WSTS-2017 Tutorial Session

Workshop on Synchronization in Telecommunications Systems
San Jose, California, April, 2017

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Tutorial Outline

- Fundamentals of Synchronization and Introduction to Clocks
- Timing Reference Sources & Atomic Clocks
- Phase-Locked Loops and Oscillators
- Measuring and Characterizing Network Time
- Timing in Packet Networks
- Standards
- Concluding Remarks

FUNDAMENTALS OF SYNCHRONIZATION AND INTRODUCTION TO CLOCKS

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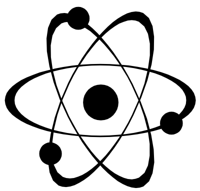
Fundamentals of Synchronization

- Time and Frequency
  - Clocks and Oscillators
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Coordinated Signal Processing requires phase alignment
  - Writing a stream into and reading the stream from a buffer must be frequency aligned
  - Time-stamping events in geographically separated locations
- Examples

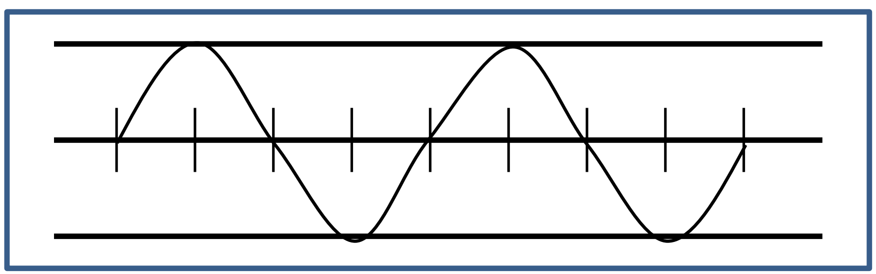
Time and Frequency

- A clock is a frequency device based on physics



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

- Electronic systems count "ticks" for time interval



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

- *Time* is a combination of a *signal* (event) and a *label* (time value)

Time and Frequency

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- *Time Interval* (e.g. 1 second) is based on a physical property of the Cesium atom
- *Time* is an artificial construct.
  - Choose an origin ("epoch") that people can agree on
  - Elapsed time interval from the origin.
  - Format (year/month/day/hour/min/sec…) [Time Zone]

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

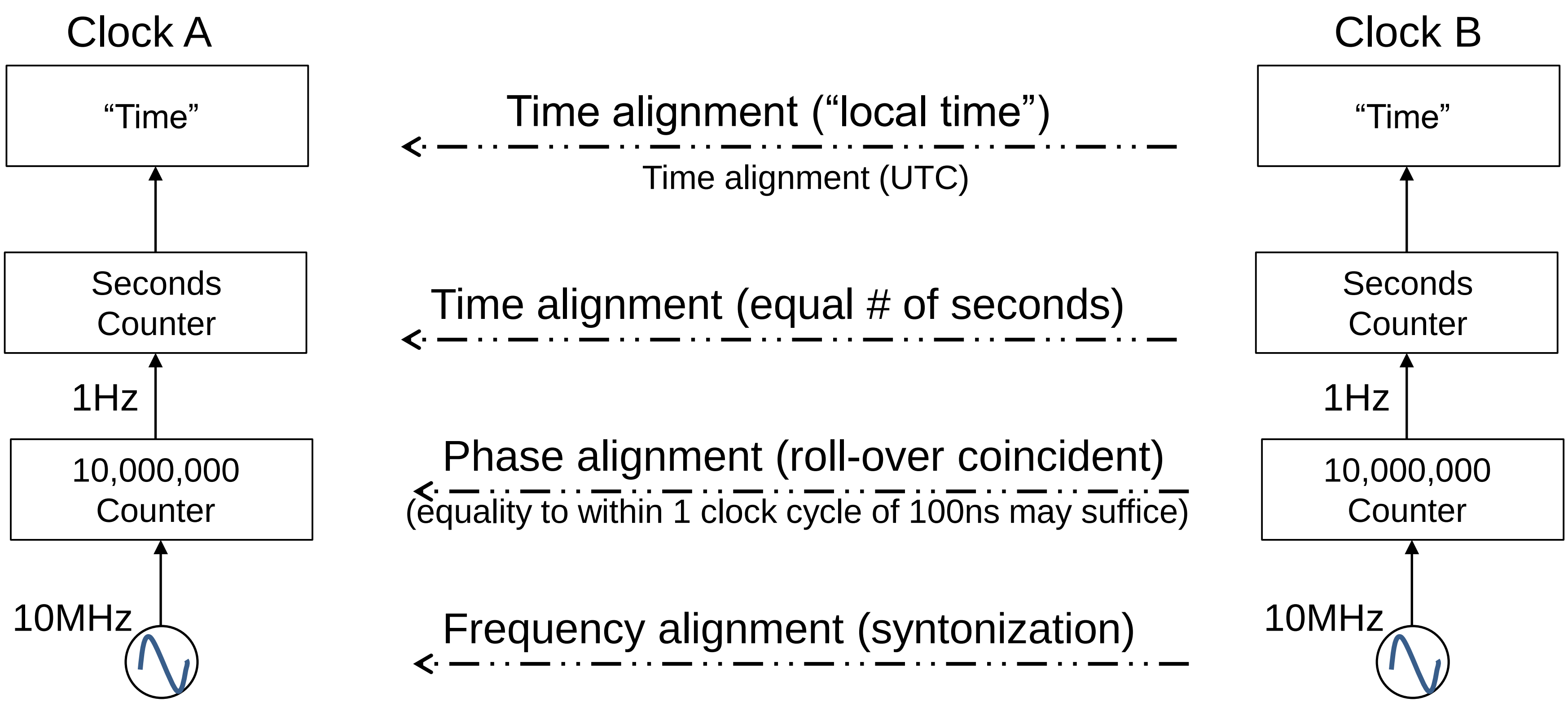
"discontinuous" timescale allows for jumps related to leap seconds

Clocks and Oligators

- 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 plus counting capability
- 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.)



Fundamentals of Synchronization

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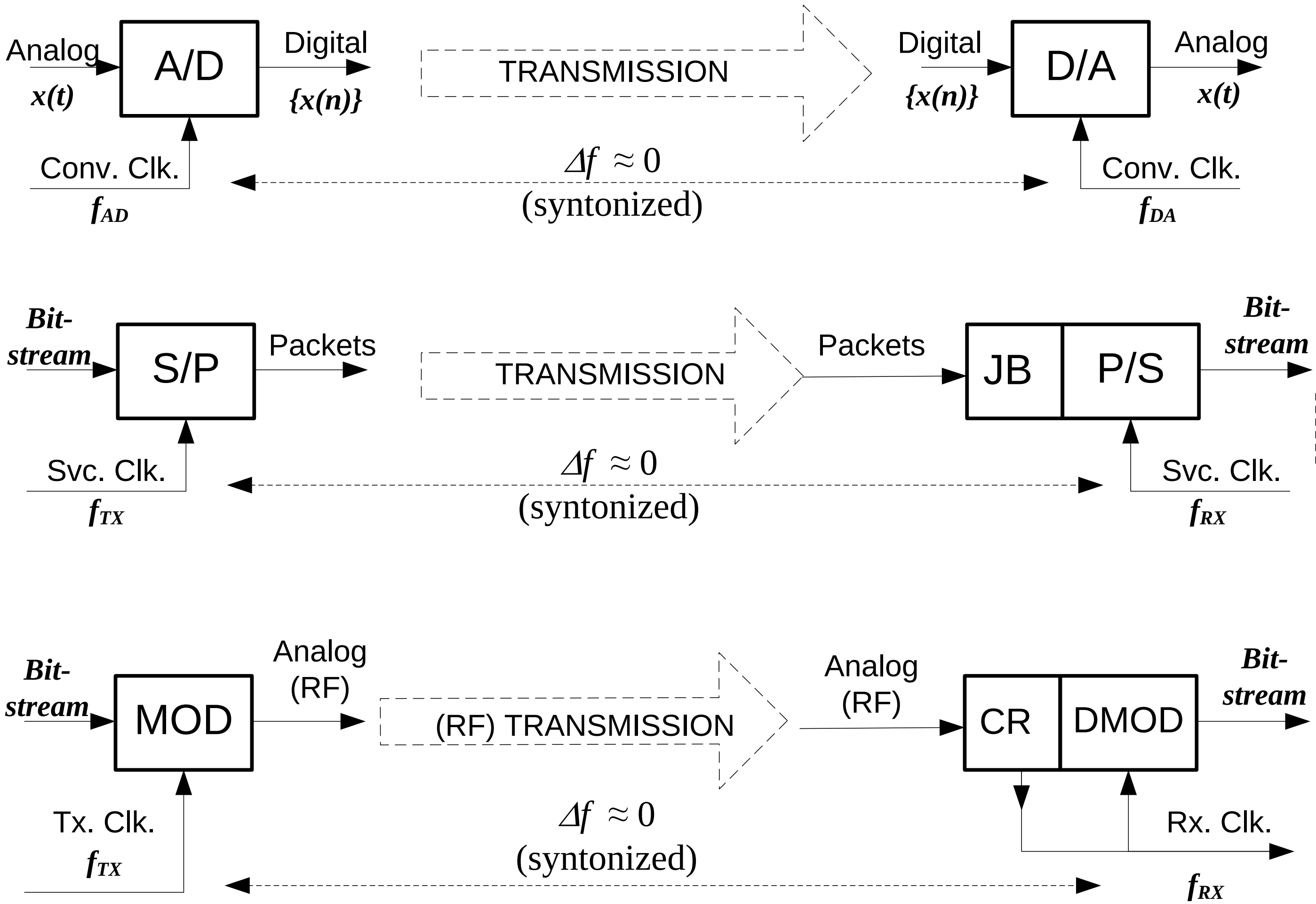
Fundamental Need for Synchronization

