INTRODUCTION TO CLOCKS

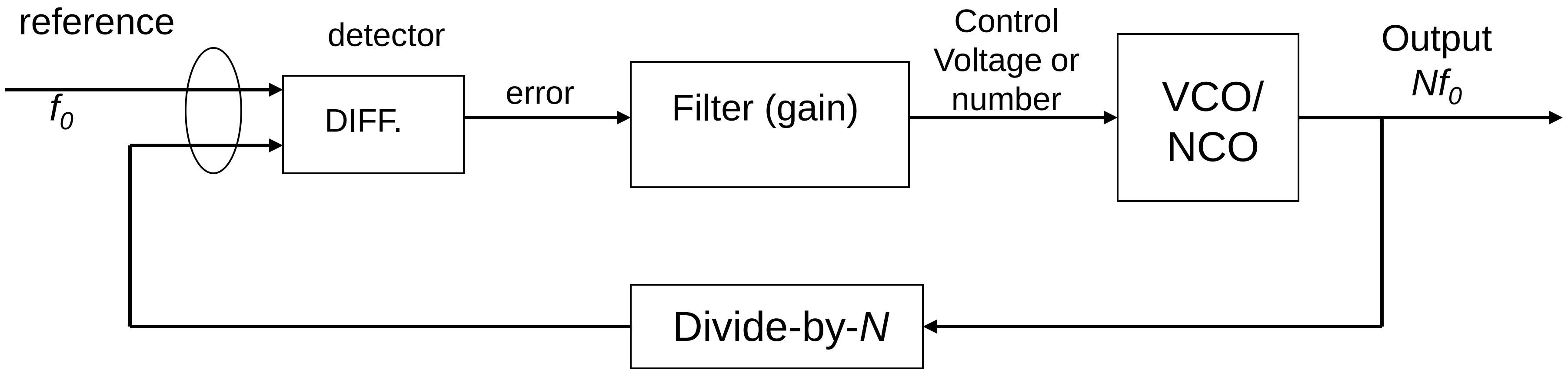
Introduction to Clocks

- Clocks and Oscillators
- Timing models for clocks and “locked loops”
- Fundamental Clock Concepts and Metrics
  - Time Interval Error
  - MTIE
  - TDEV

Clocks and Oscillators

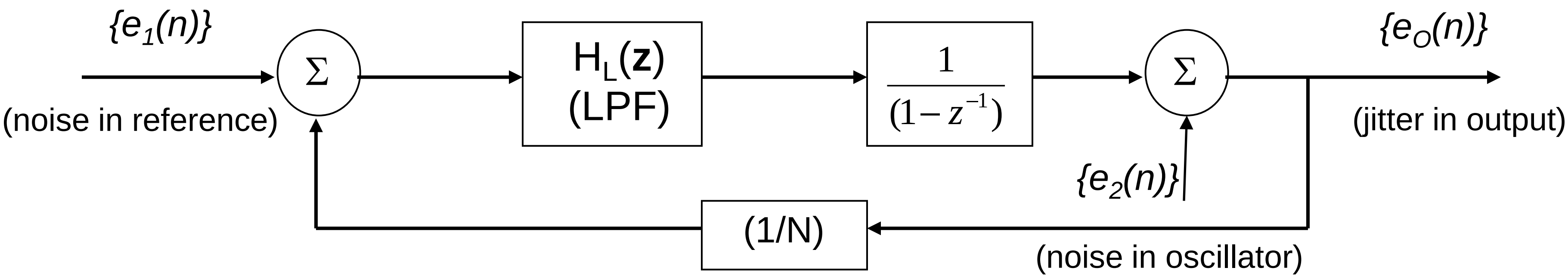
- Distinction is more in terms of emphasis
  - Both entities relate to time/frequency
  - Both entities have the notion of periodicity (time-base)
  - Both entities provide “edges”, but –
    - Clocks usually associated with edges (square waves) (digital)
    - Oscillators usually associated with waveforms (sine waves) (analog)
- Clock: Device/system that provides timing signals to other devices/systems
  - Emphasis is on time (time interval) accuracy
  - There is the notion of calibration (traceability to UTC)
  - A clock is a “disciplined” oscillator
- Oscillator: Component providing periodic signals
  - Emphasis is on frequency stability (temperature, aging)
  - Waveform integrity is important (“phase noise”)
  - Oscillators are components of clocks

