# WSTS-2015 Tutorial Session

## Workshop on Synchronization in Telecommunications Systems
## San Jose, California, March 9, 2015

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# Tutorial Outline

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- Fundamentals of Synchronization
- Introduction to Clocks
- Timing Reference Sources
- Photo-journalism: GPS Installations
- Phase-Locked Loops and Oscillators
- Physical Layer Timing
- Packet-based Timing
- Standards
- Concluding Remarks

# FUNDAMENTALS OF SYNCHRONIZATION

# Fundamentals of Synchronization

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- Time and Frequency
  - Clocks and Oscillators
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Data-transmission schemes require synchronization
  - Timing alignment required in voice-band transmission
  - Timing alignment implicit in circuit emulation
  - Timing alignment in wireless
  - Timing alignment in multimedia

# Time and Frequency Sources

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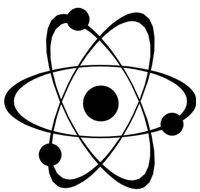
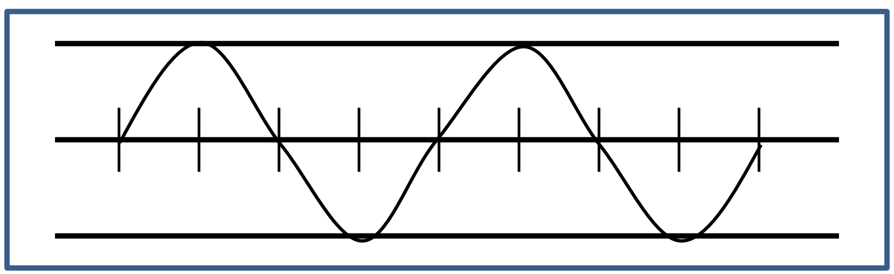
- A clock is a frequency device based on physics



Provides "ticks" at precise intervals

- Electronic systems count "ticks" for time interval



"Time-Clock" provides the time elapsed since the "start"

- Time is steered to UTC
  - Defines the "start" plus corrections for astronomy

# Time and Frequency

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- Time is an artificial construct.
  - Choose an origin ("epoch") that people can agree on
  - Count the number of seconds (milliseconds /microseconds /etc.) from the origin.
    - Define suitable units such as seconds and minutes and hours and days and so on to express the count from the origin
- Time Interval (e.g. 1 second) is based on a physical property of the Cesium atom.

| Timescale | Epoch | Relationship | Leap Seconds | Other |
|---|---|---|---|---|
| **TAI** | Jan 1, 1958 | Based on SI second | No | **Continuous** |
| **UTC** | Jan 1, 1972 | TAI-UTC = 33sec | Yes | **Discontinuous** |
| **UT-1** | Jan 1, 1958 | Earth's rotation | No | **Astronomical** |
| **GPS** | Jan 6, 1980 | TAI – GPS = 19sec | No | **Continuous** |
| **Loran -C** | Jan 1, 1958 | UTC + 23 sec | No | **Discontinuous** |
| **Local** | Jan 1, 1972 | TAI-UTC = 33sec | Yes | **Discontinuous, Based on Time zone offset** |
| **PTP** | Jan 1, 1970 | TAI – PTP = 10sec | No | **Continuous** |
| **NTP** | **Jan 1, 1900** | **UTC** | **Yes** | **Discontinuous** |



"discontinuous" timescale allows for jumps related to leap seconds

# Time and Frequency

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## Time and Frequency Need Signals!

- Signals are Physical
  - Accuracy and stability are no better than the physical layer
  - Data layers disrupt the T & F signals
  - Interference to the physical signal blocks access to T & F
- Communications systems are layered with devices only connected to the neighboring layers
  - Sync gets worse farther from the physical layer
- Time accuracy requires access to UTC through a national lab – GNSS used
- GNSS signals are vulnerable!
- Frequency Accuracy requires access to the Cs. Atomic transition

# Two Issues Here

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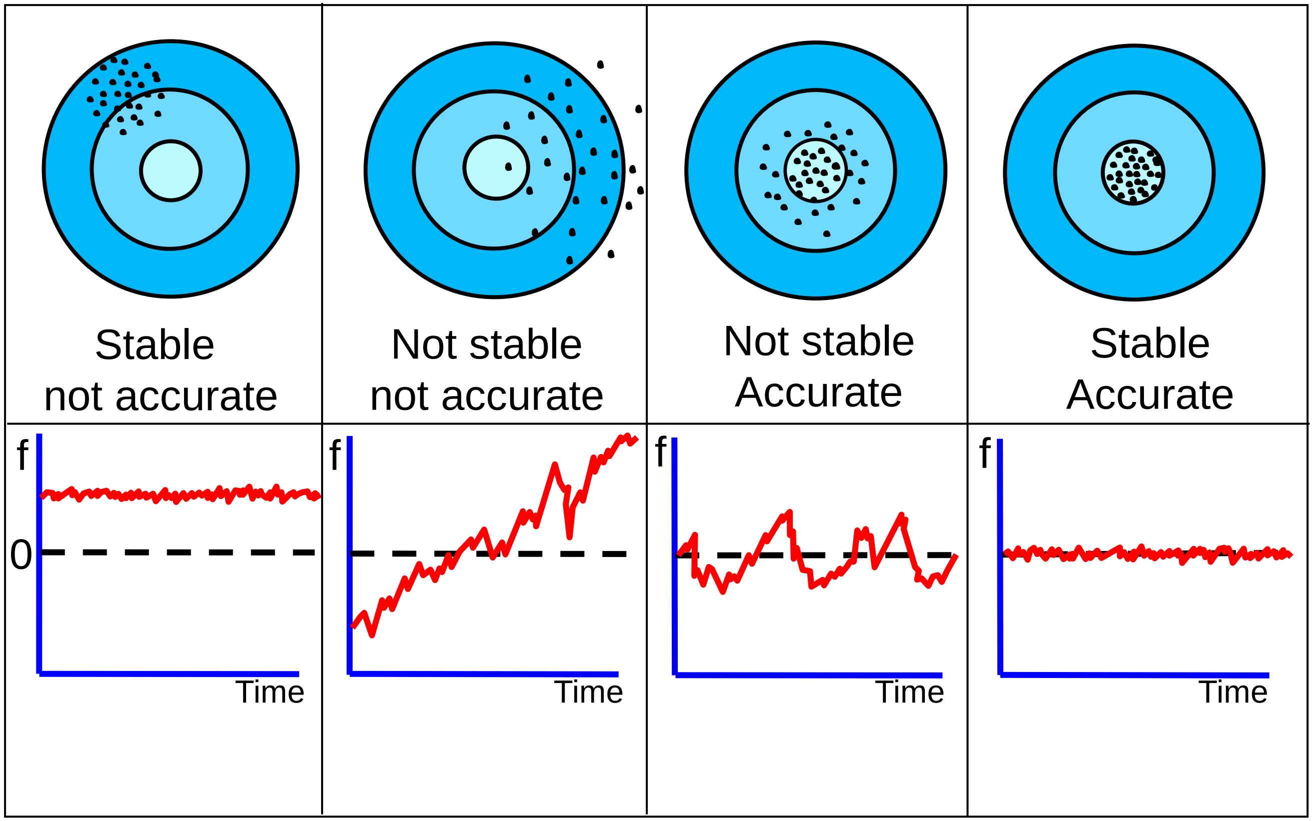
- Since a clock is a frequency device, the best clock exhibits only white noise on frequency, hence a random walk in phase.  Even the best clocks will walk off unboundedly in time.