- Information has a temporal aspect (signals) – Digital Signal Processing inherently requires synchronization



e.g. Audio/Video

Circuit Emulation

Modems
e.g. Wireless

Examples of single source, single destination

Fundamental Need for Synchronization

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- Multiple source single destination — an example
- Device receives a combination of signal + interference

$$x(t) = a(t) + b(t + \delta)$$

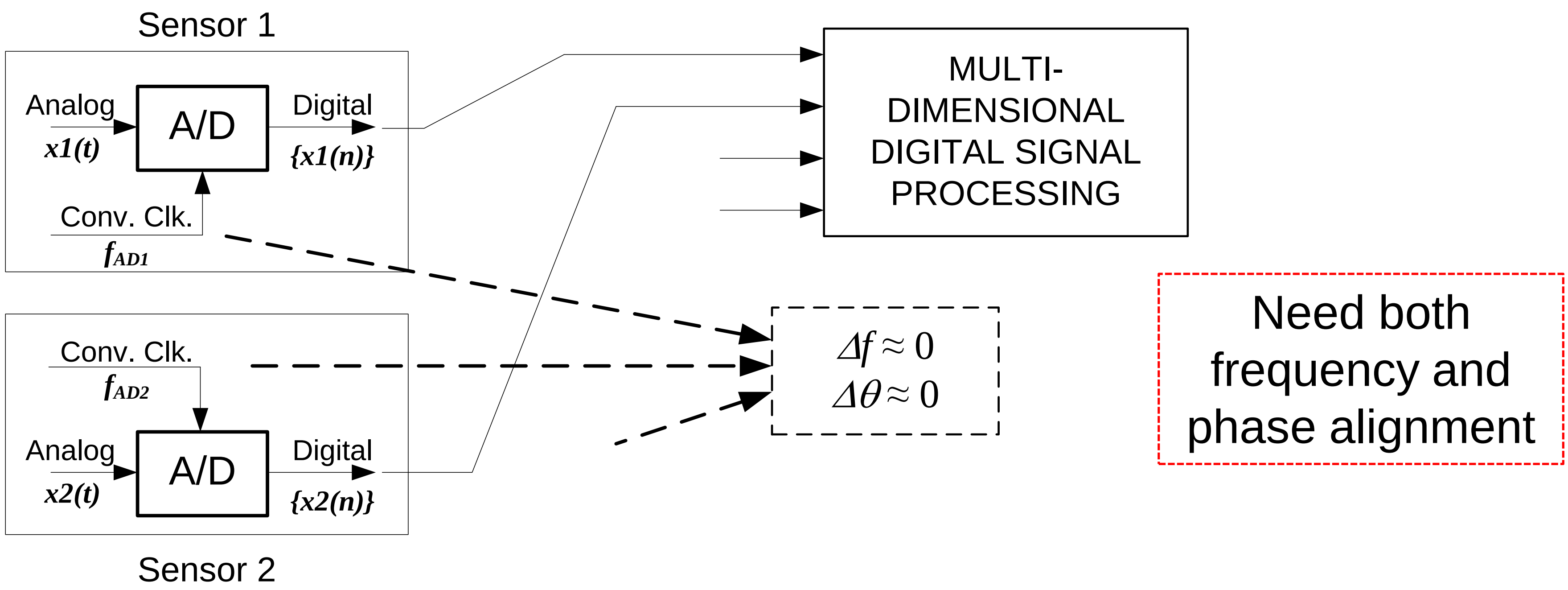
- Device has a “copy” of the interference $b(t)$ *but*….error in synchronization results in an effective time-shift of copy
- Device subtracts the “copy” from its receive signal
- What could go wrong?

$$y(t) = x(t) - b(t) = x(t) + e(t)$$ (signal + remnant)

$$\sigma_e^2 = \sigma_b^2 \cdot (1 - r_b(\delta))$$ (power of remnant depends on autocorrelation of $b(t)$ AND δ)

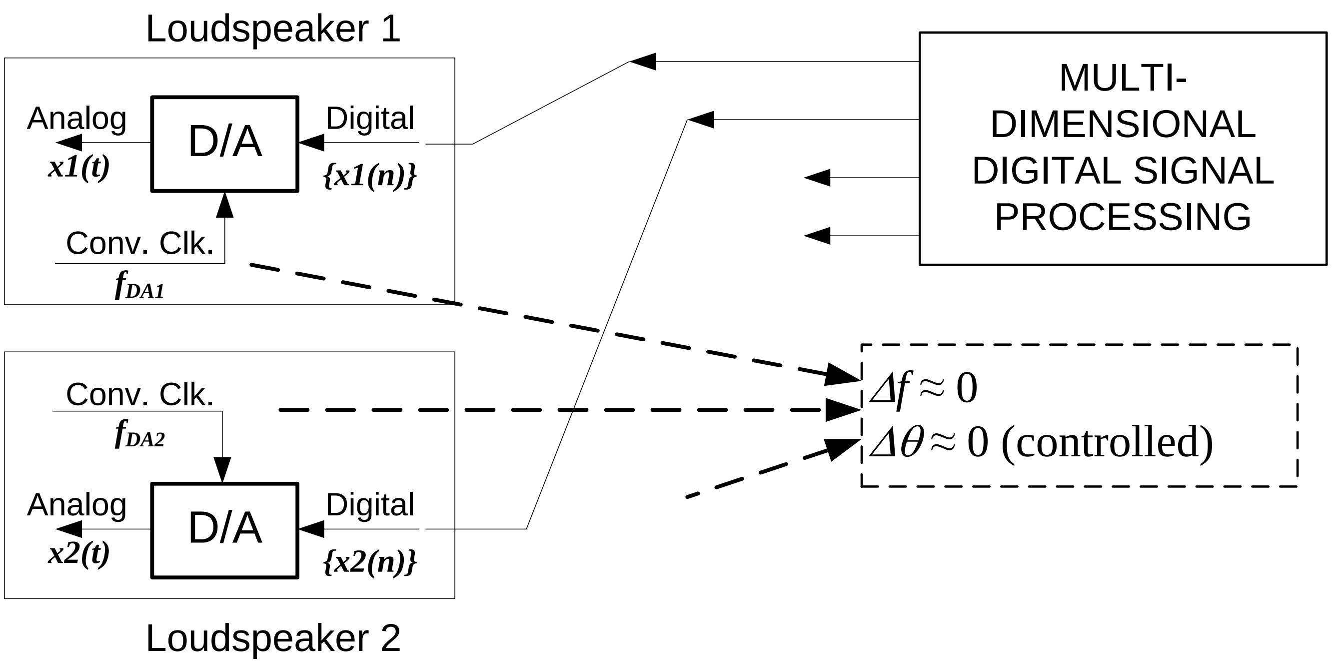
Bad synchronization leads to less than perfect cancellation of interference

Fundamental Need for Synchronization



- Multiple sources, single destination (many, many, examples)
- Wireless: MIMO, eICIC, CoMP, etc., etc.
- Multimedia: audio/video, surround-sound, 3D video, etc., etc.
- Power: synchrophasors
- Geophysical applications (e.g. mapping strata for oil exploration)

Fundamental Need for Synchronization



Need both frequency and phase alignment

- Single source, multiple destinations (many, many, examples)
- Wireless: CRAN: BBU-RRH; Antenna arrays
- Multimedia: audio/video, surround-sound, 3D video, etc., etc.
- Power: relay control

