Agenda

• What is Phase Noise?
• Why is Phase Noise Important?
• Quantifying Phase Noise
• Causes of Phase Noise
• Phase Noise Measurement Techniques
• Additive Phase Noise
• AM Noise
• Summary
What is Phase Noise?

• **Ideal Signal (noiseless)**
  \[ V(t) = A \sin(2\pi vt) \]

  where
  \[ A = \text{nominal amplitude} \]
  \[ v = \text{nominal frequency} \]

• **Real Signal**
  \[ V(t) = [A + E(t)] \sin(2\pi vt + \phi(t)) \]

  where
  \[ E(t) = \text{amplitude fluctuations} \]
  \[ \phi(t) = \text{phase fluctuations} \]

Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain.
Phase Noise is equivalent to jitter in the time domain.
**What is Phase Noise?**

- **Absolute Phase Noise**
  1 Port – Produced by Signal Source

- **Additive Phase Noise**
  2 Port – Added by device (e.g. amp, up/down converter)
Phase Noise
Important in Digital Modulation

Modulation quality (phase error, EVM) is degraded by phase noise

Increasing Phase Noise (QPSK)
Phase Noise
Important in Communication Systems Transmitters

Adjacent Channel Power

Phase Noise causes transmitter signal to leak into adjacent channels

Real LO

Ideal LO
Phase Noise
Important in Receivers

Sensitivity: Big interferer near the transmit channel

Large interferer mixes with LO energy spread by phase noise to produce a signal in the receiver IF – reduced sensitivity
Phase Noise
Important in Radar

Radar Applications – Moving Target Indication

High phase noise in radar LO spreads clutter signal and masks desired low-level target response
Phase Noise
Important in Digital Systems

High Phase Noise = High Jitter

Amplitude (AM) Noise

Digital Clock Eye Diagram

Phase Noise/Jitter

Jitter peaks can cause transmitted symbol errors which increased bit error rate and limits usable data rate
Quantifying Phase Noise

• Phase Noise Units

• Residual Noise
  – Integrated Phase Noise
  – Residual PM
  – Residual FM
  – Jitter: Time and Frequency Domain approaches
Phase Noise – Unit of Measure

- Phase Noise is expressed as $L(f)$.
- $L(f)$ is defined as single sideband power due to phase fluctuations in a 1Hz bandwidth at a specified offset frequency, $f$, from the carrier.
- $L(f)$ has units of dBc/Hz.

![Spectrum View](image)
![Phase Noise Plot](image)
Quantifying Phase Noise

- Phase Noise: $L(f)$  Units of dBc/Hz

- Plot

- Spot Noise

<table>
<thead>
<tr>
<th>Type</th>
<th>Offset Frequency [T1]</th>
<th>Phase Noise [T1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed</td>
<td>1.00 kHz</td>
<td>-107.89 dBc/Hz</td>
</tr>
<tr>
<td>Fixed</td>
<td>10.00 kHz</td>
<td>-132.72 dBc/Hz</td>
</tr>
<tr>
<td>Fixed</td>
<td>100.00 kHz</td>
<td>-134.53 dBc/Hz</td>
</tr>
<tr>
<td>Fixed</td>
<td>1.00 MHz</td>
<td>-145.83 dBc/Hz</td>
</tr>
<tr>
<td>Fixed</td>
<td>10.00 MHz</td>
<td>-149.60 dBc/Hz</td>
</tr>
</tbody>
</table>

Spot Noise offsets are user-definable (default to decade offsets)
Quantifying Phase Noise – Residual Noise

• Values calculated from integration of phase noise trace

  – Integrated Phase Noise
    \[ \int L(f) df \] (dBc)

  – Residual PM
    \[ \frac{180}{\pi} \sqrt{2 \int L(f) df} \] (deg or rad)

  – Residual FM
    \[ \sqrt{2 \int f^2 L(f) df} \] (Hz)

  – Jitter
    \[ \frac{1}{2\pi f_c} \sqrt{2 \int L(f) df} \] (sec)