- Since the time standard is artificial, time MUST be transferred from the relevant time standard
  - There is often confusion with the human experience of time vs. metrological time.  Standard time is a signal plus data
  - Often what is needed is synchronization among locations, not UTC per se, though that is often the most efficient way to achieve synchronization

# Accuracy and Stability

- **Accuracy**: Maximum (freq., phase or time) error over the entire life of the clock
- **Stability**: (Freq., 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, a.o.)

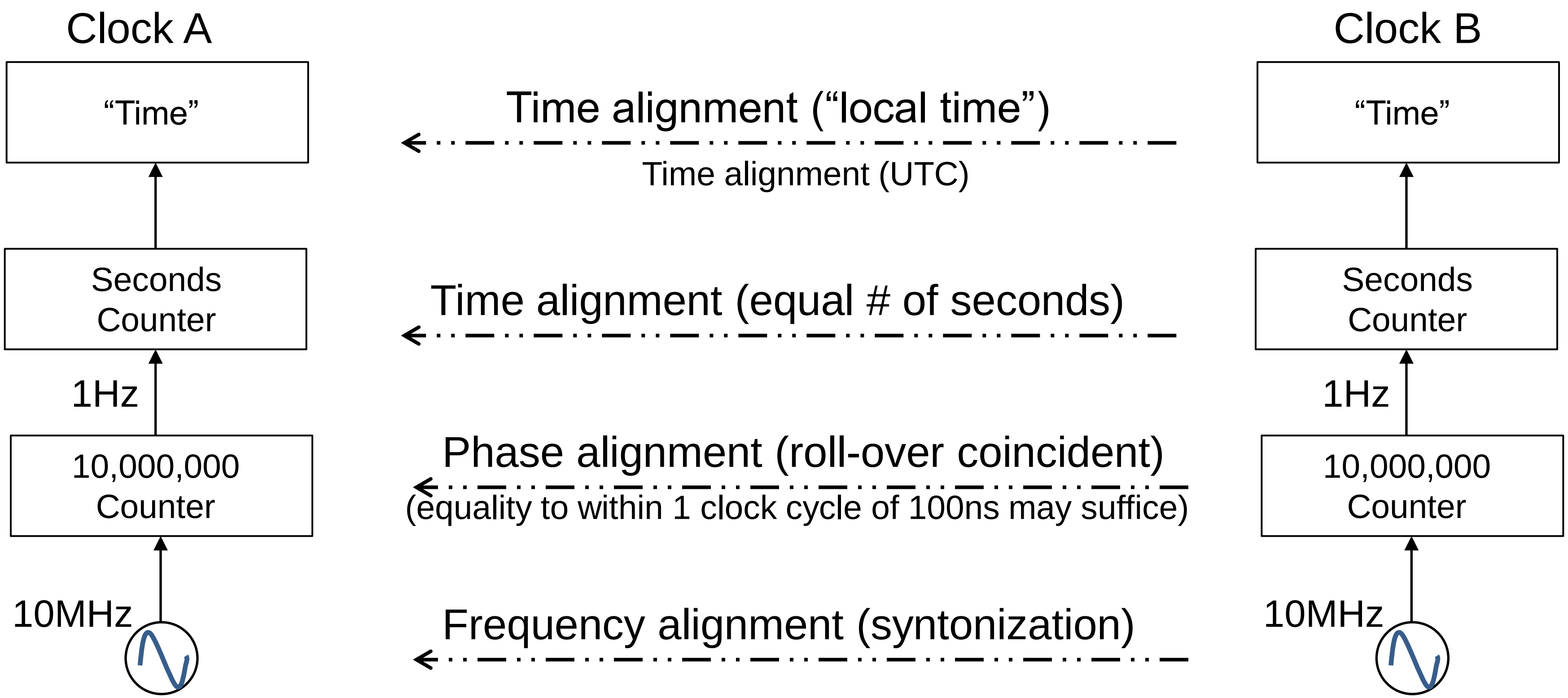


# Clocks and Oscillators

- 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

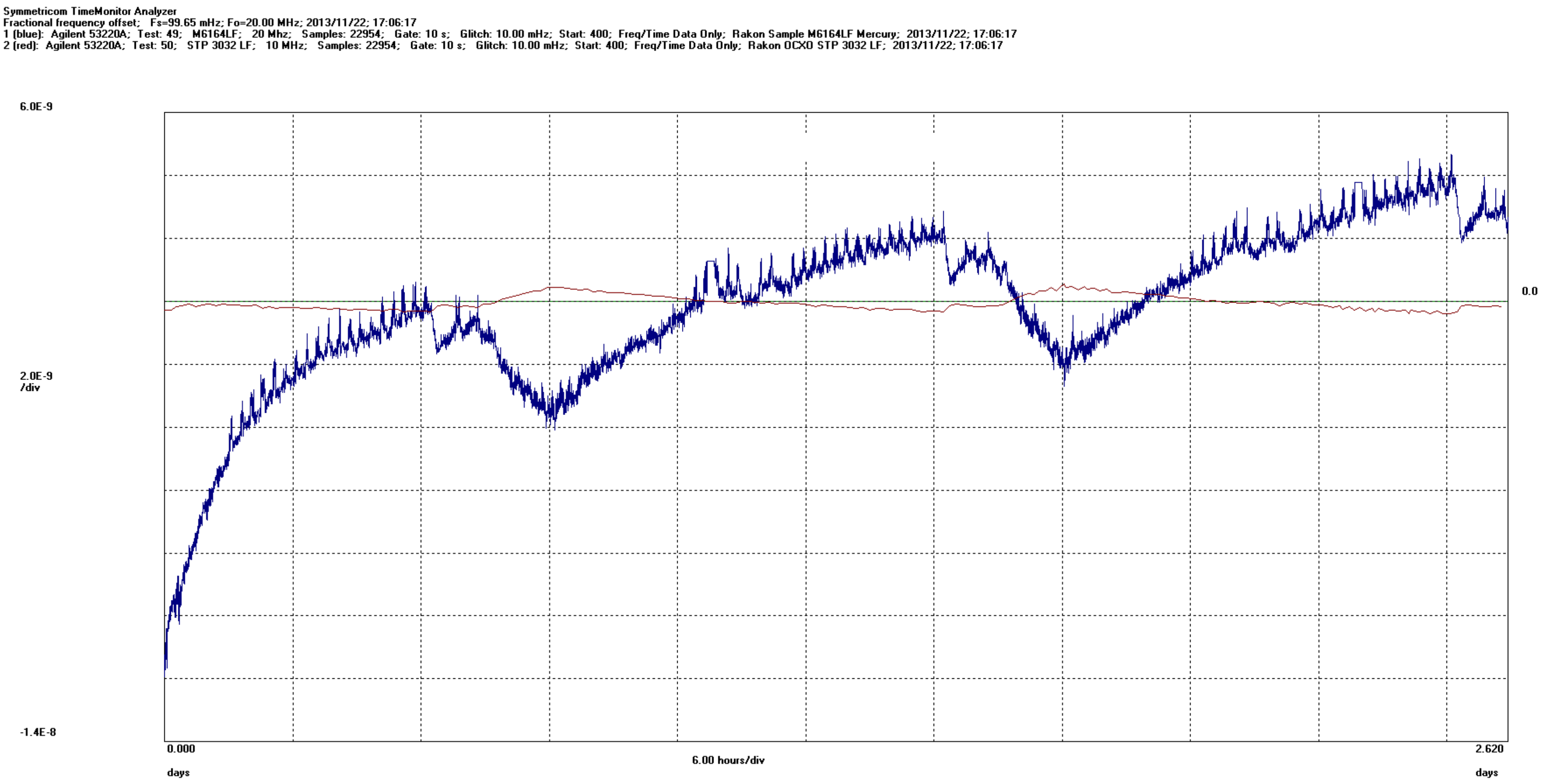
