Impact of Oscillator Controllability on System Performance
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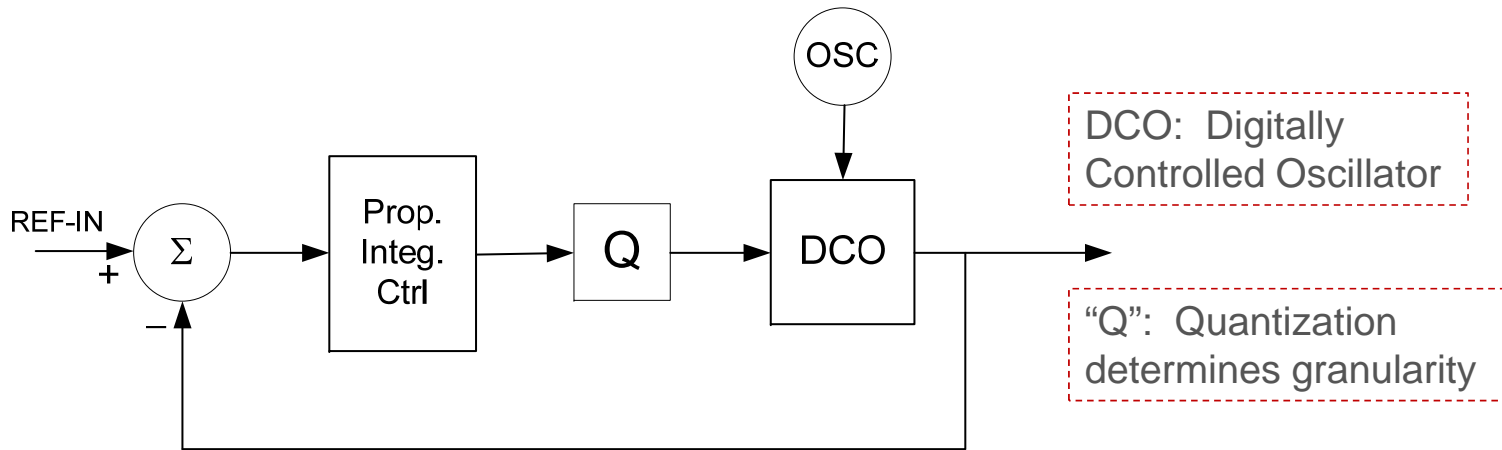
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Precise time. Synchronized.

Outline of Presentation

- General Model of a Locked Loop

- Digital Signal Processing View of a Locked Loop

- Packet-based Clocks – An Example

- Impact of control granularity on DCO performance
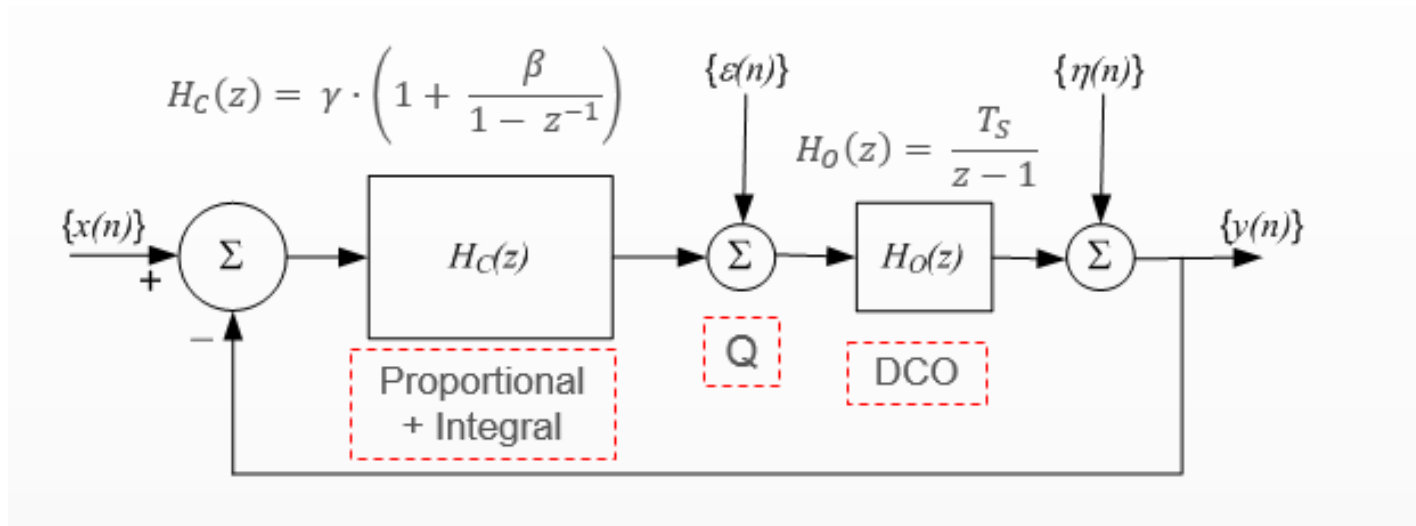
- Concluding Remarks

Simplified view of a locked loop

- Locked Loops accept a reference signal

- An error is generated by comparing the output to the reference

- A suitable control algorithm (typically proportional + integral) generates a control value

