Fundamentals of Synchronization & Timing

WSTS-2025 Tutorial Session

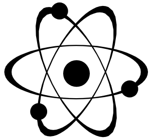
Kishan Shenoi
Kishan.shenoi@gmail.com

Fundamentals of Timing and Synchronization

- **Basic Principles**
  - **Time and Frequency**
  - **Alignment (frequency, phase, time)**
- Fundamental need for Synchronization
  - Coordinated Signal Processing requires phase alignment
  - Time-stamping events (in geographically separated locations) requires time alignment
  - Buffer read/write requires frequency alignment
- Transfer methods for frequency/time
  - Transfer methods (one-way and two-way)

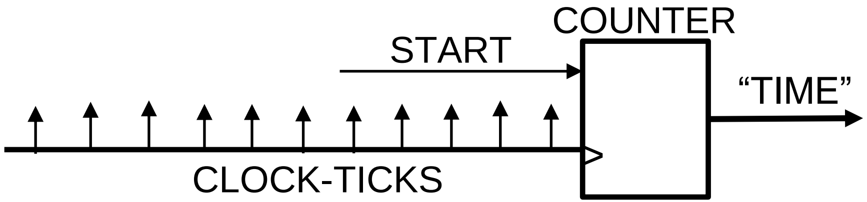
Time and Frequency

- A clock is a frequency device based on physics



Provides "ticks" at precise intervals (period);
Frequency is reciprocal of period

- Electronic systems count "ticks" for time interval



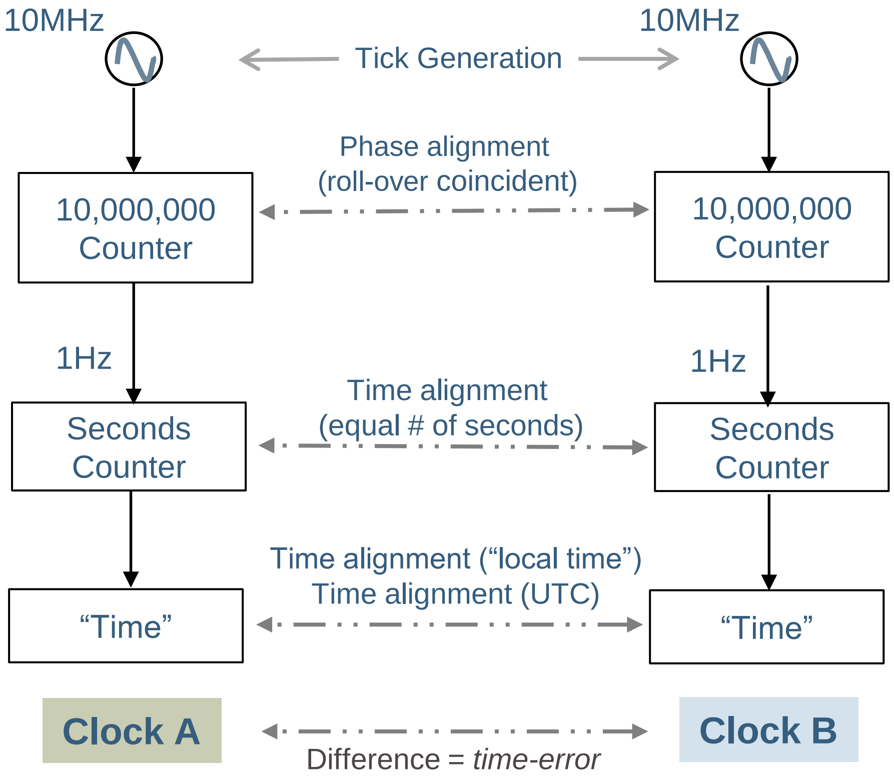
- "Time-Clock" provides the elapsed time from "start"
- Granularity of time related to tick period
- PLL…reduce tick interval; Divider…increase tick interval

- *Time* is a combination of a *signal* (event) and a *label* (time value) and is always considered in terms of elapsed time from an agreed-upon reference

Alignment in Frequency, Phase & Time

Aligning (or Synchronization) of two Time Clocks implies:			
Frequency B	=	Frequency A	Syntonization
Phase B	=	Phase A	Roll-over instant
Seconds B	=	Seconds A	Elapsed time equal
"Time": Same formatting convention, time-zone, etc.			