Buffer Write-Read – Synchronous Multiplexing

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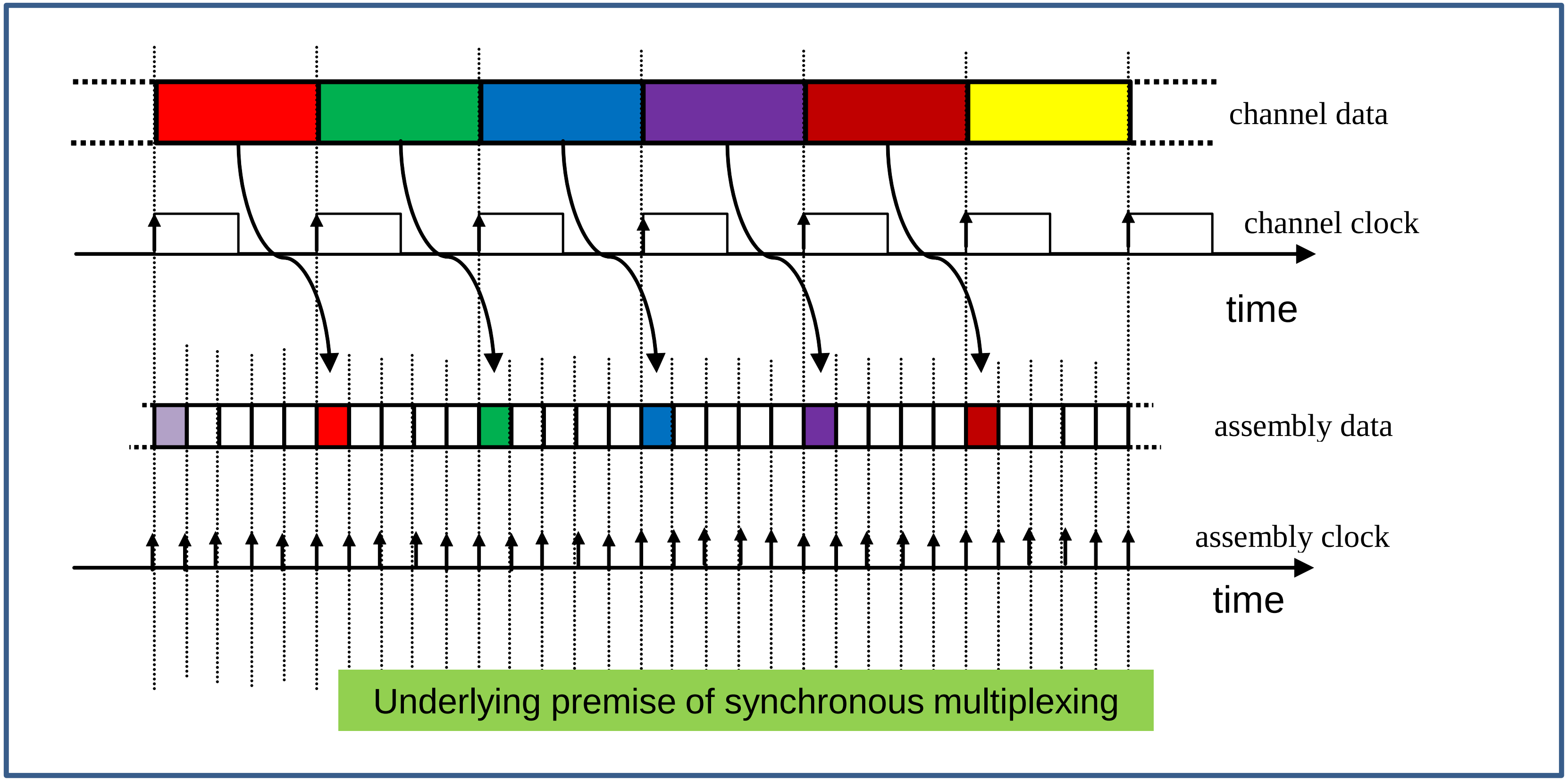

- Predetermined (rigid) ratio between channel clock and assembly clock
- 1-to-1 correspondence between channel bits and allowed bit positions
- *Fractional frequency difference between channel and assembly clocks = 0*

Coordination of actions

- What if 2 persons in geographically separated locations are “simultaneously” accessing a common database (or document) that is on a server in a third geographical location?
- How can “order” be established — by time-stamping the actions using a common clock.
- Requires end-point synchronization to this common clock.
- Many examples (distributed data base, shared documents, stock trades, sensor fusion, etc., etc.)

Fundamentals of Synchronization

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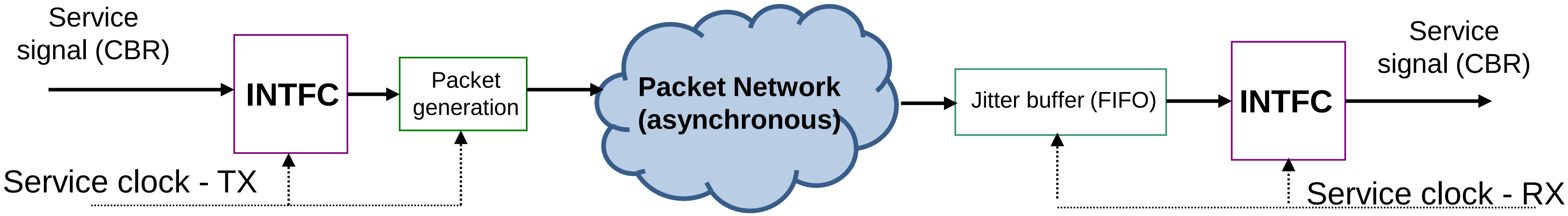
  - Coordinated Signal Processing requires phase alignment
  - Writing a stream into and reading the stream from a buffer must be frequency aligned
  - Time-stamping events in geographically separated locations
- Examples (in Telecommunications)

Fundamental need for Synchronization

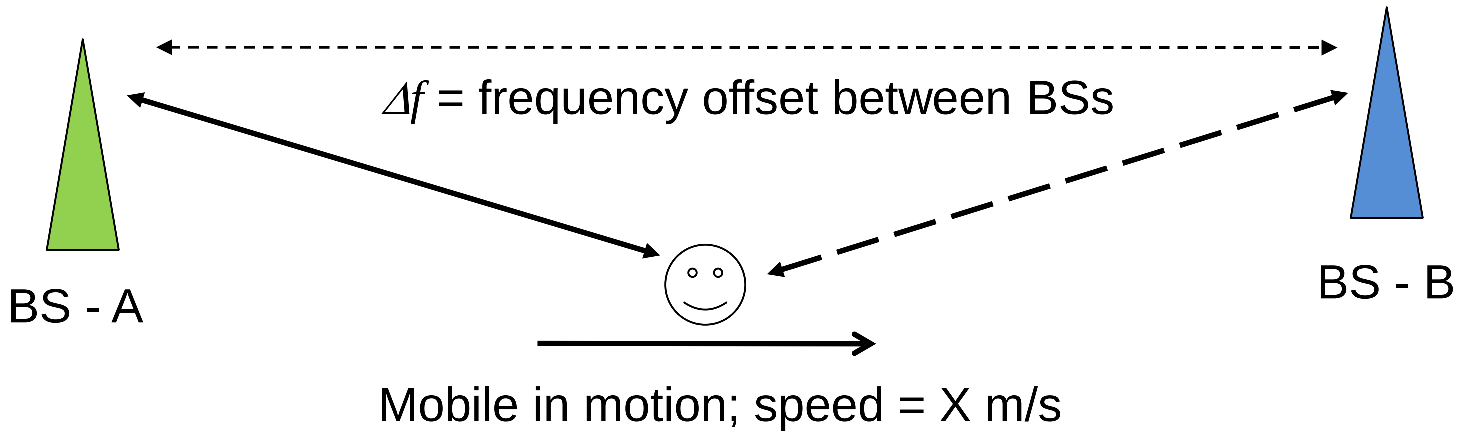
- Timing Alignment is Fundamental in Telecommunications
  - Digital transmission requires symbol-timing alignment
  - Digital network require synchronization to emulate analog channels
  - Circuit Emulation (CBR over packet) requires timing alignment
  - Wireless (Cellular) requires timing alignment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

Timing alignment implicit in Circuit Emulation



- Network impairments: delay, packet-delay-variation (PDV), 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 ***Circuit Emulation*** :
  - Ensure packet loss is (essentially) zero.
  - Make RX and TX service clocks “equal”.
  - Note: If RX ≠ TX then jitter buffer is going to overflow/underflow

