as a VCO resonator. Synergy developed 10GHz prototype VCO's with the below phase noises.



R&S FSUP 26 Signal Source Analyzer				LOCKED
Settings		Residual Noise [T4 w/o spurs]		Phase Detector +0 dB
Signal Frequency:	10.000236 GHz	Int PHN (1.0 k..30.0 M)	-50.2 dBc	
Signal Level:	2.88 dBm	Residual PM	0.252°	
PLL Mode	Harmonic 1	Residual FM	3.959 kHz	
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0699 ps	

▲ *Fig. 15 Measured phase noise plot of the 10 GHz oscillator using: hybrid coupled resonator, Möbius coupled resonator, mode-locked Möbius coupled resonator network.*

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Figure 6: The phase noise performance of the 10GHz mode-locked Mobius resonator VCO is -113dBc at 10KHz, with a 1/f corner of approximately 6kHz. Note that the -113dBc/Hz at 10kHz noise shown for the mode-locked Mobius exceeds the normalized noise performance of the very best lower frequency commercial VCO's by about 5dB.

Let us assume a commercial version can\\ be offered in the near future with -115dBc at 10KHz, with a corner of 5kHz. This VCO would feature about +/-400MHz tune range with Ko of about 50MHz/V. Let us further assume that a synthesizer can be available with Pn1Hz = -235dBc and with max Ipd of 20mA (to reduce filter noise). This leads to the below phase noise terms graph.

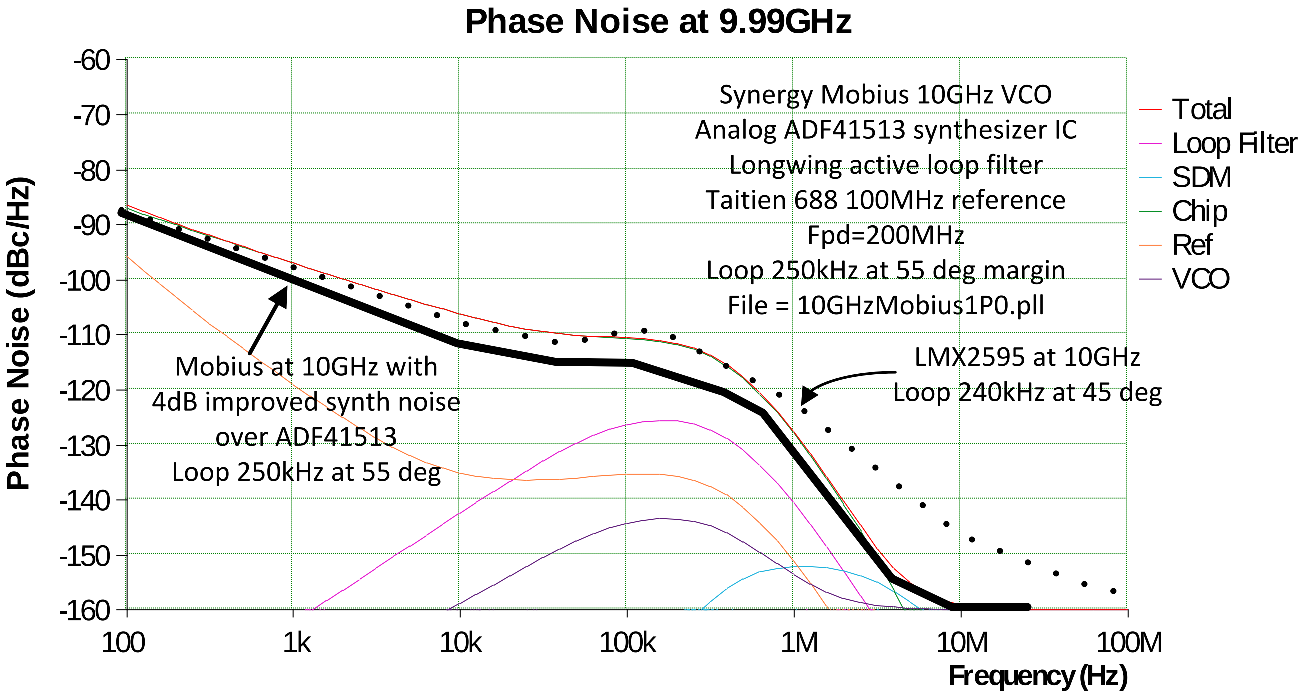

Figure 7: Possible future discrete 10GHz VCO synthesizer with Mobius resonator and 4dB improved synthesizer floor (same Pn1Hz as LMX2595) would excel LMX2595 by about 3-4dB in-band and 6-20 dB out of band. The integrated noise superiority of the Mobius approach would be about 6-7dB.

Final Summary

This five-part series has been about creating a detailed understanding of noise sources, shaping, and performance in modern synthesizer design. The first three parts covered theory, and the last two covered practical parts and results. A key issue was if and when synthesizers designed with the classic method of packaged VCO's could outperform the latest fully integrated synthesizers with on-die VCO's. The answer is that for the majority of applications, the integrated noise VCO performance is perfectly fine, though for some portable applications the power consumption may not be acceptable. This was achieved architecturally by the IC companies by the use of the wide bandwidth delta-sigma synthesizer with a large set of narrowband VCO's on die emulating a wide tuning VCO, supported by a new generation of reasonably priced low noise higher frequency crystal reference oscillators. The fact that currently the available synthesizer chips that support external VCO's do not come closer than about 4dB of the chip induced noise of the chips featuring on-die VCO's is also a factor. The wide bandwidth allows closed loop suppression of the phase noise of the on-die VCO's, down to levels approaching the multiplied noise of the crystal reference.

However, past the loop bandwidth that is generally in the range of 40kHz to 400kHz, the discrete VCO approach is still superior, by amounts that can exceed 20dB. This is important in some applications. However, there are few VCO's that have this performance, and currently none above 4GHz where the full advantages of the high bandwidth delta-sigma synthesizer can be applied. For the discrete VCO approach to regain its previous market dominance in low noise applications will require that VCO's with similar low normalized phase noise as the outstanding lower frequency VCO's be developed, but at frequencies above 4 GHz. The Mobius resonator pioneered by Synergy Microwave has the potential to deliver this advance. However, even if that development occurs, the applications not requiring the very best noise will likely still utilize the newer on-die VCO approach.

Part 5 References

1. "Design Methods of Modern Ultra-Low Noise Synthesizers," Farron Dacus, *Microwaves & RF*, Dec. 2018.
2. "Noise Sources in Ultra-Low-Noise Synthesizer Design", Farron Dacus, *Microwaves & RF*, Feb. 2019.
3. "Noise and its Shaping in Ultra-Low-Noise Synthesizer Design", Farron Dacus, *Microwaves & RF*, Mar. 2019.
4. "Key Parts for Ultra-Low-Noise Synthesizer Design", *Microwaves & RF*, Oct. 2019.

Long forms of these articles with more detail are posted at www.longwingtech.com.