# Time and Frequency

- Aligning two time clocks (synchronization) implies:
  - Make frequency B = frequency A (syntonization)
  - Make phase B = phase A (e.g. roll-over instant of $10^7$ counter)
  - Make seconds B = seconds A (elapsed time equal; same time origin)
  - Choose same formatting convention (and time-zone, etc.)



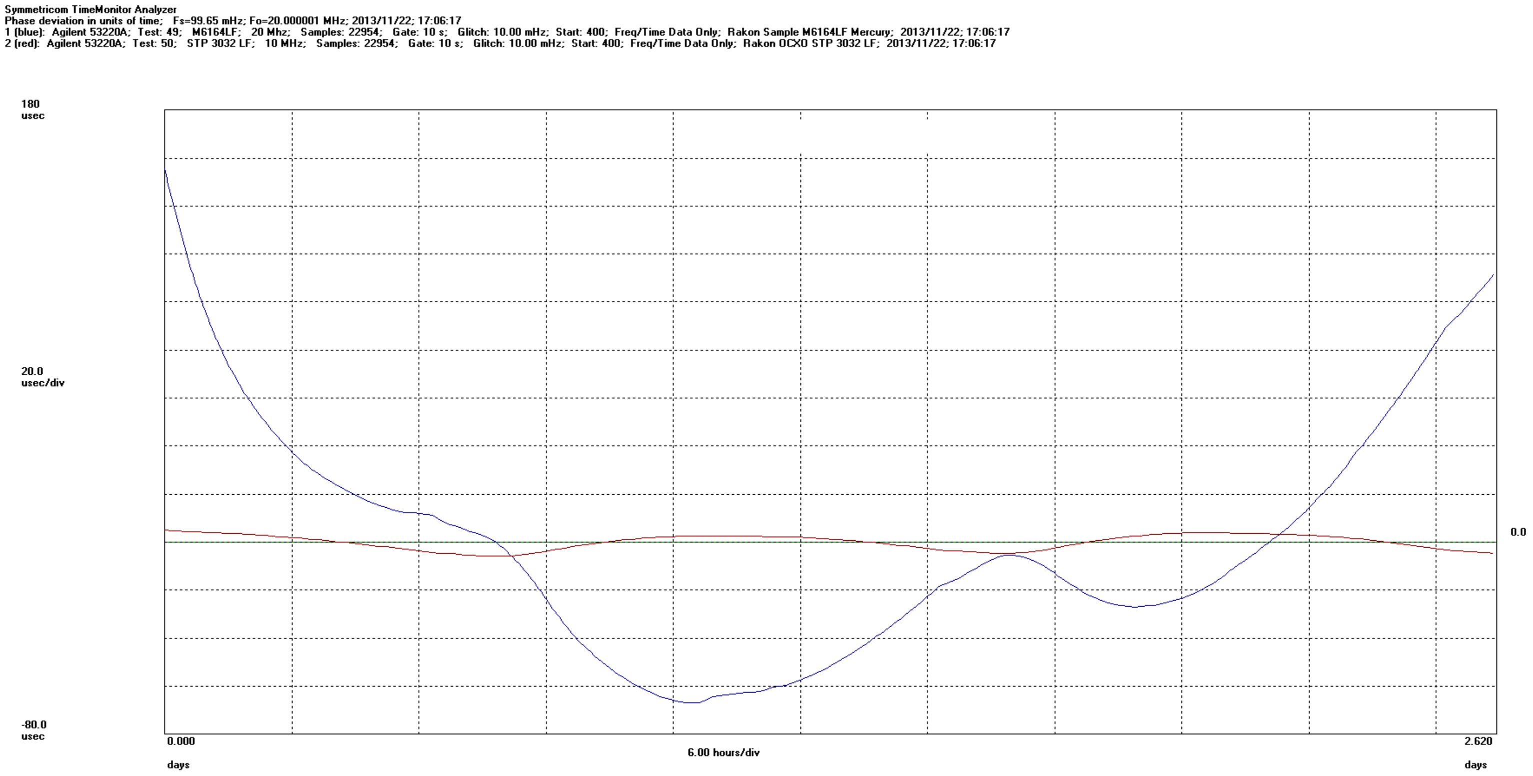
# Time and Frequency

- Does an oscillator labelled “10MHz” provide a 10MHz output?
  - Two <u>good</u> oscillators measured over >2 days
  - Frequency is close to 10MHz BUT not exactly equal nor constant



# Time and Frequency

- Does an oscillator labelled “10MHz” provide a 10MHz output?
  - Two <u>good</u> oscillators measured over >2 days
  - Phase error accumulation is small BUT not exactly zero nor constant