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 Δf 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

INTRODUCTION TO CLOCKS

Introduction to Clocks

- Clocks and Oscillators
- Fundamental Clock Concepts and Metrics
  - Time Error (TE) and Time Interval Error (TIE)
  - MTIE
  - TDEV

Clocks and Oscillators

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Common Mathematical Models

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

signal

Mathematical time

Phase function

(radian) frequency

"Clock Noise"

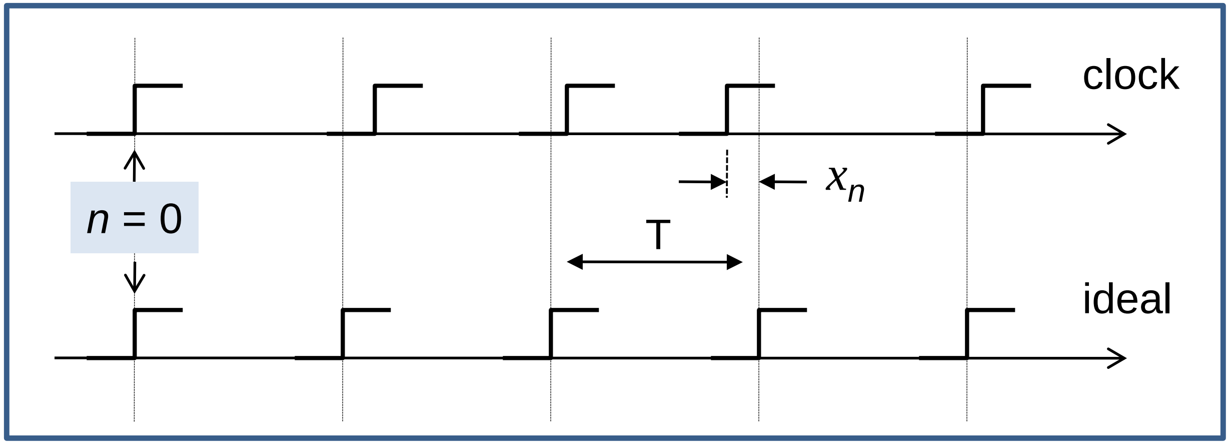
- A: Amplitude of signal. Does not figure in timing metrics.
- ϕ_0: Initial phase. Depends on choice of time origin. Usually assumed to be 0.
- $\varepsilon(t)$: Can be further decomposed into different categories such as frequency error, frequency drift, and random noise components
- ideal periodic signal: $\Phi(t)$ is a linear function of t ($\varepsilon(t) \equiv 0$)

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

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

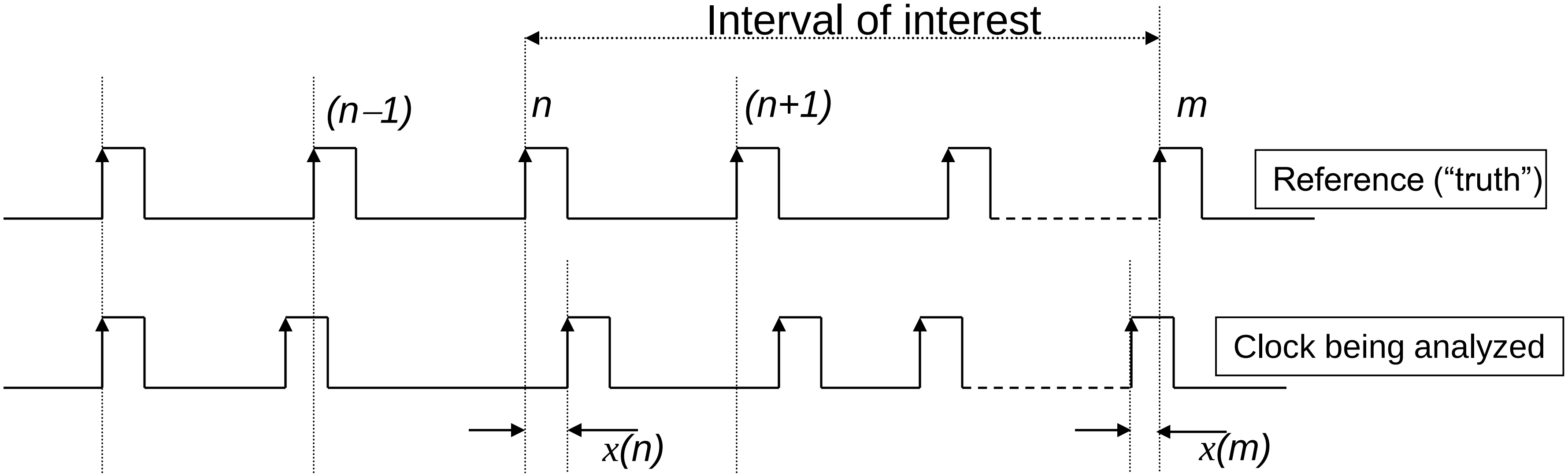
Time Error Models

Clock Metrics – Basics: 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 Sequence : $\{x_n\}$ or $\{x(n)\}$
  - *All clock metrics derived from time error sequence*
  - Note: the time error varies “slowly” so we can divide down to a convenient rate (However: careful when dividing down – aliasing)
  - Common assumption: $x_0 = 0$.

Time Interval Error

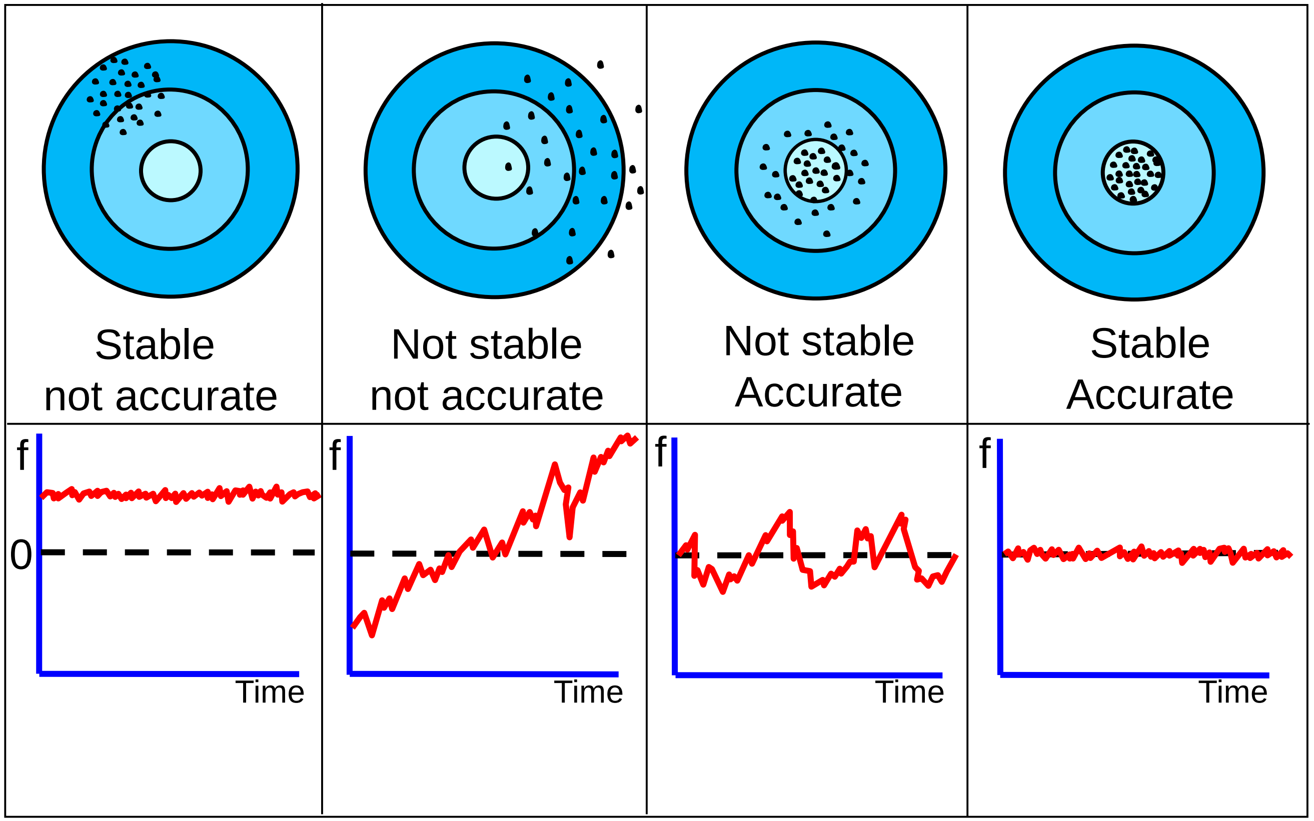


- Consider an interval of interest (e.g. 100m dash)
- Duration measured by ideal clock ("truth") : $(m - n) \cdot T_S$
- *Error* in measurement of same interval by clock being analyzed:

$$TIE(m,n) = x(m) - x(n)$$

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, etc.)



