The most important thing we build is trust

Lunch and Learn: High Performance Synthesizers
Defining Specifications and Considering Tradeoffs
Presented by Ed McQuillen June 2, 2015

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Agenda

• Introduction

• High Performance Synthesizers
  – Basic synthesizer parameters and performance tradeoffs
  – Parameters which distinguish different types of Synthesizers
  – Results from a typical fast switching, phase coherent system
  – Other considerations

• Cobham Signal & Control Solutions Product Map
  – Synthesizers & LO Generators
  – Integrated Microwave Assemblies
  – Switch Matrices
  – Components

• Reference Info

• Conclusion
Specifying Synthesizers is Complicated!

There are many (sometimes conflicting!) considerations when specifying a high performance synthesizer:

- Ensure the system will meet performance requirements
- Account for margin & future growth
- Minimize Size, Weight and Power
- Meet aggressive schedule & cost targets
- Convey this information to prospective vendors
- Consider a wide variety of vendors, acronyms & technologies
“High Performance” Synthesizers Terminology

Various Names:
- Custom Synthesizer
- LO Generator
- PLL
- Oscillator
- Frequency Generator
- CWI
- STALO
- STAMO

Simultaneous combination of parameters adds complexity

“High Performance”

Low Noise

Low Spurious

Fast Switching

Other Factors

Other Factors:
- Bandwidth
- Resolution
- Size
- Coherence
- Multiple Outputs
- Power
- Environmental
- Modulation

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This Presentation has a Practical Focus

**This Presentation will:**

- Provide questions to consider when specifying an application-specific, custom-designed synthesizer
  - Examine commonly unspecified characteristics of common parameters
  - Goal is to facilitate creation of an optimal specification
- Consider specs from perspective of cost vs performance
- Offer some examples of data to demonstrate concepts
- Minimize discussion of particular numbers

**This Presentation will not:**

- Relate synthesizer parameters to system performance
- Delve into mathematical theory
- Explain how to design a synthesizer
Different technologies are used within different architectures with different combinations of performance for each parameter:

- Crystal, PLL/VCO Devices, DDS, DRO
- Do you care?

Details eliminate assumptions and help to produce an optimal result:

- Specifying details will ensure you get what you really need
- Details give Synthesizer designer flexibility to pick the optimal architecture
One Way to Rank Synthesizers Based on Phase Noise

Proponents of various approaches can argue about where a particular product should be located

PHASE NOISE “PERFORMANCE” * (*not to scale)
An Alternative Synthesizer Ranking System Based on Switching Speed

Again we can debate where a particular product should be located, but more importantly, we are often not comparing apples to apples...

SIZE, WEIGHT, POWER & COST *

SWITCHING SPEED “PERFORMANCE” * (*not to scale)
Another Alternative Synthesizer Ranking Based on Bandwidth

Depending on what parameter we choose, each of the various types of Synthesizer will excel ...

BANDWIDTH "PERFORMANCE" * (*not to scale)
Yet Another Alternative Ranking System

Various devices types are again juxtaposed. Like the others, this ranking by itself is clearly insufficient...

STEP SIZE "PERFORMANCE" * (*not to scale)
Multi-Dimensional Synthesizer Rankings?

All of these rankings are relative and subjective, and almost any product type can be “High Performance”, depending on what dimensions you choose.

Ideal System is highest performance, lowest Size, Weight, Power & Cost.

"PERFORMANCE" * (*not to scale)
Even Simple Parameters Involve Tradeoffs

- Consider the need for a 0.5-18 GHz source
- What happens if we ask for 10 MHz to 18 GHz instead?
  - Should be “free”
    - Add <3% extra bandwidth & provide flexibility for other applications
  - That 3%, however, adds over a decade of bandwidth
    - Roughly double the number of octaves of bandwidth and in that sense double the complexity of the system
- For some simple architectures, this type of change may be achieved by using a few different components
- For some high performance Synthesizers, this change may require numerous extra filters, switches, mixers, amplifiers, etc.
  - Size, weight, power and cost will increase
- Margin can add cost, even for simple parameters
The Reference Configuration is Critical

Reference configuration requirements affect SWAP:

• Free running internal reference only
• External reference only
  – Does input close-in phase noise support the output requirements?
  – What is the input power range? Frequency range?
  – Are there requirements for output phase stability versus input power?
• Automatic switching between internal and external
  – Switchover Time?
  – Phase discontinuities?
• Is a sample of the reference required as an output?
• Vibration effects due to internal and external references may influence choice of loop bandwidth
• Is there a warm-up requirement?
What Do You Mean By…Frequency?