# Fundamental need for Synchronization

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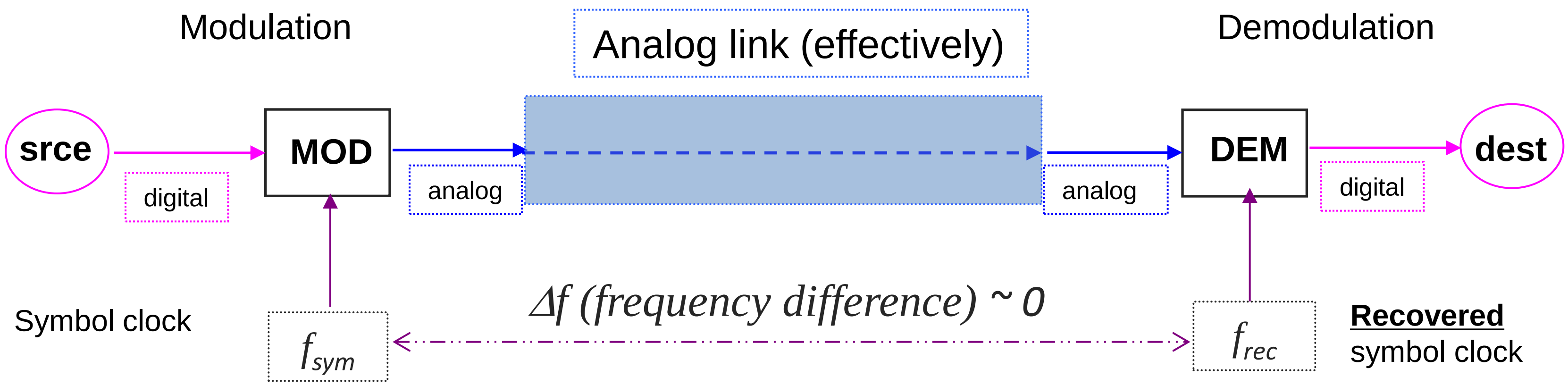
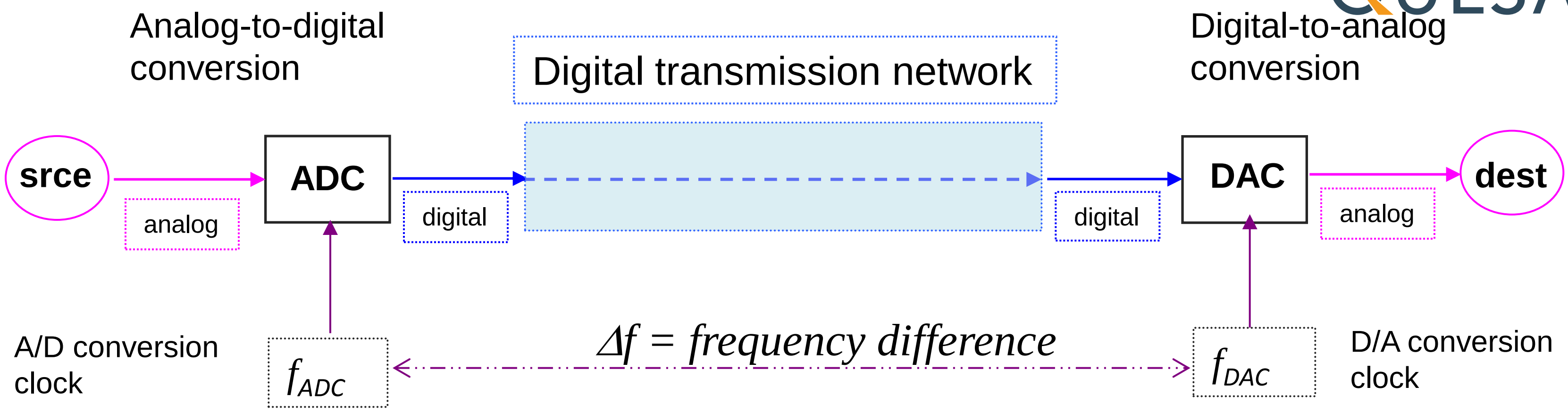
- Timing Alignment is Fundamental in Telecommunications
  - Digital transmission requires symbol-timing alignment
  - Digital network require synchronization to emulate analog channels
  - Circuit Emulation (CBR over packet) requires timing alignment
  - Wireless (Cellular) requires timing alignment
  - Multimedia requires timing alignment
- Timing in Circuit-Switched (TDM) Networks
  - Synchronous time-division multiplexing
  - The synchronization network
- Timing in Next Generation (Packet) Networks
  - Impact of packet delay variation (PDV)

# Data transmission schemes require synchronization




- Source/Destination : modulator and demodulator
- Transmitter (modulator) uses a particular symbol clock
  - receiver (demodulator) must extract this clock ($\Delta f \sim 0$) for proper data recovery
- The "Analog link" must, *effectively*, mimic an analog wire pair
  - Frequency translation (e.g. DSB-AM) is benign, Doppler (pitch modification effect, PME) is not benign ($\Delta f \sim$ Doppler)

# Timing Alignment required in Voice-Band Transmission




**$\Delta f \neq 0$ implies conversion mismatch**

Primarily affects voice-band data (Fax, modem) and real-time video

- Source/Destination : Voice/video/fax terminal
- The digital transmission network *emulates* an analog circuit (the original circuit emulation)
- Impact of frequency difference ($\Delta f$ ):
  - Eventually buffers will overflow/underflow (e.g. slips) ("obvious")
  - Pitch Modification Effect (PME) (analogous to *Doppler*) makes recovered symbol clock ≠ transmit symbol clock (not so "obvious")
  - Recovered waveform ≠ original waveform (more than just additive noise)