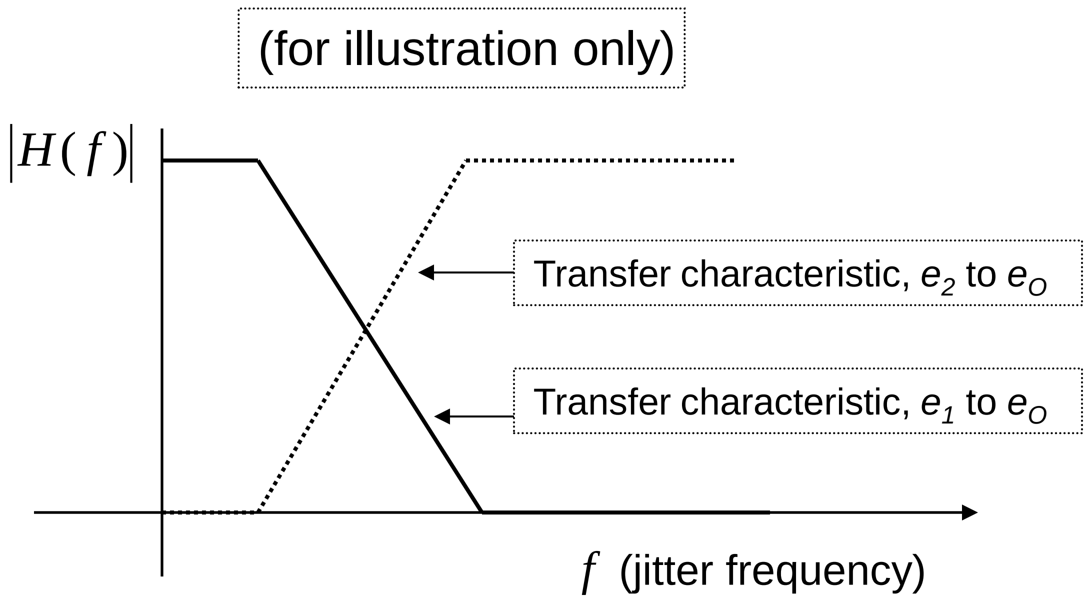
Loops and Holdover



- Closed loop to discipline oscillator to align with reference
- What if reference fails … Holdover operation
  - retain the last "good" value for control voltage/value
- What happens then?
  - frequency initially "good" (assuming instantaneous operation)
  - drift away (aging, temperature, noise, etc.)
  - "stable" value will better than value associated with stratum
  - quality of oscillator becomes the determining factor

Analytical Model of Locked Loop





- High-freq. Noise (jitter) in output depends on the oscillator.
- Low-freq. noise (wander) depends on the reference.
- Narrow-band (LPF) implies a long time-constant.
- How large time-constant can be is governed by TDEV(τ) of oscillator and reference (flicker floor)

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Common Mathematical Models

$$clock(t) = A \cdot \cos\big(\Phi(t)\big) = A \cdot \cos\big(\omega \cdot t + \phi_0 + \varepsilon(t)\big)$$

- signal → $clock$
- Mathematical time → t
- Phase function → $\Phi(t)$
- (radian) frequency → ω
- “Clock Noise” → $\varepsilon(t)$

• A: Amplitude of signal. Does not figure in timing metrics.

• ϕ_0: Initial phase. Depends on choice of time origin. Usually assumed to be 0.

• $\varepsilon(t)$: Can be further decomposed into different categories such as frequency error, frequency drift, and random noise components