When you program a Synthesizer to a particular frequency with a certain resolution/step size, different architectures may produce subtly different signals:

• Output Frequency = “240 MHz” may really be 239,999,999.9906870 or 240,000,000.223517 Hz

• Binary DDS versus DDS with precise decade step
  – Determined by Clock Frequency

• If your system can tolerate minor differences between the nominal value and actual value of frequency, the synthesizer design may be simplified

• On the other hand, if you need the frequencies to be exactly what you program, beware of any device that purports to provide precise fine steps over a wide range with excellent spurs and noise
What Do You Mean By...Spurious?

• Spurious of various types may be identified:
  – Carrier related spurs
  – Non-carrier related spurs
  – “Close-in” spurs
  – 60 Hz spurs
  – Harmonics
  – Integrated spurious

• Different types of spurs may arise from different sources
  – Different architectures may be required to support different levels of performance
  – Not all spurs are created equal – typical vs. worst case

• Breaking spurious into different types according to the system needs provides the synthesizer designer with flexibility and options for optimization
Digital Synthesis is Great, but has Limits

Synthesizer technology is similar to other fields where digital methods are supplanting analog methods for many applications

- Direct Digital Synthesis technology continues to evolve and enable improvements, but it is particularly important to understand details and limitations of various parameters in order to ensure the best use of this technology

- Clock selection is critical:
  - Frequency Resolution
  - Spur Free Zones
  - Modulation capabilities
  - Calibrations may be required
  - Still require a clean clock – phase noise & spurs
Spurs Can Jump Around (Part 1)

Here are two plots of a DDS with two clock frequencies operating at a particular output frequency = 284.8 MHz.

Clock 1: A Bunch of Spurs within +/-20 MHz of Carrier with Clock 1

Clock 2: No Spurs within +/- 20 MHz of Carrier with Clock 2
Spurs Can Jump Around (Part 2)

Here are two plots of the same DDS with the same two clock frequencies operating at a different output frequency = 292.8 MHz

Clock 1

No Spurs within +/- 20 MHz of Carrier with Clock 1

Clock 2

-51 dBc Spur less than 20 MHz from Carrier with Clock 2
Phase Noise Is Not a Single Spec!

All three curves meet -100 dBc/Hz @ 100 Hz offset

PLL/VCO Device

Both Tunable Units meet -130 dBc/Hz @ 500 kHz offset

Full Synthy

Multiplied Crystal Oscillator

• Don’t forget that Loop Bandwidth affects Switching Speed!
Determining Phase Noise Specifications

• Specify Phase Noise in as much detail as possible:
  – What offsets are of most (or least) importance?
  – What assumptions are made?
    • Straight line interpolation?
    • 20\*\log(N) scaling between reference frequencies?
  – Is integrated noise what really matters?
  – Does loop bandwidth matter?
  – Does your system distinguish AM Noise from FM Noise?
  – Noise at one offset does not necessarily imply performance at other offsets
    • Consider two sources with different profiles on previous slide

• These details can require different architectures to support the different types of performance, with order of magnitude impacts on size, power and/or cost
Phase Noise Under Vibration
Part 1

When specifying Phase Noise, it is critical to define the conditions for measurement and details of reference

• Specify performance in environment
  – Output phase noise & spurious for a particular vibration stimulus profile
    • Sine & Random profiles for each axis
  – In terms of sensitivity – “Total Gamma” or “Gamma by Axis”

• Reference configuration will determine architecture
  – If the external reference supports the required phase noise under vibration
    • It may be used directly, or as the reference to a PLL with a Loop bandwidth greater than the maximum vibration stimulus frequency
    • The complexity of the design is minimized
  – If not, the internal reference configuration becomes complex
    • A low sensitivity cleanup loop is required
Phase Noise Under Vibration
Part 2

• The system performance is typically determined by the most sensitive component, which is usually a crystal
  – Different types of crystals have dramatically different sensitivities