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

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:

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

Clock Metrics – MTIE and TDEV

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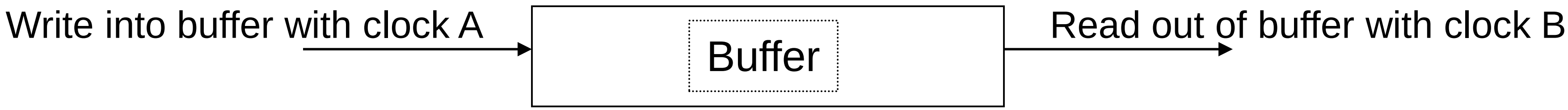
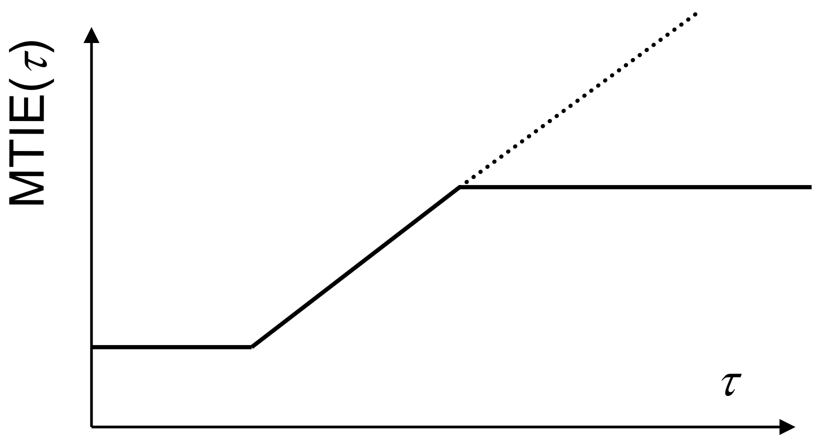
MTIE

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

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

Given a set of N observations {$x(k)$; $k=0,1,2,\ldots,(N-1)$} with underlying sampling interval τ_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: $x(k) \Leftrightarrow x_k$

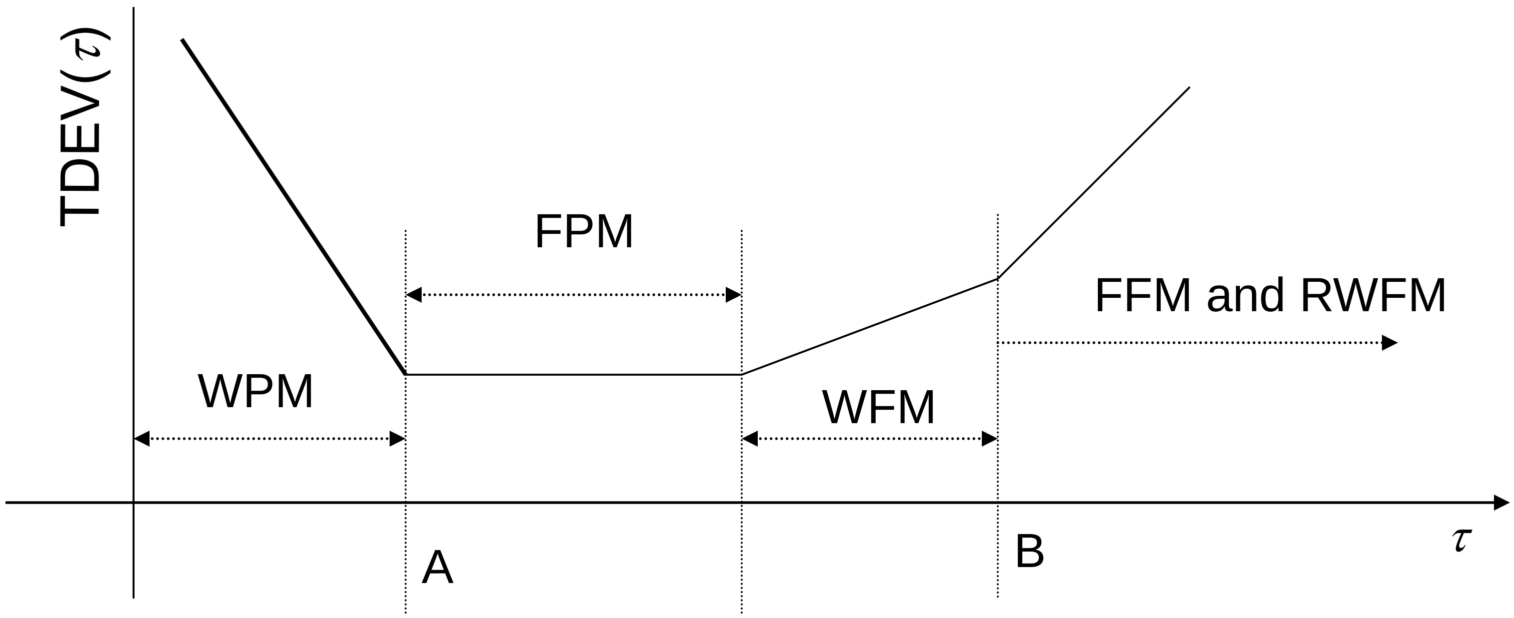
TVAR = square of TDEV

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(τ) versus τ



"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

Stratum Levels - Telecom

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- Stratum level represents the intrinsic accuracy of a clock
  - Stratum-1: $1\text{x}10^{-11}$ (one part in 10^{11})
  - Stratum-2: $1.6\text{x}10^{-8}$ (16 parts per billion, ppb)
  - Stratum-3: $4.6\text{x}10^{-6}$ (4.6 parts per million, ppm)
  - Stratum-4: $32\text{x}10^{-6}$ (32 parts per million, ppm)
- Implication:

  output frequency is always accurate to *xxx* even if the reference fails and the clock goes into an autonomous mode of operation
- Normal operation:

  output frequency is as accurate as the reference frequency (locked condition) – maintain a hierarchy in any chain of clocks (why?)
- Time-constant achievable:

ST2	of the order of 10^5 sec	(bandwidth ~mHz)
ST3E	of the order of 10^3 sec	(bandwidth ~mHz)
ST3	of the order of 10 sec	(bandwidth ~Hz)
ST4	of the order of 1 sec	(bandwidth ~10Hz)

Order of magnitude!

Concluding Remarks

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- Time and Frequency
  - Clocks and Oscillators
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Coordinated Signal Processing requires phase alignment
  - Writing a stream into and reading the stream from a buffer must be frequency aligned
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- Fundamental Clock Concepts and Metrics
  - Time Error (TE) and Time Interval Error (TIE)
  - MTIE and TDEV
- Examples

Thank you …

Questions?