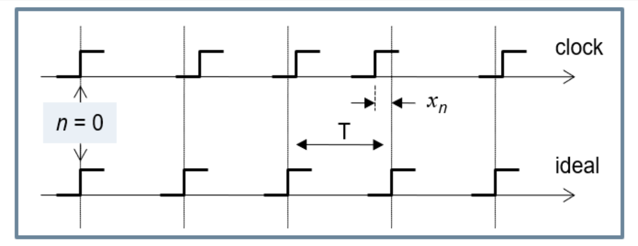
Clock is a frequency device, provides "ticks" → Electronic Systems count "ticks" for time interval → Time is a combination of a <u>signal</u> (event) and a <u>label</u> (time value)



Clock Metrics

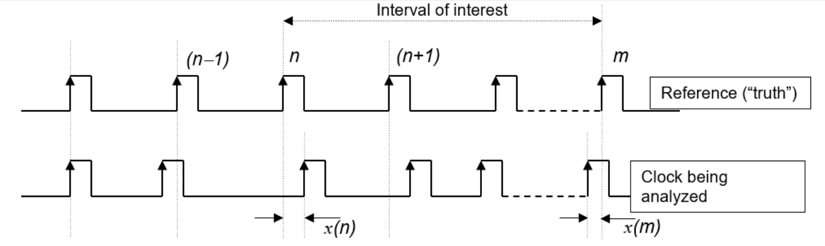
Time Error

- Clock signals are (<u>almost</u>) periodic (<u>nominal</u> period ~ T)
- Time Error (Phase Error): Edge does not line up – phase error (expressed in time units)
- Time Error is the basis for all other metrics



Time Interval Error (TIE)

- Consider an interval of interest
- Start: "n" ; Stop: "m"
- Duration measured by ideal clock ("truth") : $(m - n) \cdot T_S$
- Error in measurement of same interval by clock being analyzed: $TIE(m,n) = x(m) - x(n)$



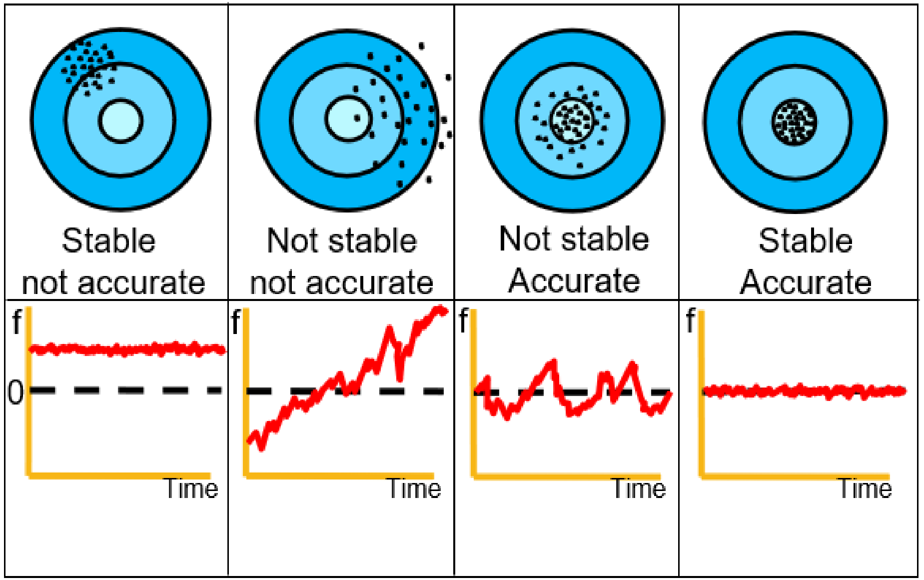
MTIE and TDEV

Maximum Time Interval Error (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. MTIE is a useful indicator of the size of buffers and for predicting buffer overflows and underflows