• Different means to handle vibration effects
  – Manage sensitivity of crystal performance by itself
  – Mechanical isolation
    • Requires extra size, especially if actively controlled
    • Classical passive lowpass damping has practical limits
    • Typically not isotropic
  – Electrical Compensation is effective but can be expensive

• Requirements for phase noise under vibration can be a major cost driver
Look at Switching/Phase Settling/Coherence

The next several slides present example plots of measurements of switching speed/phase settling/phase coherence

• Test Setup must be carefully designed
• Need to understand relationships among reference signals
• Different setups reveal different characteristics
• Details matter!
Test Setup for Measuring Switching Speed
Phase Coherent Switching

Control Signal

Phase Detector Output

Phase Coherent Switching
Zoom in to Measure Switching Speed - On

Approximately 40-60 ns Switching Speed

Control Signal

Phase Detector Output
Zoom in to Measure Switching Speed - Off

~20 ns Switching Speed?
Example of Non-Phase Coherent Switching

Multiple Phase States
Test Setup for Phase Coherent Switching

- Beat Freq Sig Gen
  - \( F_{\text{BEAT}} = 20 \text{ MHz} \)

- Fixed Synthesizer
  - \( F_{\text{REF}} \)

- Hopping Synthesizer
  - Frequency hopping between \( F_{\text{REF}} \) and \( F_{\text{REF}} + F_{\text{BEAT}} \) at 100nSec PRI

- Controller

- 10 MHz Reference

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**CH 4**

**CH 1**

- Tek VV

**Tek VV Settings**

- Coupling: DC
- Invert: Off
- Bandwidth: 20 MHz
- Fine scale: 50.0mV/V
- Position: 360mdiv
- Offset: 0.000 V
- Probe setup: 1 X
Phase Coherent Switching <100 ns

Ch1 Freq 18.18MHz
Ch1 Period 55.00ns

Ch1 50.0mVΩ
Ch4 500mV

Δ: 150ns
@: 2.59μs

Δ: 13.0mV
@: 69.0mV

M 40.0ns A Ch4 -260mV

T° 2.64000μs
Consider Control Interface Setup & Latency

**INPUT DATA**

DATA NOT VALID

DATA VALID

BCD INPUT DATA

150 ns (Minimum)

60 ns Min.

STROBE*

* INPUT DATA STROBED ON TRAILING EDGE

OUTPUT DATA

DATA VALID

20 ns Min.
What Do You Mean By “Fast Switching”? Answers to These Questions Determine Architecture & Cost

• Time required for the frequency to change to within X Hz of final value, or to the exact frequency?

• Amplitude settling to within what limits?

• Phase settling to within what limits?

• Phase continuous? Phase coherent?

• How are these parameters measured?
  – Including calibration/setup time and control interface overhead, or measured just from strobe?

• Do you need to “pipeline” at a particular rate through an arbitrary sequence of frequencies?
  – Can the desired control interface support this rate?

• Can you simply hop between two frequencies?
Cancellation of Correlated Noise

• This is an interesting and important topic for Synthesizer specification and design
  – Particularly for systems using multiple local oscillators to feed both upconverters and downconverters

• When you add signals, the noise adds

• When you subtract signals, correlated noise might subtract
  – Phase Noise cancellation is a function of offset frequency and delay

• Different Synthesizer architectures enable different levels of noise correlation between particular outputs
  – The correlation between those outputs will determine the associated cancellation achieved within an up/downconverter system whose LO’s are fed by those outputs

• A simple lab test setup was used to demonstrate this concept as described on the following slides
Consider a 1 GHz Source used to Generate 14 GHz & 15 GHz Sources

A basic signal generator was used to create a 1 GHz signal. An amplifier added some noise at around 100 kHz.
The phase noise of the multiplied signal is \( \geq 20 \log N \) (= \( \sim 23 \) dB) worse than the reference for offsets below \( \sim 100 \) kHz. Test setup artifacts degrade the noise at higher offsets.
The phase noise of the multiplied signal is $\geq 20\log N (\approx 23.5 \text{ dB})$ worse than the reference for offsets below $\sim 100 \text{ kHz}$. Test setup artifacts again degrade the noise at higher offsets.
Correlated Noise Cancels if the 14 GHz & 15 GHz Sources are Mixed Together to Create a 1 GHz Signal

The phase noise of the Downconverted 1 GHz is very close to the original profile for offsets < ~100 kHz because the correlated noise cancelation is almost perfect. However, the un-correlated test setup artifacts at higher offsets do not cancel.
Measuring Noise & Spurs within Modulation