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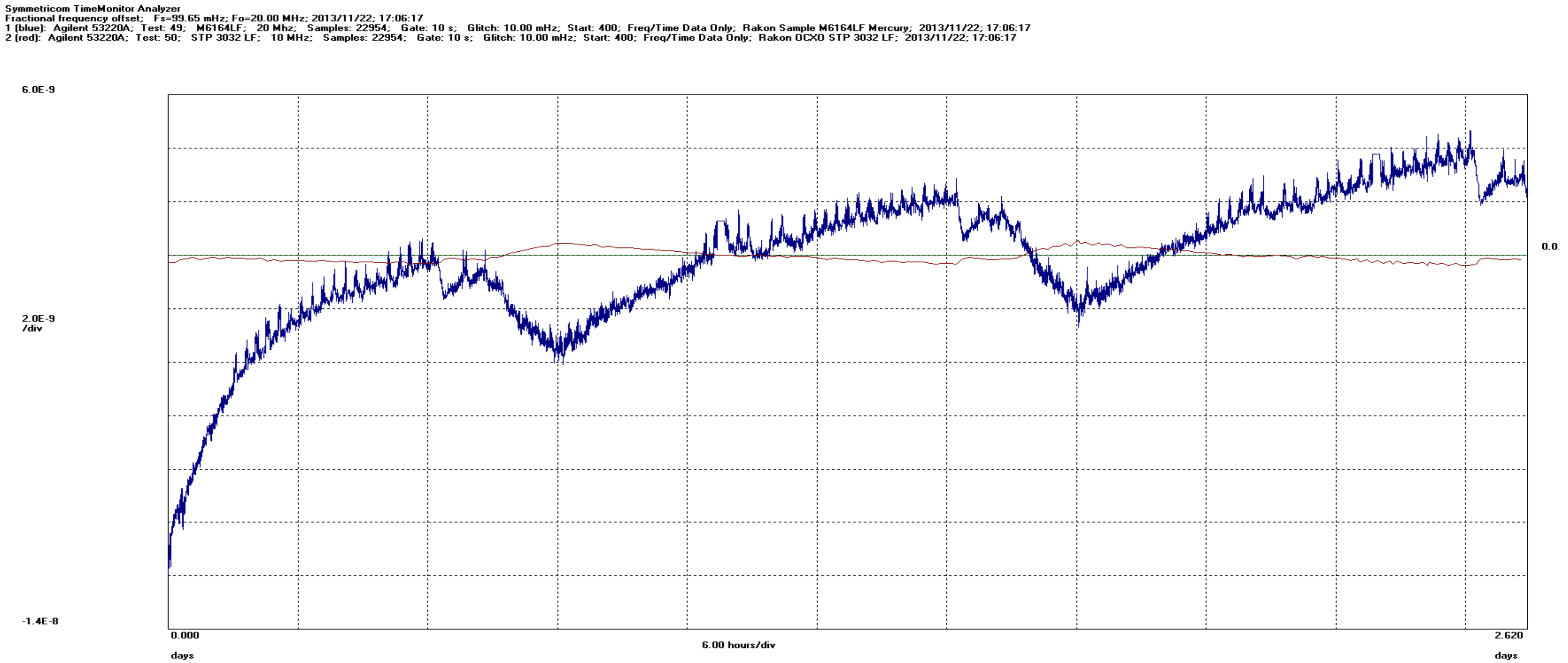
Backup Slides

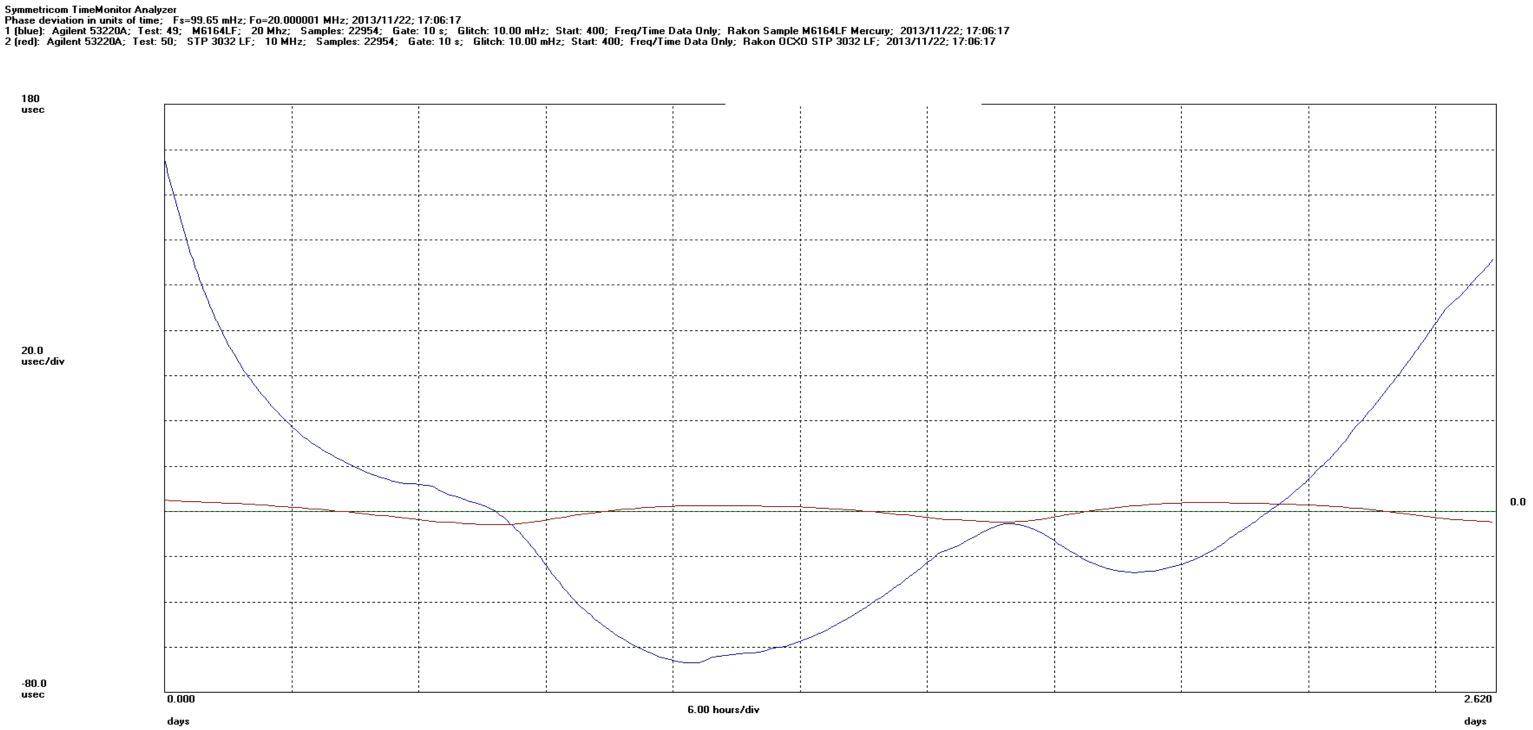
Time and Frequency

- 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 good oscillators measured over >2 days
  - Phase error accumulation is small BUT not exactly zero nor constant



Data transmission schemes require synchronization

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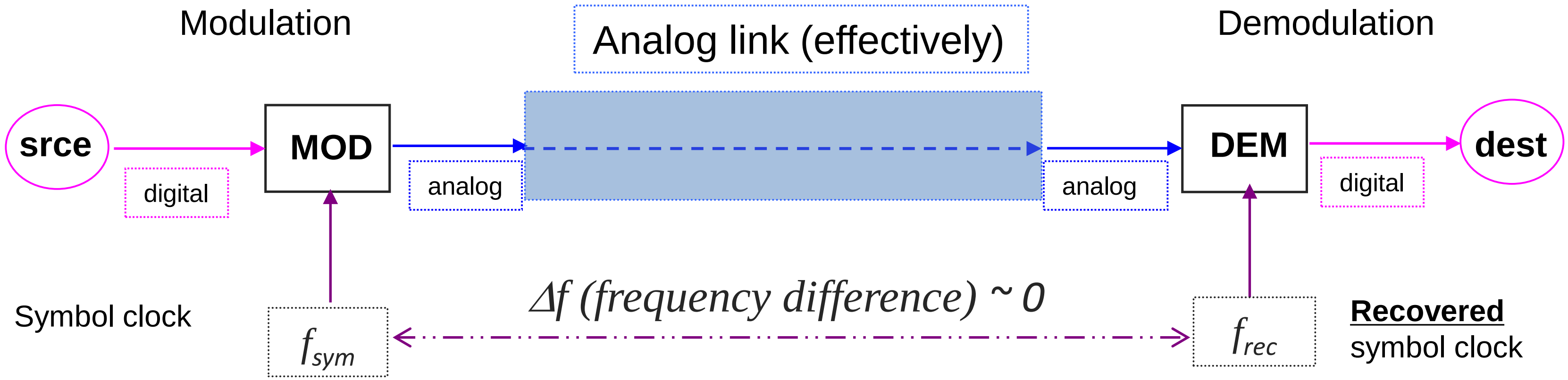
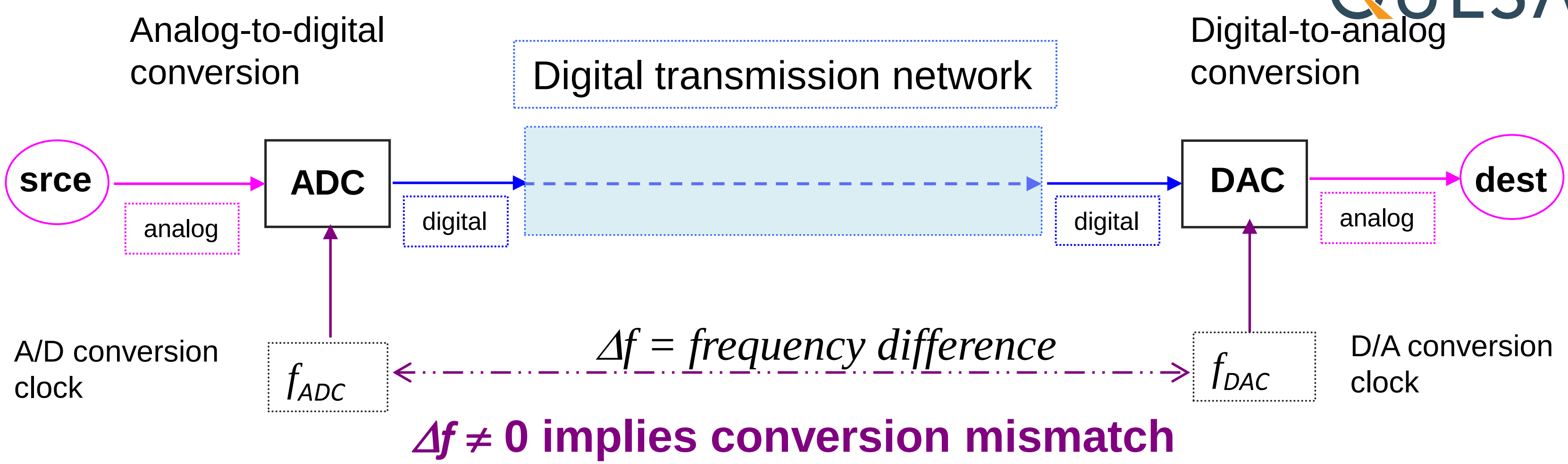