Time Deviation (TDEV): A measure of stability expected over a given observation interval, τ (τ is a parameter). TDEV provides guidance on the noise process type

Accuracy and Stability

- **Accuracy**: Maximum (freq., phase or time) error over the entire life of the clock
- **Stability**: (Frequency, phase or time) change over a given observation time interval
- **Stability** is expressed with some statistical dispersion metric as a function of observation interval (e.g. ADEV, TDEV, MTIE, etc.)
- All metrics are computed on the *time-error* sequence



Samples of measurements of time-error or frequency offset

Fundamentals of Timing and Synchronization

- Basic Principles
  - Time and Frequency
  - Alignment (frequency, phase, time)
- **Fundamental need for Synchronization**
  - **Coordinated Signal Processing requires phase alignment**
  - **Time-stamping events (in geographically separated locations) requires time alignment**
  - **Buffer read/write requires frequency alignment**
- Transfer methods for frequency/time
  - Transfer methods (one-way and two-way)

Fundamental Need for Synchronization: Signal Processing

- Combining signals from different sources necessitates that the signals be in proper "phase"
  - Example: Interference cancellation involves subtracting the "known" interference from the received signal (e.g. EICIC, echo cancellation)
  - Analysis is application specific
- In interference cancellation, the received signal, $y(t)$, contains an interfering signal, $x(t)$, which is "known"…imperfect representation of $x(t)$ results in degraded performance that can be quantified in terms of signal-to-noise ratio (SNR):
  - Proper signal : $x(t)$; *Synchronization* error manifests as a delay: $x(t + \delta)$
  - "Noise" resulting just from synchronization error is

$$\epsilon(t) = x(t) - x(t + \delta)$$

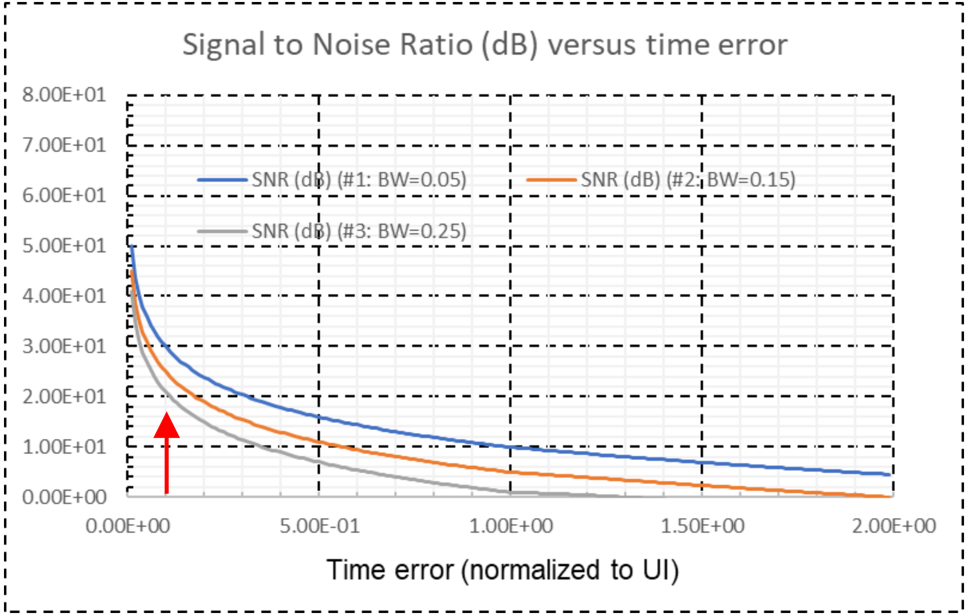
- Synchronization error can be quantified in terms of *Signal-to-Noise Ratio* (SNR)