# Timing alignment implicit in Circuit Emulation

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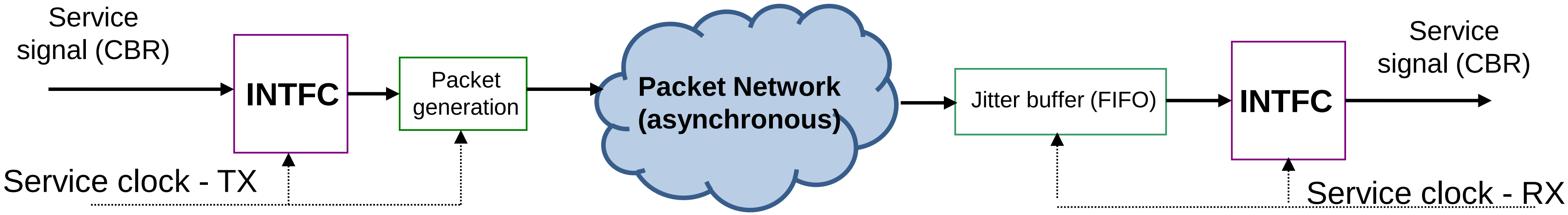
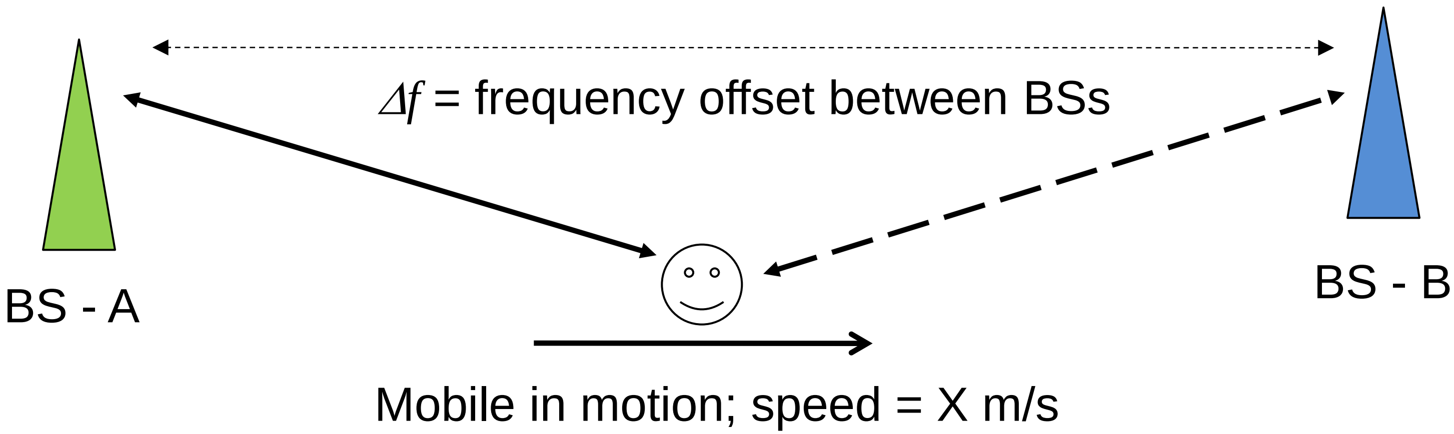


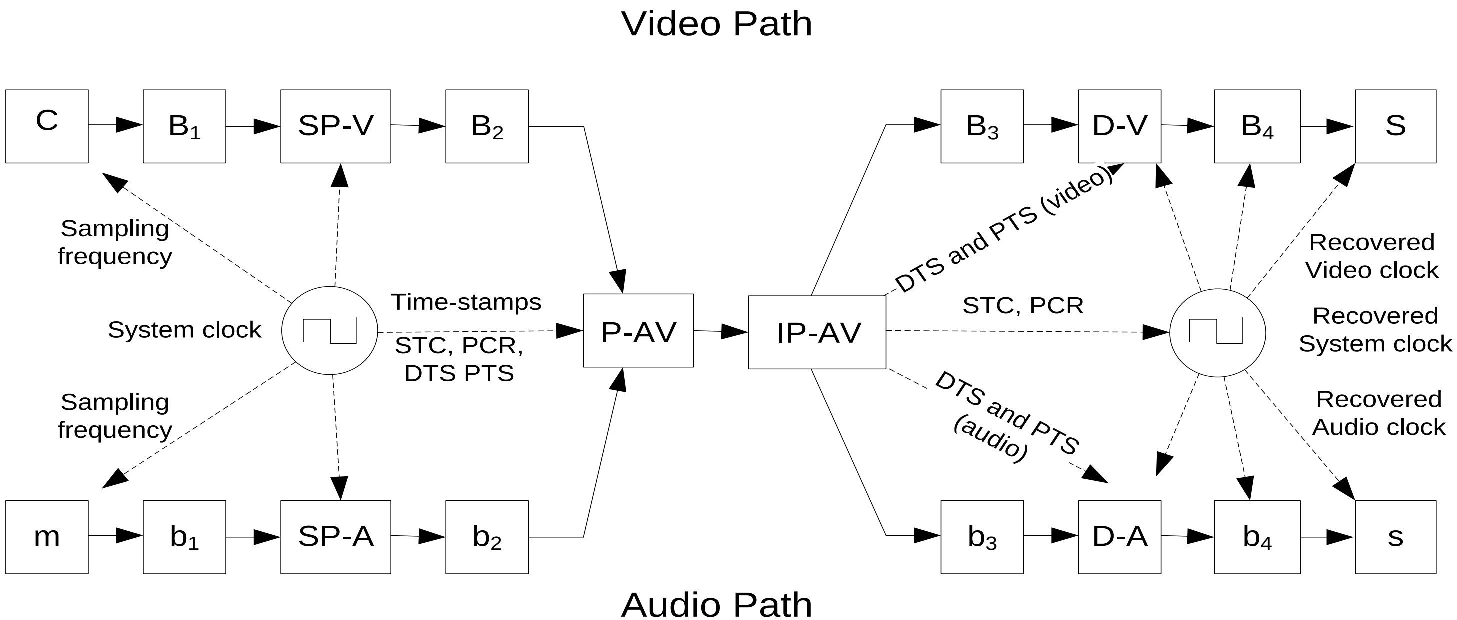

- Network impairments: delay, <u>packet-delay-variation (PDV),</u> discarded packets
- Jitter buffer size: large enough to accommodate greatest (expected) packet-delay-variation. Packet loss concealment is not an option.
- Causes of packet "loss":
  - Network drops packets (bit errors, congestion)
  - Jitter buffer empty/full (excessive packet-delay-variation)
- Key to ***<u>Circuit Emulation</u>*** :
  - Ensure packet loss is (essentially) zero.
  - Make RX and TX service clocks "equal".
  - Note: <u>If RX ≠ TX then jitter buffer is going to overflow/underflow</u>

# Timing Alignment in Wireless




- Mobile in motion (X m/s) introduces a Doppler shift (X/c)
  - When hand-over occurs, the mobile must reacquire carrier frequency
  - Large $\Delta f$ compromises the reliability of hand-over
- Modern Wireless (LTE) requires stringent timing to support special services/functions
  - BS-A and BS-B can cooperate for providing enhanced bandwidth to mobile
  - Frequency as well as relative phase

# Timing Alignment in Multimedia




- Frequency offset (wander) between audio and video sampling results in loss of lip-sync
- Frequency offset (wander) between send-side and receive-side system clock results in freeze (video), breaks (audio), and possible loss of lip-sync