- Source/Destination : modulator and demodulator
- Transmitter (modulator) uses a particular symbol clock
  - receiver (demodulator) must extract this clock (Δf ~ 0) for proper data recovery
- The "Analog link" must, *effectively*, mimic an analog wire pair
  - Frequency translation (e.g. DSB-AM) is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

Timing Alignment required in Voice-Band Transmission



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 (Δf):
  - 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 in Multimedia

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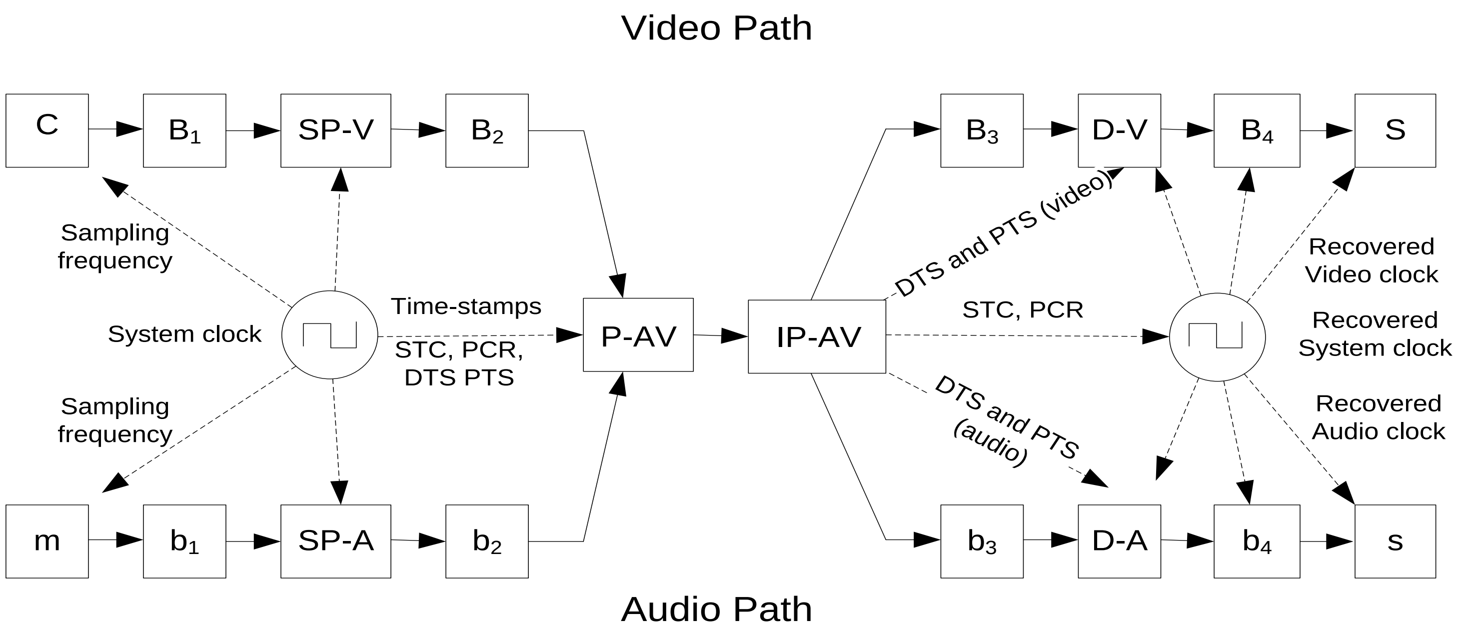
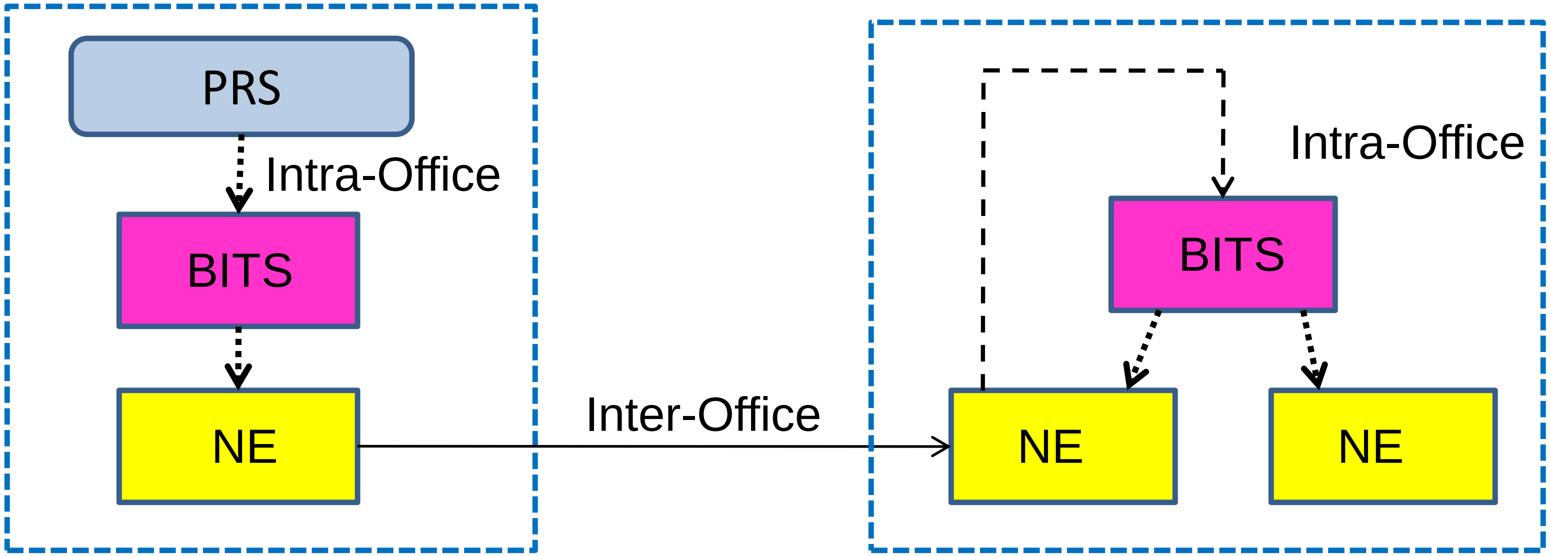


- Frequency offset (wander) between audio and video sampling results in loss of lip-sync
- Frequency offset (wander) between send-side and receive-side system clock results in freeze (video), breaks (audio), and possible loss of lip-sync

Timing in TDM Networks

- Synchronization is essential for synchronous multiplexing
  - To avoid information loss
- Synchronous multiplexing assemblies are used as carriers of timing information (DS1/E1, SONET/SDH)
  - The recovered clock is used as a reference for the BITS
  - The transmit signals must meet the “sync” mask for timing information
- Some Thumb Rules in TDM Networks:
  - Asynchronous multiplexing can preserve timing (up to a point) *if done correctly*
  - Bearer signals (DS1/E1) in asynchronously multiplexed assemblies (e.g. DS1 in DS3) can be used as carriers of timing
  - DS1/E1 bearer signals in SONET/SDH are <u>not</u> suitable as carriers of (good) timing because SONET/SDH encapsulation of DS1/E1 was done in a way that protects data but not (good) timing information

Distribution of timing (frequency)