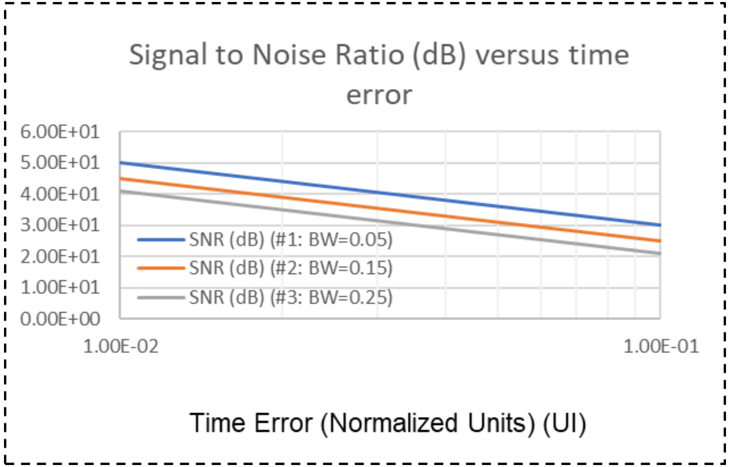
Fundamental Need for Synchronization: Signal Processing

- "Noise" resulting just from synchronization error of δ is

$$\epsilon(t) = x(t) - x(t+\delta)$$

SNR drops to ~25dB just due to 0.1 UI time error; impact increases with signal bandwidth





Signal Processing requires good synchronization

Fundamental Need for Synchronization – More

- Time-Stamping Events
  - Required if events occur “simultaneously” in separate equipment/locations
  - Ordering of events established by time-stamping using a common clock (e.g. traceable to UTC or TAI or GPS, etc.).
  - Requires end-point synchronization to this common clock.
  - Many examples (distributed database, shared documents, stock trades, sensor fusion, multi-player gaming, etc., etc.)
- How can an action or event be verified or validated?
  - Time-stamp using a common clock (usually UTC)
  - Important in Blockchains, crypto-currency, etc.
  - Important for stock market to chronologically order trading activities
- Synchronous multiplexing (“TDM”)
  - Lack of synchronization (syntonization) results in buffer overflow/underflow events (aka slips)

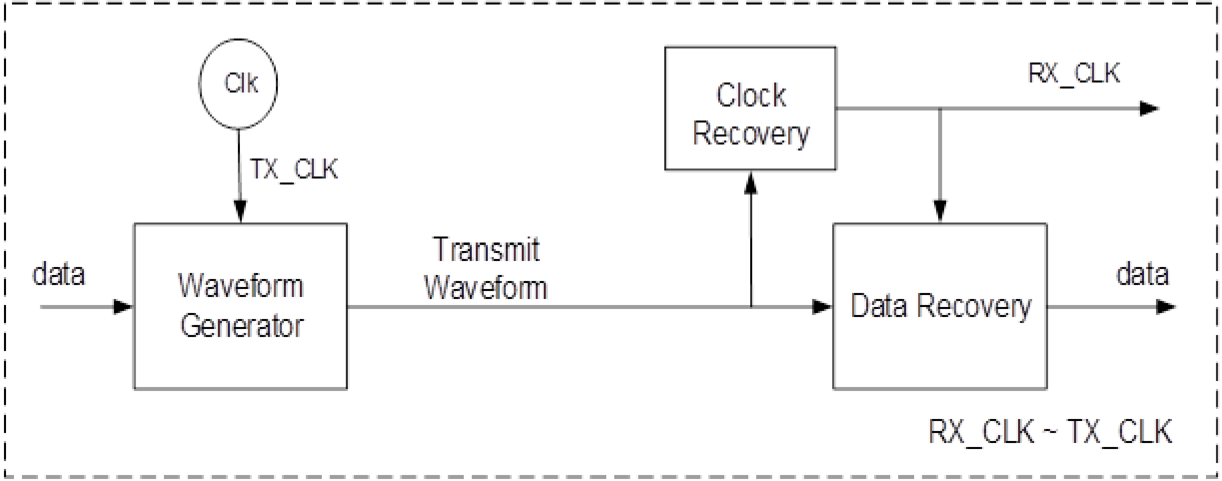
Time-stamping events (in geographically separated locations) requires time alignment
Chronological ordering requires time-stamps with time aligned to common reference
Synchronous multiplexing requires frequency alignment of streams