<table>
<thead>
<tr>
<th>Residual Noise</th>
<th>Trace</th>
<th>Start Offset</th>
<th>Stop Offset</th>
<th>Int PHN</th>
<th>PM</th>
<th>FM</th>
<th>Jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1.00 kHz</td>
<td>10.00 MHz</td>
<td>-77.45 dBc</td>
<td>10.85 m° / 189.39 μrad</td>
<td>544.60 Hz</td>
<td>30.14 fs</td>
<td></td>
</tr>
</tbody>
</table>
Jitter – Time Domain Approach

- Oscilloscopes measure jitter directly in the time domain, but the scope’s internal jitter (phase noise) limits sensitivity to the range of picoseconds.
- Some very high-end scopes can measure in the range of 100 femtoseconds, but are very expensive.
Jitter – Frequency Domain Approach (Phase Noise)

- Jitter: 
  \[ \frac{1}{2\pi f_c} \sqrt{2 \int \mathcal{L}(f) df} \]  
  Units of sec

- RMS Jitter can be calculated by integrating phase noise.
- Phase noise techniques can measure jitter with excellent sensitivity. Jitter measurements well below 10 femtoseconds (1 fs = 10^{-15} s) are possible (much more sensitive than an oscilloscope).
- Phase noise plot makes it easy to distinguish random and deterministic jitter (difficult using an oscilloscope).
- Only clocks can be measured, not random data streams.
Causes of Oscillator Phase Noise

**Random Walk:** Close to carrier, generally caused by environmental effects

**Flicker FM:** Related to active oscillator physical resonance mechanism, power supply noise

**White FM:** Related to passive resonator oscillators

**Flicker $\phi M:** Related to noisy amplifiers and multipliers

**White $\phi M:** Far from carrier, generally caused by broadband output amplifier noise

Absolute Phase Noise Measurement Techniques

- Direct Spectrum Analyzer
- Phase Detector
- Phase Detector with Cross-Correlation
- Delay Line Discriminator
Direct Spectrum Analyzer Measurement

Simple setup, but how good is the measurement?
Direct Spectrum Analyzer Measurement

- Spectrum analyzer is a multistage receiver with multiple LOs
- Each LO adds phase noise to the input signal – Measurement result is the **sum** of phase noise from DUT and all LOs
- Full signal amplitude is present at every stage of the SA receiver – Measuring low level phase noise is limited by the SA’s dynamic range
- SA minimum resolution bandwidth limits close-in offset

![Diagram of spectrum analyzer](image-url)

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- Each LO adds phase noise to the input signal – Measurement result is the **sum** of phase noise from DUT and all LOs
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- SA minimum resolution bandwidth limits close-in offset
Direct Spectrum Analyzer Measurement

- Measurement sensitivity is limited by internal phase noise of spectrum analyzer.
- Check data sheet for internal phase noise of spectrum analyzer.
- Instrumentation noise always adds to measurement (error, not uncertainty).

![Graph showing phase noise measurement](image)

<table>
<thead>
<tr>
<th>Center frequency (dBc/Hz)</th>
<th>Offsets from carrier (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 GHz</td>
<td>1 Hz</td>
</tr>
<tr>
<td>40 GHz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>25 GHz</td>
<td>100 Hz</td>
</tr>
<tr>
<td>10 GHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>2 GHz</td>
<td>10 kHz</td>
</tr>
<tr>
<td>1 GHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>500 MHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td>100 MHz</td>
<td>10 MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$L_{\text{DUT}} - L_{\text{SA}}$ (dB)</th>
<th>Meas Error (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.0</td>
</tr>
<tr>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
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<tr>
<td>5</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>15</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Phase Noise Marker function corrects for ratio of RBW to 1Hz and Effective Noise Bandwidth (ENB) of the RBW filter (typically <1dB)

Must use averaging to get stable measurement and specifically, power averaging (not log averaging) to avoid measurement error from averaging noise samples in dB domain (-2.51dB)

This technique is correct, but is the measurement accurate?