- PRS: *Primary Reference Source* – provides stratum-1 quality output signal
- BITS: Building Integrated Timing Supply (also TSG – Timing Sig. Gen.)
  - Provides clock reference to the different NEs in the CO
  - Accepts a reference input and performs clock-noise filtering (removes jitter/wander)
- NE: Network Element (e.g. SONET) – uses BITS timing for its outputs
  - Recovers clock from incoming signal and provides a reference for the BITS

Time Error

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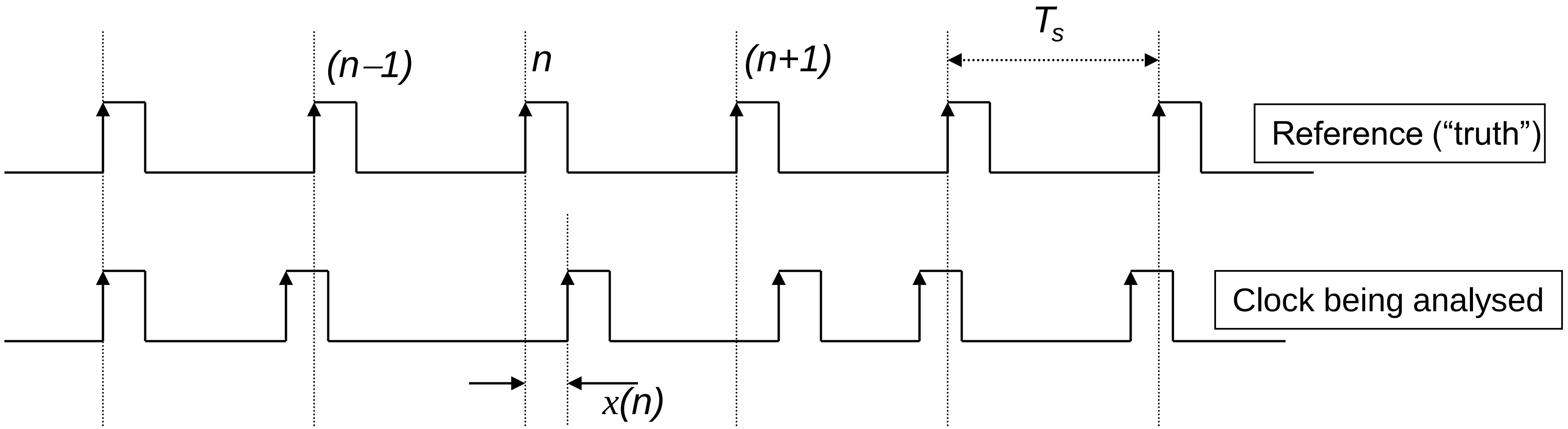


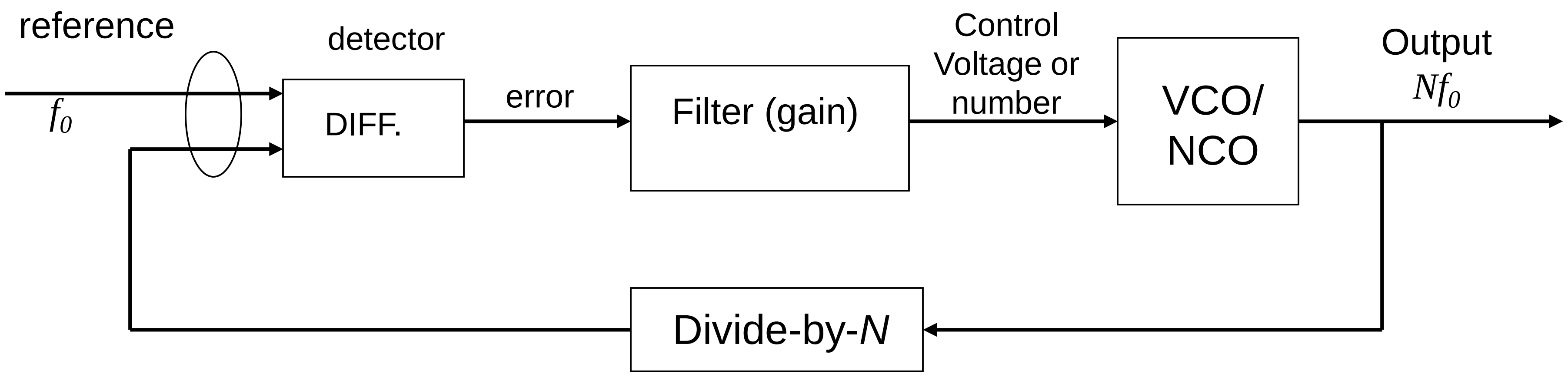
Basic premises:

- 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 Error" (TE) and is the basis for quantifying the performance of the clock (relative to reference)

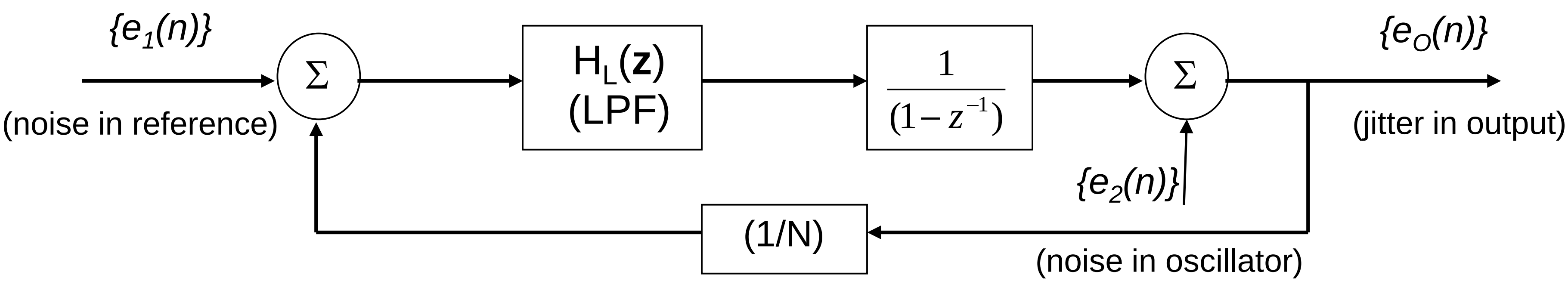
$\{x(n)\}$ can be viewed as the samples of a (analog) signal, $x(t)$, taken every T_S seconds (implied sampling rate = $f_S = 1/T_S$) [Think DSP]

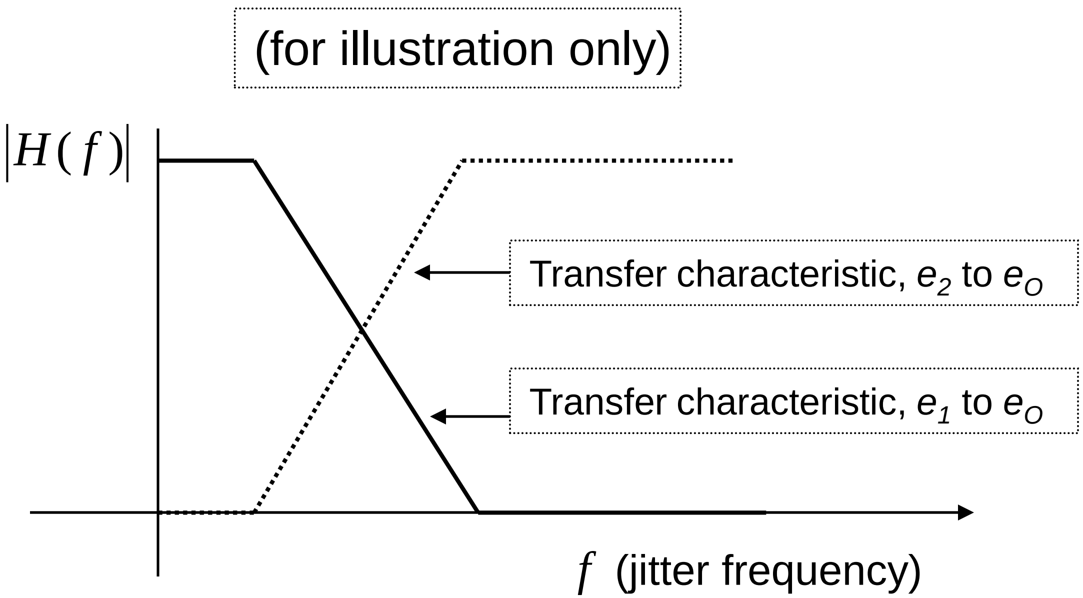
Loops and Holdover



- 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 be 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)