Fundamentals of Timing and Synchronization

- Basic Principles
  - Time and Frequency
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Coordinated Signal Processing requires phase alignment
  - Time-stamping events (in geographically separated locations) requires time alignment
  - Buffer read/write requires frequency alignment
- **Transfer methods for frequency/time**
  - **Transfer methods (one-way and two-way)**

Transfer of frequency – *Timing Signal (one-way)*

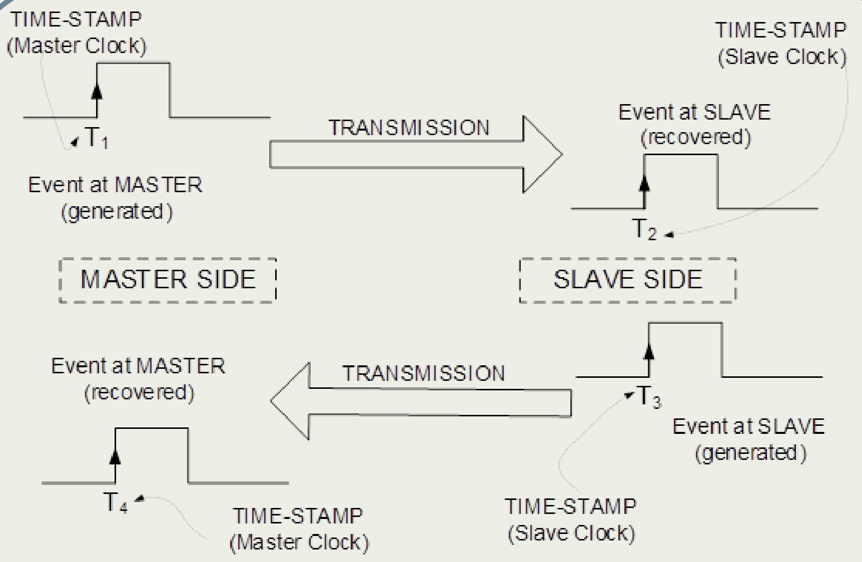
- A timing signal is a signal that inherently includes the clock properties of the source, allowing the destination to extract a timing reference
- Using this timing reference the destination can construct a (near) replica of the source clock
- Example: the transmit waveform used to deliver digital information can provide a *frequency reference*.



Transfer of Time (e.g. Precision Time Protocol: IEEE 1588™)

- Transfer of time and/or phase requires two-way exchange to determine round-trip delay
- Utilizes time-stamped packets to provide a timing reference
- Transfer quality affected by variable transmission delay and asymmetry
- PTP (*aka* IEEE 1588™):
  - Master sends *Sync_Message* (with T_1)
  - Slave time-stamps arrival (T_2)
  - Slave sends *Delay_Request*; time-stamps departure (T_3)
  - Master time-stamps arrival (T_4)
  - Master sends *Delay_Response* (with T_4)

Modern terminology evolution:
"Slave" → "Subordinate" → "TimeReceiver"
"Master" → "TimeTransmitter"



1. Round Trip Delay (RTD) $=(T_4-T_1)+(T_2-T_3)$
2. Assuming symmetric delays upstream and downstream, One Way Delay (OWD) = (1/2) RTD
3. Slave Offset from Master, OFM $= (1/2)[(T_4+T_1) - (T_3+T_2)]$

Fundamentals of Timing and Synchronization

Topics Addressed

- Basic Principles
  - Time and Frequency
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Coordinated Signal Processing requires phase alignment
  - Time-stamping events (in geographically separated locations) requires time alignment
  - Buffer read/write requires frequency alignment
- Transfer methods for frequency/time
  - Transfer methods (one-way and two-way)

Thank You

Questions, comments, suggestions?

kishan.shenoi@gmail.com