# 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

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- Distinction is more in terms of emphasis
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- Oscillator: Component providing periodic signals
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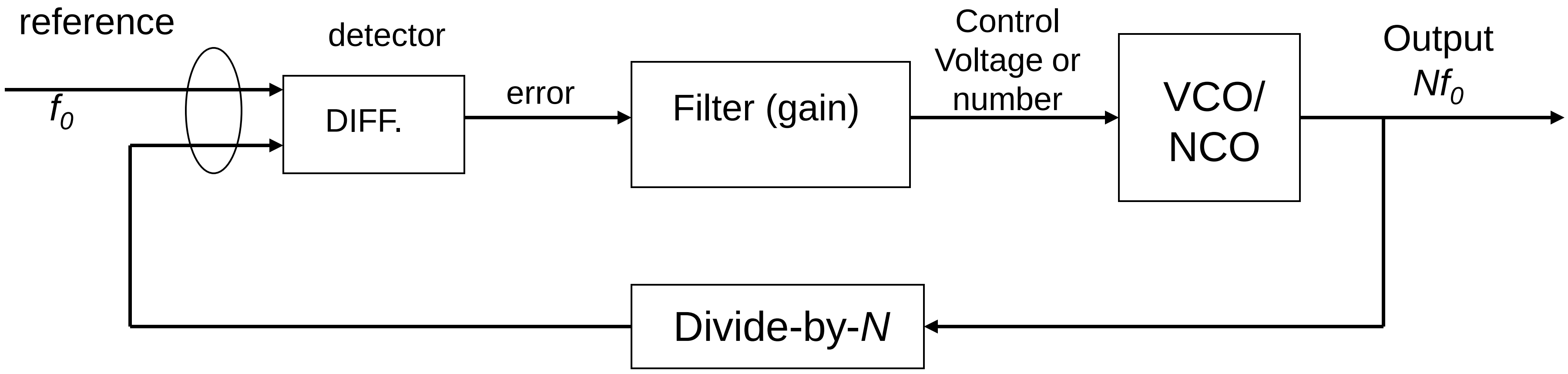
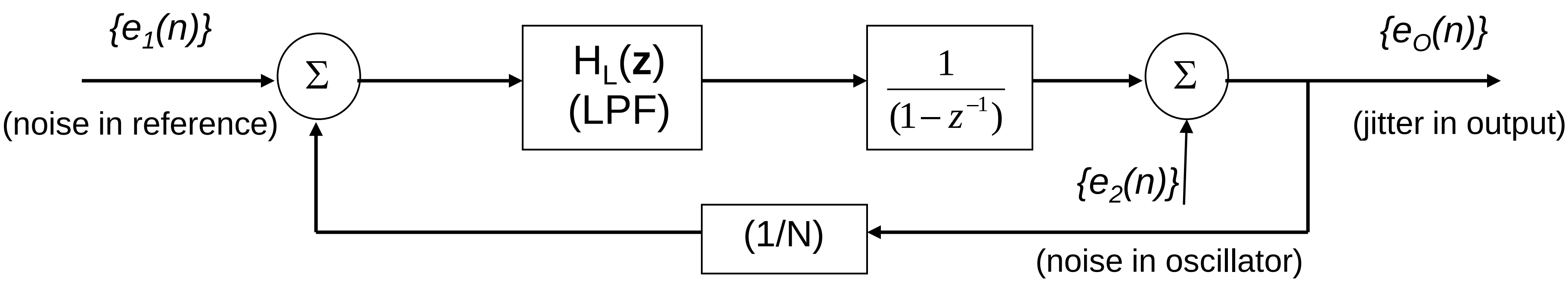
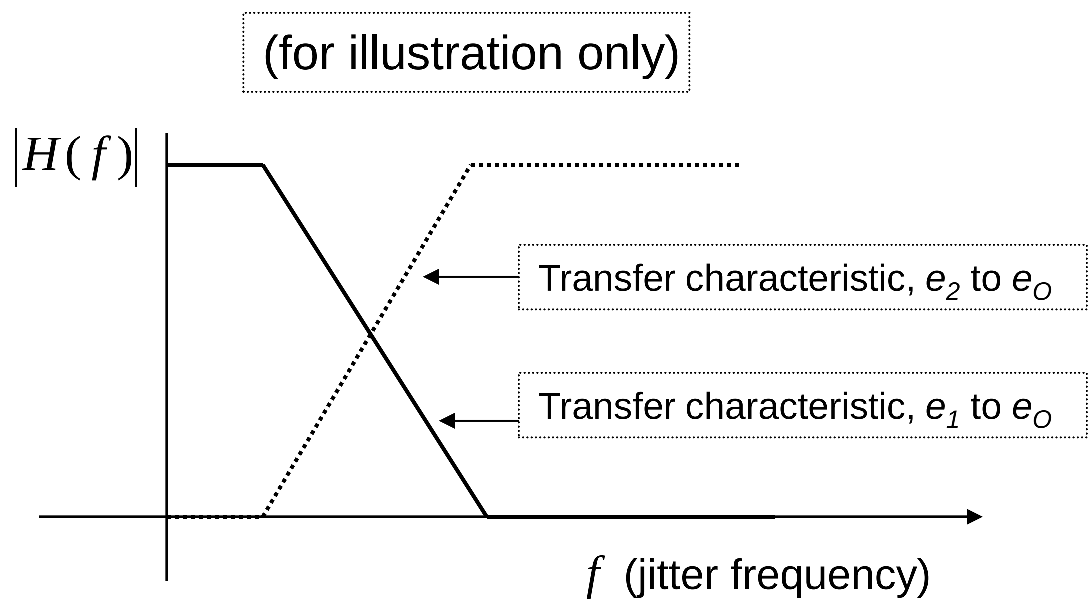
# Loops and Holdover




- 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($\tau$) of oscillator and reference (flicker floor)

# Common Mathematical Models

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

signal

Mathematical time

Phase function

(radian) frequency

"Clock Noise"

- A: Amplitude of signal. Does not figure in timing metrics.
- $\phi_0$: 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