What about the noise of the analyzer?

What if we want a phase noise curve instead of a point measurement?

What about AM noise?

What if I want to measure closer than 1Hz to the carrier?
Direct Spectrum Analyzer Measurement

Phase Noise Measurement Personality

- Phase noise is measured over a user specified offset range
- Spot noise is available
- Residual PM, FM, Integrated Phase Noise, and RMS Jitter are calculated from phase noise trace over user specified integration range
- Convenient, fast, and nicely formatted, but still has the limitations of the spectrum analyzer measurement method (phase noise of analyzer, limited close-in capability, etc.)
Direct Spectrum Analyzer Measurement
Drifting DUT using traditional approach

- Measurement is done in half-decade spans
- Center frequency re-tuning done at start of each half-decade
- Measurement bandwidth is reduced for each half-decade making drift more difficult to track
- Close-in offsets take longer to measure which gives the signal more time to drift
- Measurement error occurs if DUT drifts out of RBW filter
Direct Spectrum Analyzer Measurement
Drifting DUT using advanced IQ capture/DSP approach

• Measurement is still done in half-decade spans
• Signal is captured with wider IQ bandwidth in all half-decades
• Drifting signal stays within captured bandwidth
• Bandwidth reduction done using DSP
• Drift is compensated using digital PLL
• Even drifting signal is measured correctly
• Additional benefit: IQ capture approach also provides AM rejection
Direct Spectrum Analyzer Measurement – Summary

**Advantages**
- Fast and easy measurement setup
- High offset frequency range (up to 30GHz)
- Spectrum Analyzer can make many other measurements necessary for signal source characterization:
  - Harmonics
  - ACPR
  - Spurious emissions, etc.

**Limitations**
- Sensitivity is limited by inherent phase noise of the internal LO’s in the instrument
- Sensitivity also limited by dynamic range since low level noise must be measured in the presence of the carrier
- Most SA’s cannot reject AM noise
- Lower offset frequency is limited to 1Hz due to minimum 1Hz RBW
Absolute Phase Noise Measurement Techniques

- Direct Spectrum Analyzer
- Phase Detector
- Phase Detector with Cross-Correlation
- Delay Line Discriminator
Phase Detector Method

- Only phase noise of Ref Source adds to signal’s phase noise
- Main carrier energy is removed by PD and LPF
- LNA and Baseband Analyzer measure noise signal with high sensitivity
- Offsets closer than 1Hz can be measured (down to 0.01Hz)
Phase Detector Method

• Why offset DUT and Reference by 90°?

Phase detector most sensitive (most volts per degree) when nominal phase difference is 90°
Phase Detector Method

- Spectrum analyzer added phase noise of several internal LO’s
- With phase detector approach, only the single reference source phase noise is added – lower measurement floor, better sensitivity
- Same relationship between DUT noise and instrument noise applies, but instrument phase noise is lower

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Phase Detector Method

• Same presentation of results as with Spectrum Analyzer measurement.

• Phase Noise curve, Spot Noise, and Residual calculations are available.

• Spur detection algorithm displays and reports spurs separately (in dBc).

• Sensitivity is limited by the phase noise of the reference source which is lower than the multiple LO’s in the spectrum analyzer.
Absolute Phase Noise Measurement Techniques

• Direct Spectrum Analyzer
• Phase Detector
• Phase Detector with Cross-Correlation
• Delay Line Discriminator
Phase Detector with Cross-Correlation

- DUT
- PD
- Low Pass Filter
- LNA
- ADC
- PLL
- Noise Ref 1
- Ref 1
- Noise Ref 1

$\Delta \phi = 90^\circ$
Phase Detector with Cross-Correlation

![Diagram of Phase Detector with Cross-Correlation](image_url)
Phase Detector with Cross-Correlation