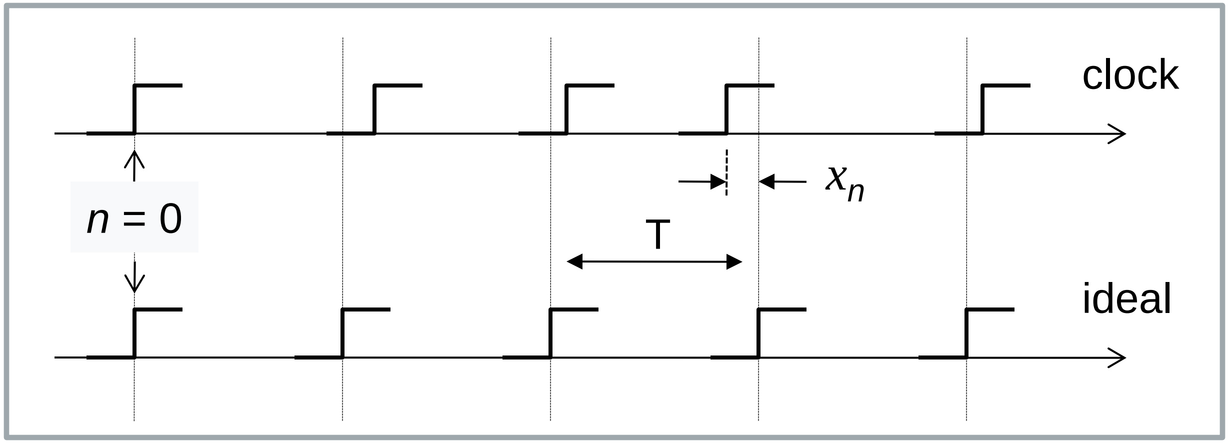
• ideal periodic signal: $\Phi(t)$ is a linear function of t ($\varepsilon(t) \equiv 0$)

$$x(t) = a_0 + y \cdot t + \left(\frac{1}{2}\right) \cdot D \cdot t^2 + \phi(t)$$

$$x(nT_s) = a_0 + y \cdot nT_s + \left(\frac{1}{2}\right) \cdot D \cdot (nT_s)^2 + \phi(nT_s)$$

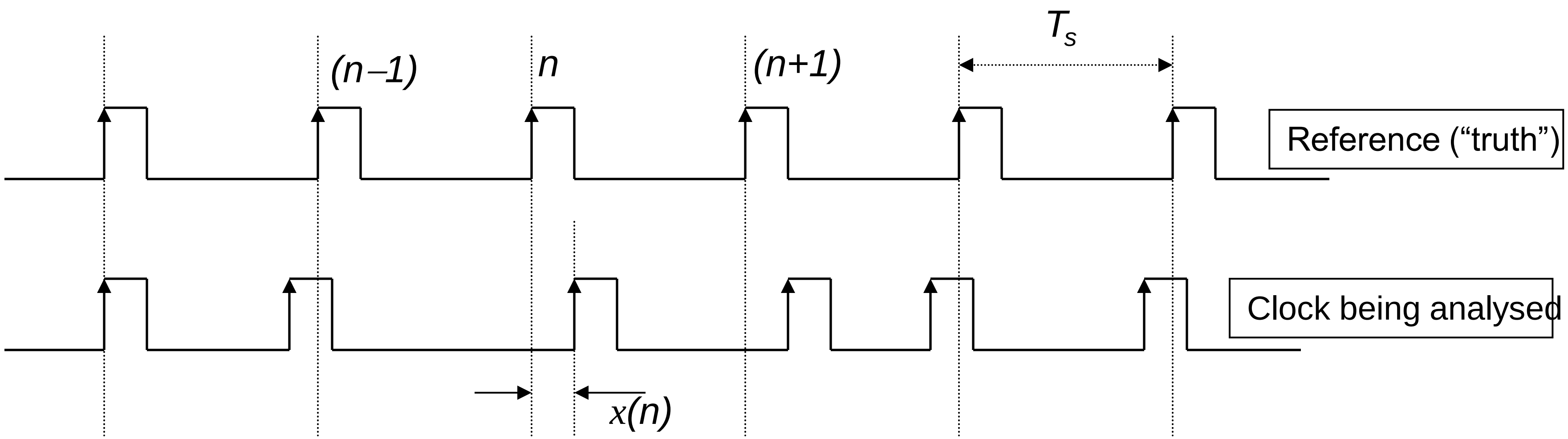
Time Error Models

Clock Metrics - Basics



- Clock signals are (<u>approximately</u>) periodic (<u>nominal</u> period ~ T)
- Errors:
  - Edge does not line up – *phase* error (expressed in time units)
- Time Error Sequence : $\{x_n\}$ or $\{x(n)\}$
  - All clock metrics derived from time error sequence
  - Note: the time error varies "slowly" so we do not need every edge of a high-speed signal and can divide down to a convenient rate (e.g. 4 kHz or even less) (However: careful when dividing down)
  - Common assumption: $x_0 = 0$.