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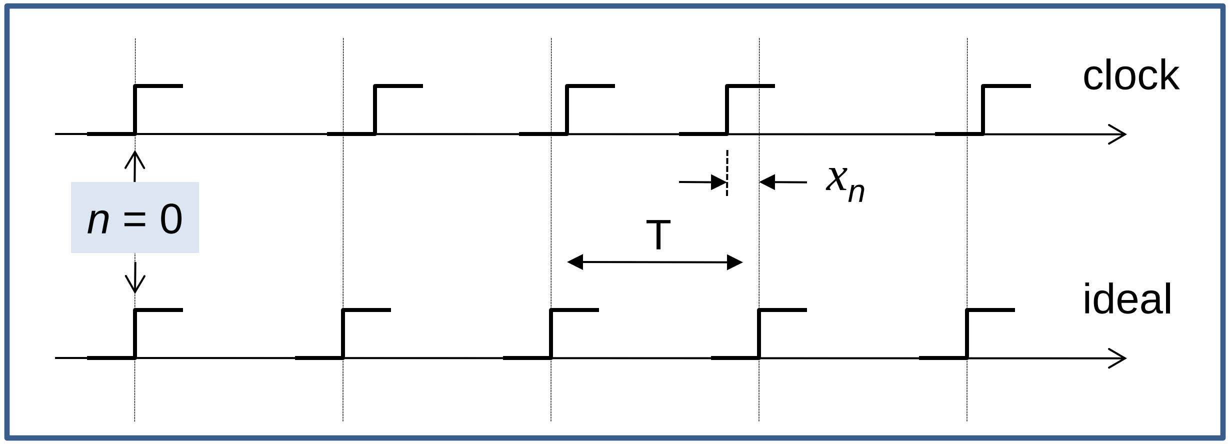
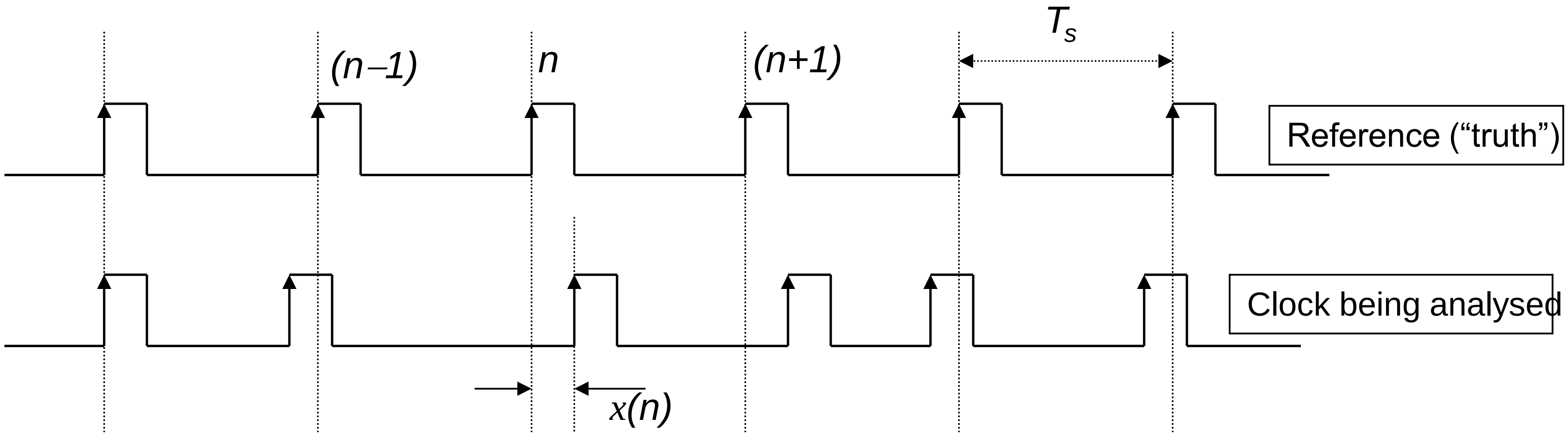



- Clock signals are (<u>approximately</u>) periodic (<u>nominal</u> period ~ T)
- Errors:
  - Edge does not line up – *phase* error (expressed in time units)
- Time Error Sequence : $\{x_n\}$ or $\{x(n)\}$
  - All clock metrics derived from time error sequence
  - Note: the time error varies “slowly” 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, $\tau$ ($\tau$ is a parameter). The observation interval is scanned with a moving window of duration $\tau$ and MTIE($\tau$) is the maximum excursion.

Given a set of N observations {*x(k); k=0,1,2,…,(N-1)*}, with underlying sampling interval $\tau_0$, 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:

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

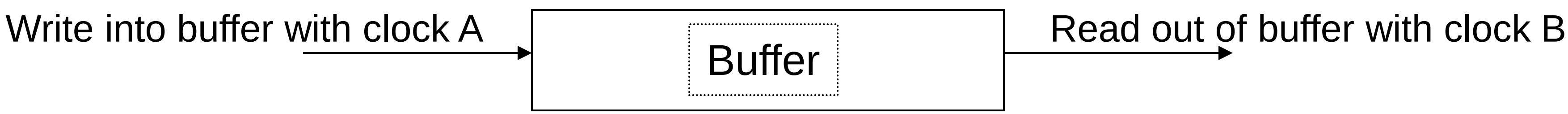
MTIE(*n*), or MTIE($\tau$), is the largest value of this peak-to-peak excursion:

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

# Clock Metrics – MTIE and TDEV

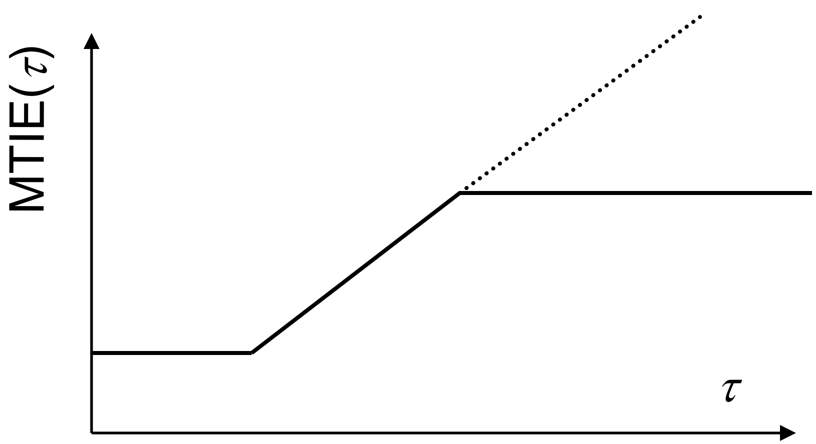
MTIE

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




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

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




Observations regarding MTIE:

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

# Clock Metrics – MTIE and TDEV

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**TDEV** A measure of stability expected over a given observation interval, $\tau$ ($\tau$ is a parameter).