- Uncorrelated noise from Ref 1 and Ref 2 is suppressed by the cross-correlation function
  - Ref Noise Suppression: 10dB for 100 CC, 20dB for 10000 CC
  - DUT noise is common to both paths and is unaffected by cross-correlation
Phase Detector with Cross-Correlation

- Same presentation of measured data
- Cross-correlation effectively reduces the phase noise of the reference oscillator
- Up to 20dB sensitivity improvement over the standard phase detector method is possible
Phase Detector Method – Summary

**Advantages**

- Carrier Suppression
  - Analyzer dynamic range is not a limiting factor as it can be with the spectrum analyzer method
  - Measurements at very small offsets are possible (down to 0.01Hz)
- Phase Noise and AM Noise can be distinguished
  - AM Noise is inherently suppressed by the phase detector
- Cross-Correlation improves the sensitivity of the test system
  - 10dB for CC=100, 20dB for CC=10000

**Limitations**

- Restricted upper offset range (limited by digitizer bandwidth in baseband analyzer)
- Spectrum Analyzer is still necessary for measurement of other parameters:
  - Spurious Emissions, ACPR, Harmonics
Absolute Phase Noise Measurement Techniques

- Direct Spectrum Analyzer
- Phase Detector
- Phase Detector with Cross-Correlation
- Delay Line Discriminator
Delay Line Discriminator

- The delay line converts frequency fluctuations to phase fluctuations which are applied to a phase detector.
- No reference source required – good for noisy or drifting DUTs.
- Longer delay ($T$) gives better sensitivity, but reduces maximum usable offset.
- Maximum offset is limited to $\sim 1/(2\pi T)$ due to $\sin(x)/x$ term ($T \leq 160\text{ns}$ for 1MHz offset).
- Longer delay line also has higher loss which reduces PD sensitivity.
- Manual adjustment of phase shifter over 180° required for calibration.

Mathematical expression:

$$V = (2\pi T) \left( \frac{\sin(\pi f T)}{\pi f T} \right) K_{PD} \Delta f(t)$$
Delay Line Discriminator

- First measurement null occurs at \( f = 1/T \)
- Useful offset range up to \( f \approx 1/(2\pi T) \)
- Longer delay line gives better sensitivity, but has lower useful upper offset limit

\[
PD = (2\pi T) \left( \frac{\sin(\pi f T)}{\pi f T} \right) K_{PD} \Delta f(t)
\]

\( T = 100\text{ns} \) delay line
(useful to 1.6MHz, null at 10MHz)

\( T = 200\text{ns} \) delay line
(useful to 800kHz, null at 5MHz)

\[ L(f) \]

\[ f \]

\[ 5\text{MHz} \quad 10\text{MHz} \quad 20\text{MHz} \]
Additive Phase Noise Measurement

- Two-port DUT (e.g. amplifier)
- Source noise is correlated on both PD inputs – cancels out so only added noise of DUT is measured
- Manual adjustment of phase shifter over 180° required for calibration
- Phase detector may be external or internal to analyzer
AM Noise Measurement

• Recall the expression of a real-world sine wave:
  \[ V(t) = [A + E(t)] \sin(2\pi vt + \phi(t)) \]

• \( E(t) \) is the AM noise component

• AM noise is usually lower than phase noise – especially at close-in offsets

• AM Noise is traditionally measured using an external diode detector along with the baseband noise analyzer

• A signal generator with a known AM modulation index can be used to calibrate the measurement system
Summary

• Phase noise is unintentional phase modulation on a signal
• Residual parameters can be calculated from phase noise data – Integrated Phase Noise, Residual PM, Residual FM, and Jitter
• Absolute Phase Noise can be measured using several methods – each with its own strengths and weaknesses
  – Direct Spectrum Analyzer
  – Phase Detector, Phase Detector + Cross-Correlation
  – Delay Line Discriminator
• Additive Phase Noise is measured using a power splitter, phase shifter, and baseband noise analyzer
• AM Noise is measured using an external diode detector along with a baseband noise analyzer
Thank You!