Time Interval Error



Basic premises:

- Both reference and clock being analyzed have same *nominal* period, T_S
- The *nominal* value for $x(n)$ is zero (or a constant)
- $T_0 = 0$ (common assumption) $\Rightarrow$ $x(n) = n \cdot T_S - T_n$

The discrete-time signal $\{x(n)\}$ is the "Time Interval Error" (TIE) and is the basis for quantifying the performance of the clock (relative to reference)

$\{x(n)\}$ can be viewed as the samples of a (analog) signal, $x(t)$, taken every T_s seconds (implied sampling rate = $f_s = 1/T_s$) [Think DSP]

Clock Metrics – MTIE and TDEV

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MTIE

A measure of peak-to-peak excursion expected within a given interval, τ (τ is a parameter). The observation interval is scanned with a moving window of duration τ and MTIE(τ) is the maximum excursion.

Given a set of N observations {*x(k); k=0,1,2,…,(N-1)*}, with underlying sampling interval τ_0, let $\tau = n \cdot \tau_0$ ("window" = *n* samples; *n* = *1,2,…,N*).

Peak-to-peak excursion over *n* samples starting with sample index *i* is:

$$peak-to-peak(i) = \{ \max_{k=i}^{k=i+n-1} x(k) - \min_{k=i}^{k=i+n-1} x(k) \}$$

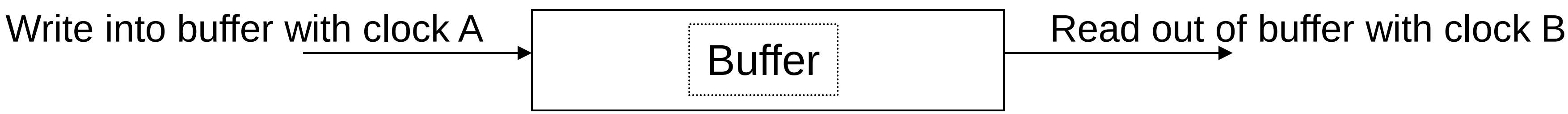
MTIE(*n*), or MTIE(τ), is the largest value of this peak-to-peak excursion:

$$MTIE(n) = \max_{i=0}^{N\text{-}n} \{ \max_{k=i}^{k=i+n-1} x(k) - \min_{k=i}^{k=i+n-1} x(k) \}$$

Clock Metrics – MTIE and TDEV

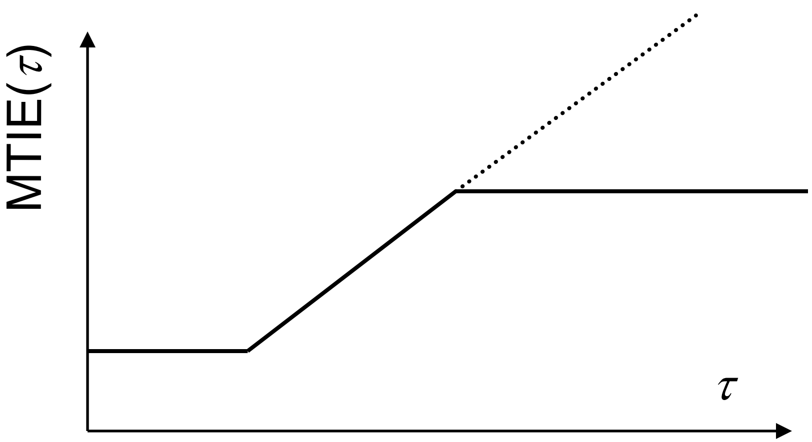
MTIE

MTIE is a useful indicator of the size of buffers and for predicting buffer overflows and underflows.



Buffer size > MTIE(τ) implies that overflow/underflow unlikely in any interval < τ

Buffer size = MTIE(τ) implies that overflow/underflow occurs approx. every τ seconds



Observations regarding MTIE:

- monotonically increasing with τ
- linear increase indicates freq. offset
- for small τ, MTIE(τ) $\leftrightarrow$ jitter
- for medium τ, MTIE(τ) $\leftrightarrow$ wander
- for large τ, indicates whether "locked"

Clock Metrics – MTIE and TDEV

TDEV

A measure of stability expected over a given observation interval, τ (τ is a parameter).