For Synthesizers with modulation capabilities, thought may need to be put into how to measure parameters such as noise and spurs, particularly if there are requirements within the modulation envelope

- Consider how to measure spurs at -80 dBc at a 1 MHz offset on a signal chirping over +/- 10 MHz
- Dynamic Range may be extraordinarily difficult to measure due to the presence of the modulation
- Customized test sets may be required so that the measurement method will not remove the spectral characteristics being measured
Extracting Spurs within Modulated Signals (Part 1)

Here is a plot of a modulated signal that has spurious buried within the modulation envelope.
Extracting Spurs within Modulated Signals
(Part 2)

Here are plots of spurious signals extracted from the modulated signal. These plots are made possible by a custom test setup and properly designed synchronization features within the synthesizer.
Here is a composite plot that shows both the modulated signal and the spurious signals.
Cobham Signal & Control Solutions
Product Map

- **Integrated Microwave Assemblies**
  - Custom Synthesizers
  - LO Generators
  - CWI
  - PLL Oscillators
  - Frequency Generators

- **Synthesizers & Frequency Sources**
  - PIN Diode Switches
  - Phase Shifters
  - Phase Modulators
  - Attenuators
  - Multipliers
  - Splitters / Dividers
  - Combiners and Couplers

- **Control & Receive Components**
  - Limiters and Detectors
  - Switch Matrices
  - Up/Down Converters
  - Multi-Function Modules
  - Rx/Exciters
  - Distribution Assemblies
  - Beam Former Networks
  - Time Delay Units
  - Switched Filter Banks
Synthesizers & LO Generators

- Custom & Standard Synthesizers
  - Typically used to provide LO’s
  - Custom Frequency Coverage
  - Custom Form Factor & Cooling
  - Various Reference Frequency Configurations
  - Modulation Options
  - Direct (DDS) and Indirect Solutions

- High Performance
  - Low Phase Noise, Low Spurious
  - Fast Switching (<100 nS)
  - Phase Coherent
  - Frequencies to >40 GHz

- Military Applications
  - Harsh Environment
  - Small Size
  - Low Weight
Integrated Microwave Assemblies

• Wide Range of Custom Assemblies
  – Switch Matrices
  – Up/Down Converters
  – Front End Receivers
  – Local Oscillator & Synthesizer Modules
  – Time Delay Units
  – Multipliers
  – Gating and Modulator Modules
  – High Power IFF Assemblies

• High Performance
  – Blocking or Non-Blocking
  – Low Phase Noise, Low Spurious
  – Wide Bandwidth, Fast Switching
  – Frequencies to >40 GHz

• Military Applications
  – Harsh Environment
  – Small Size
  – Low Weight
Switch Matrices

- Bandwidths to 40 GHz
- N x N Inputs to Outputs
- Blocking or Non Blocking
- Full MIL-SPEC compliance including hermetically sealed switch modules available
- Full BIT including temperature and on-board diagnostics
- Phase and gain matching
- Various interfaces and controller solutions
- Redundant capabilities for high service availability
- Designs optimized for high thermal loads
Components

• **Wide Range of Catalog Components**
  – Limiters
  – Detectors
  – Oscillators
  – Multipliers
  – Switches
  – Attenuators
  – Phase Shifters
  – Couplers/Dividers

• **High Performance**
  – Broadband
  – Low Insertion Loss
  – Excellent Flatness over frequency

• **Custom Components**
  – Suitable for Harsh Environments
  – Space Level Designs
  – Flexibility for small lot sizes
  – Scalable for high volume
List of Useful References

For those interested in learning more about these subjects, here are some references we find useful:

- “Phase Noise Characterization of Microwave Oscillators” Hewlett Packard Product Note 11729C-2
- “Phase Noise Under Vibration in Crystal Oscillators” by Glenn R Kurzenknabe, Piezo Crystal Company, 1988
- “Local Oscillator Phase Noise and its Effect on Receiver Performance” by C. John Grebenkemper, WJ Tech-note
- “Frequency Synthesizers Theory and Design” by Vadim Manassewitsch
- “A Technical Tutorial on Digital Signal Synthesis” Analog Devices, 1999
Conclusion

• Questions?
• Thank you!

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