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

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

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

Conventional Definition

Note: $x(k) \Leftrightarrow x_k$

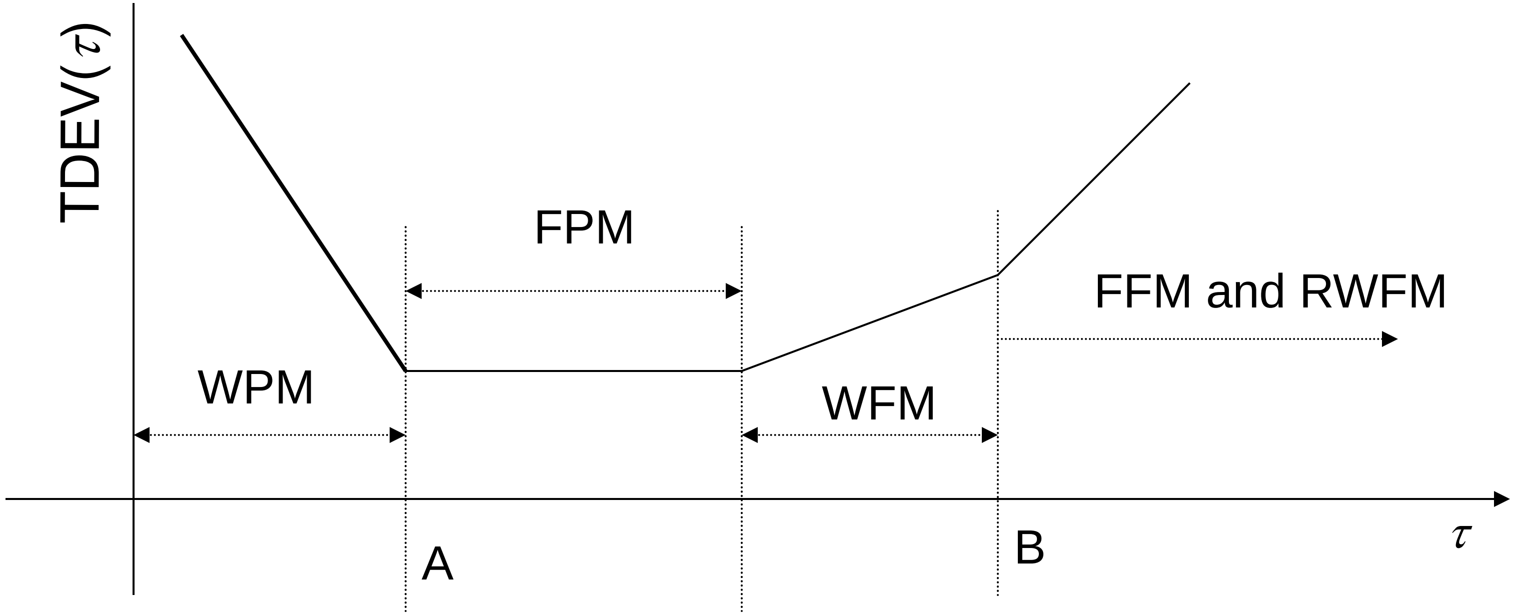
TVAR = square of TDEV

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($\tau$) versus $\tau$




"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

# TIMING REFERENCE SOURCES

# PHASE-LOCKED LOOPS AND OSCILLATORS

# PHOTO-JOURNALISM : GPS INSTALLATIONS

# PHYSICAL LAYER TIMING

# PACKET-BASED TIMING

# STANDARDS

# CONCLUDING REMARKS

# What did we cover?

QULSAR

- Fundamentals of Synchronization
- Introduction to Clocks
- Timing Reference Sources
- Phase-Locked Loops and Oscillators
- Physical Layer Timing
- Packet-based Timing
- Standards

# Fundamentals of Synchronization

- Time and frequency concepts
  - Time is always transferred
  - Frequency is transferred for economic reasons

- Timing Alignment is Fundamental in Telecommunications
  - Digital transmission requires symbol-timing alignment
  - Digital network require synchronization to emulate analog channels
  - Circuit Emulation (CBR over packet) requires timing alignment
  - Wireless (Cellular) requires timing alignment
  - Multimedia requires timing alignment

# Introduction to Clocks

- Clocks and Oscillators
- Model of a Locked Loop
- Stratum Levels
- Fundamental Clock Concepts and Metrics
  - Time Interval Error
  - MTIE
  - TDEV

# Phase-Locked Loops and Oscillators

1. Phase Locked Loops (PLL)
   - PLL with VCO
   - PLL with DDS
   - Comparison

2. Quartz Crystal Oscillator (XO) Technology
   - TCXO
   - OCXO
   - DOCXO

# Timing Transfer

- Physical Layer Timing
  - SONET/SDH
  - Synchronous Ethernet
- Packet-Based Timing
  - Circuit Emulation
  - Two-way Methods for Time Transfer
  - Protocols (NTP and PTP)

# Standards Bodies

- Standards Bodies (related to Telecom):
  - ITU-T – International Telecommunication Union – Telecom Sector (United Nations)
  - ANSI – American National Standards Institute
  - ATIS – Alliance for Telecommunications Industry Solutions
  - IEEE – Institute of Electrical and Electronics Engineers
  - Telcordia – Formerly BellCore
  - IETF – Internet Engineering Task Force
    - TICTOC – Timing over IP Connection and Transfer of Clock
- Relevant Workshops/Forums:
  - NIST - National Institute of Standards and Technology (annual Workshop on Synch. In Telecom. Systems, WSTS is co-sponsored by ATIS and IEEE)
  - ITSF - International Telecom Synchronization Forum

# Mini Glossary

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- **GPS** – Global Positioning System, is a satellite navigation system consisting of at least 24 satellites that have redundant on-board atomic clocks and linked to USNO
- **UTC** or Coordinated Universal Time – A high precision atomic time standard that is used as a time_of_day reference for many applications. Specified in ITU-R TF.460-4.
- **Accuracy** – A measure of how closely the frequency generated by the standard corresponds to its assigned value (e.g., the atomic transition frequency for an atomic standard).
- **Precision** – A measure of the repeatability of a frequency measurement. It is generally expressed in terms of a standard deviation of the measurement.
- **Stability** – A measure of the maximum deviation of the standard's frequency when operating over a specified parameter range.
- **Holdover** – The mode that a clock enters into when it loses connectivity with an input reference. While in holdover, the clock uses stored data to control its output and its stability depends on the stability of its internal oscillator.
- **Jitter** – deviation of a time signal from its ideal point in time. Generally the high frequency component (> 10 Hz) is considered jitter and the low-frequency component considered wander.
- **Wander** – Wander is a phase variation at low frequency (DC to 10Hz); above 10Hz is considered jitter.
- **BITS** – Building Integrated Timing System – A standard for distributing a precision clock among telecommunications equipment
- **TIE** – Time Interval Error – The variation in time delay of a given timing signal with respect to an ideal timing signal over a particular time period
- **TDEV** - a measure (standard deviation) of how much the phase (in time units) of a clock could change over an interval of duration T assuming that any systematic (i.e. constant) frequency offset has been removed
- **MTIE** – Maximum Time Interval Error – A measure of the worst case phase variation of a signal with respect to a perfect signal over a given period of time
- **PDV** – Packet Delay Variation – The variation in the amount of Latency among Packets being received, has an impact on jitter and wander for pseudo-wire implementations
- **ACR** – Adaptive Clock Recovery – method of recovering frequency from the arrival rate of packets

# Thank you …

## Questions?

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