- The DCO control is a quantized version of the ideal control value

DSP view of a locked loop

$$H_C(z) = \gamma \cdot \left(1 + \frac{\beta}{1 - z^{-1}}\right)$$

$$\{\varepsilon(n)\}$$

$$\{\eta(n)\}$$

$$H_O(z) = \frac{T_S}{z - 1}$$

$\{x(n)\}$ Σ $H_C(z)$ Σ $H_O(z)$ Σ $\{y(n)\}$

Proportional + Integral   Q   DCO

- Update interval = T_S is equivalent to sampling interval

- The DCO control is a quantized version of the ideal control value

- Quantization (granularity) manifests itself as a noise sequence $\{\varepsilon(n)\}$

- Oscillator also adds noise $\{\eta(n)\}$ (typically white-FM)

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Analysis of the DSP based Locked Loop

$$H_{xy}(z) = \frac{\gamma T \cdot [(1+\beta)z - 1]}{z^2 - [2 - \gamma T \cdot (1 + \beta)]z + (1 - \gamma T)}$$

Transfer Function from input (x) to output (y)   Low Pass

$$H_{\varepsilon y}(z) = \frac{T \cdot [z - 1]}{z^2 - [2 - \gamma T \cdot (1 + \beta)]z + (1 - \gamma T)}$$

Transfer Function from quantizer (ε) to output (y)   "Bandpass Like"
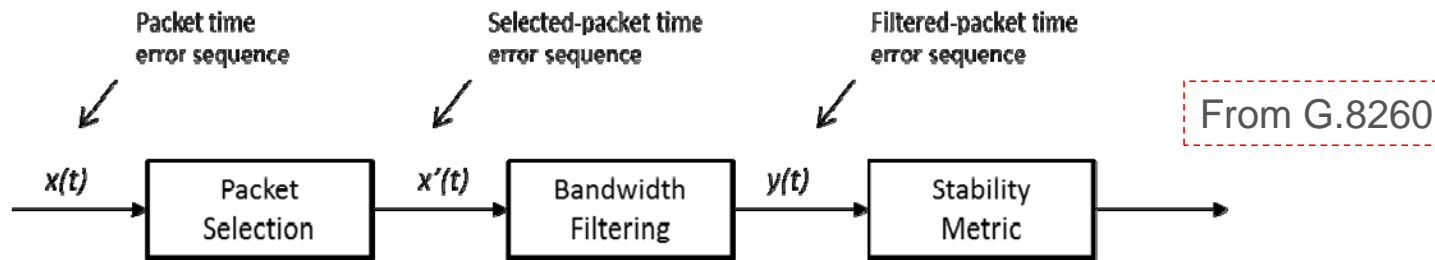
$$H_{\eta y}(z) = \frac{z^2 - 2z + 1}{z^2 - (2 - \gamma T \cdot (1 + \beta)) \cdot z + (1 - \gamma T)}$$

Transfer Function from oscillator (η) to output (y)   High Pass

- Transfer functions determine the behavior of the loop

- From input to output the response is low-pass

- From oscillator to output the response is high-pass

- White quantization noise manifests as white-noise-FM (random-walk phase) in clock output outside the loop bandwidth

- T : sampling interval (loop update interval)

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Example – Packet-Based Clock

Packet time error sequence		Selected-packet time error sequence		Filtered-packet time error sequence	

$x(t)$ → **Packet Selection** → $x'(t)$ → **Bandwidth Filtering** → $y(t)$ → **Stability Metric** →

- "Bandwidth Filtering" achieved with locked loop
- Assume packet selection provides a reference value every 100s ($T = 100s$)
- With $gT = 0.275$; $b = 0.05$; the 3-dB bandwidth is 0.5mHz with 0.2dB gain peaking
- The effective noise-gains for the input reference (noise) and the quantization (noise) are:

$$\sum_k \left| h_{xy}(k) \right|^2 = 0.16$$

$$\sum_k \left| h_{\varepsilon y}(k) \right|^2 = 2.1 \times 10^4$$

← Granularity amplification!

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Granularity Requirement

- Viewpoint #1 (Input Noise)
  - Assume reference input noise (PDV post selection) standard deviation is typically of the order of 1us (1×10^{-6})
  - Assume quantization noise effect is one order of magnitude less than the noise in the reference
  - Then quantization noise standard deviation should be less than 0.28×10^{-9} or **280 ppt**

- Viewpoint #2 (Holdover)
  - In holdover, the granularity of the DCO affects time error in holdover. To hold 1us in 100,000s (~1day) granularity must be less than 1.0×10^{-11} or **10 ppt**

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Granularity Requirement

- Viewpoint #3 (TDEV Performance)
  - Output performance is defined by TDEV mask. Assuming T = 100s and factor of 10 "margin",

$$\sigma_\epsilon < \left(\frac{1}{10}\right) \cdot \frac{TDEV(\tau = 100s)}{\sqrt{2.1 \times 10^9}}$$

  - Example: Fig.2 in G.8262 (EEC Option-1), allowed TDEV at 100s is ~6.4ns. This limits granularity (standard deviation) to ~4.4×10^{-12} or **4.4 ppt**

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Concluding Remarks

❑ DCO Granularity is important when implementing DSP based locked loops

❑ An approach to analyzing the constraints on DCO granularity is provided

❑Typical granularity requirement is between 200 ppt and 4 ppt

Questions?