Given a set of N observations {*x(k); k=0,1,2,…,(N-1)*} with underlying sampling interval τ_0, let $\tau = n \cdot \tau_0$ ("window" = *n* samples; *n = 1,2,…,N*).

$$\sigma_x(\tau) = TDEV(\tau) = \sqrt{\frac{1}{6n^2(N-3n+1)} \sum_{j=0}^{N-3n} \left[\sum_{i=j}^{n+j-1} \left(x_{i+2n} - 2x_{i+n} + x_i \right) \right]^2}$$

$$for\ \ n = 1,2,\ldots,\left\lfloor \frac{N}{3} \right\rfloor$$

Conventional Definition

Note: $x(k) \Leftrightarrow x_k$

TVAR = square of TDEV

Modified Allan Variance (related to TDEV) : $\sigma_y(\tau) = \frac{\sqrt{3}}{\tau}\sigma_x(\tau)$

TDEV suppresses initial phase and frequency offset and quantifies the strength of the frequency drift and noise components {i.e. $\varepsilon(t)$}

TDEV provides guidance on the noise process type.

Implication of TDEV(τ) versus τ

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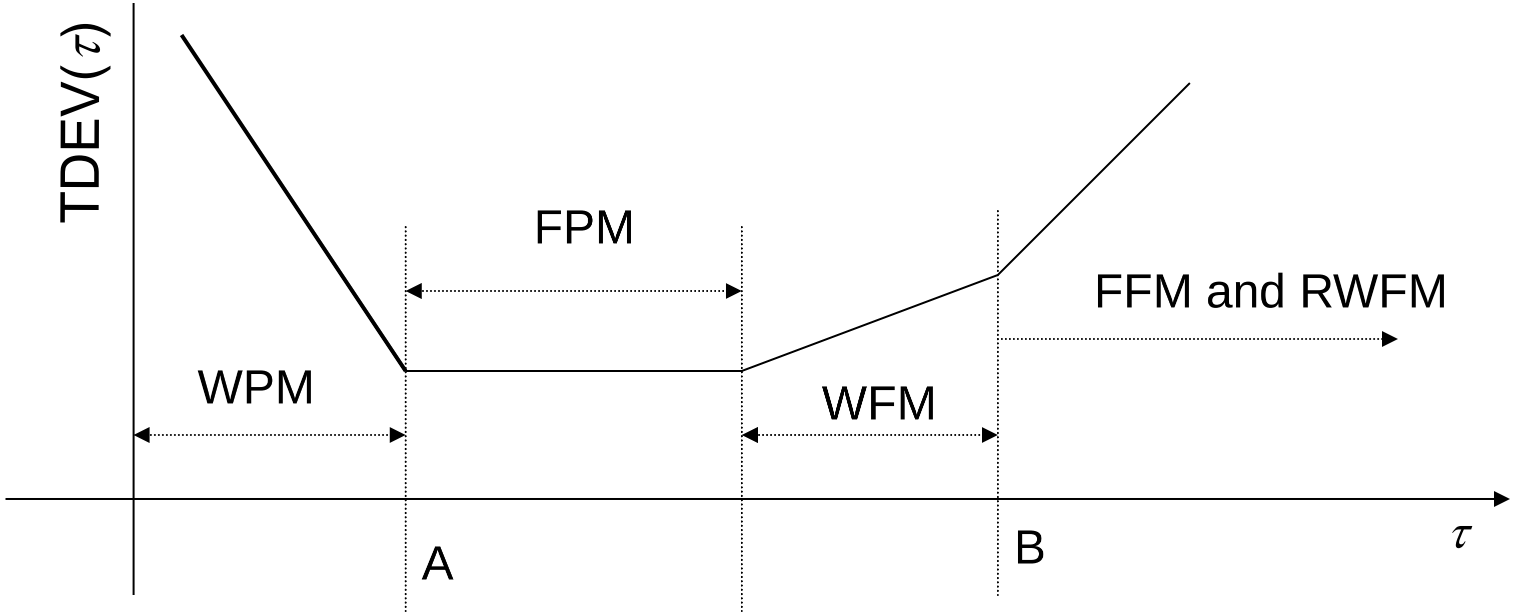

"Phase coherence" for up to A sec.
$\Rightarrow$ Keep PLL time constants less than A sec.

Phase Flicker Floor

"Frequency coherence" for up to B sec.
$\Rightarrow$ Keep FLL time constants less than B sec.

Frequency Flicker Floor