WSTS-2016 Tutorial Session

Workshop on Synchronization in Telecommunications Systems

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Tutorial Outline

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- 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

Fundamentals of Synchronization

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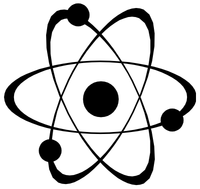
- Time and Frequency
  - Clocks and Oscillators
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Coordinating Analog-to-Digital and Digital-to-Analog Conversions requires synchronization
  - Coordinating Signal Processing requires synchronization
- Examples in Telecommunications

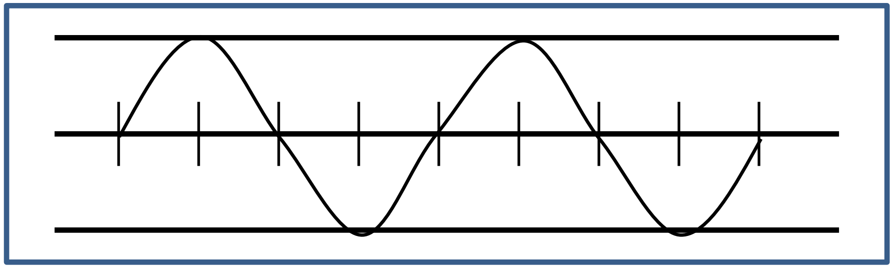
Time and Frequency

- 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

- *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

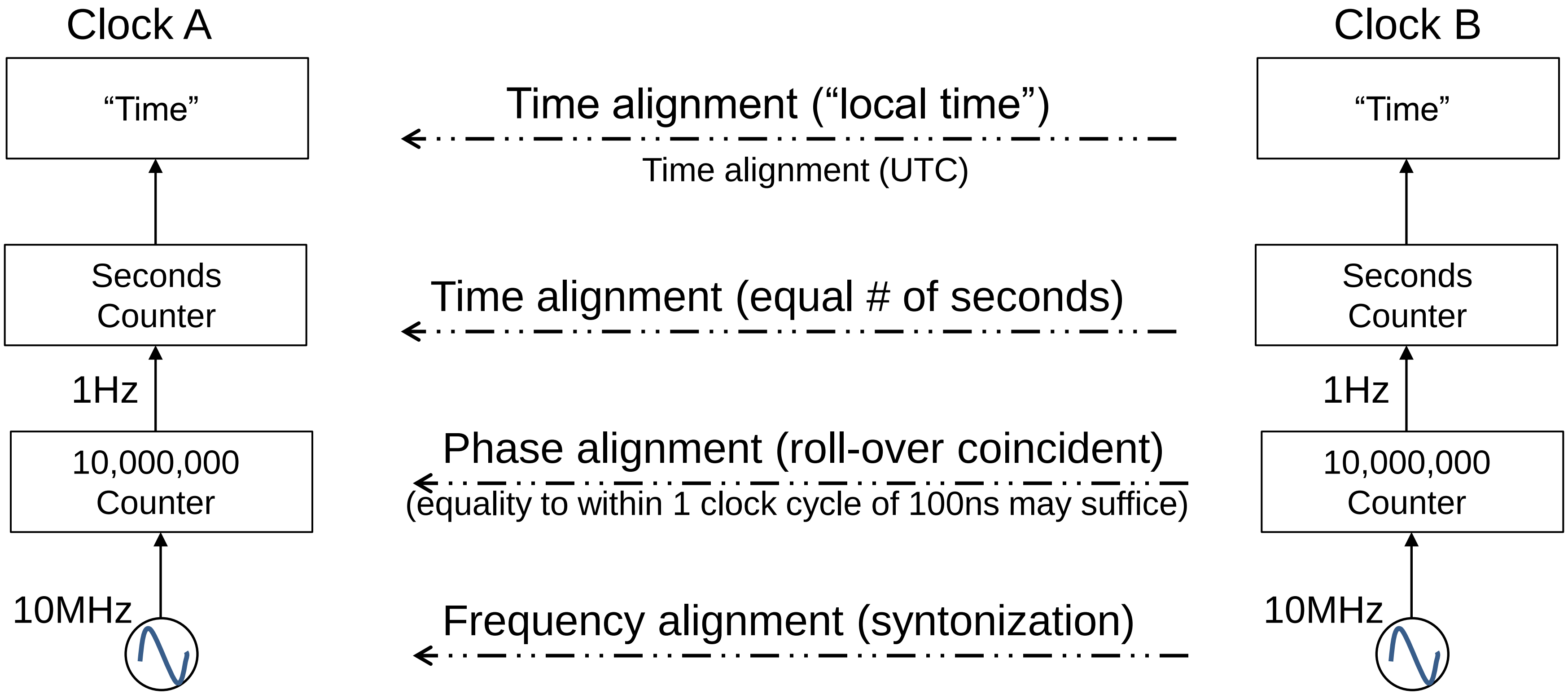
"discontinuous" timescale allows for jumps related to leap seconds

Clocks and Oclillators

- 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

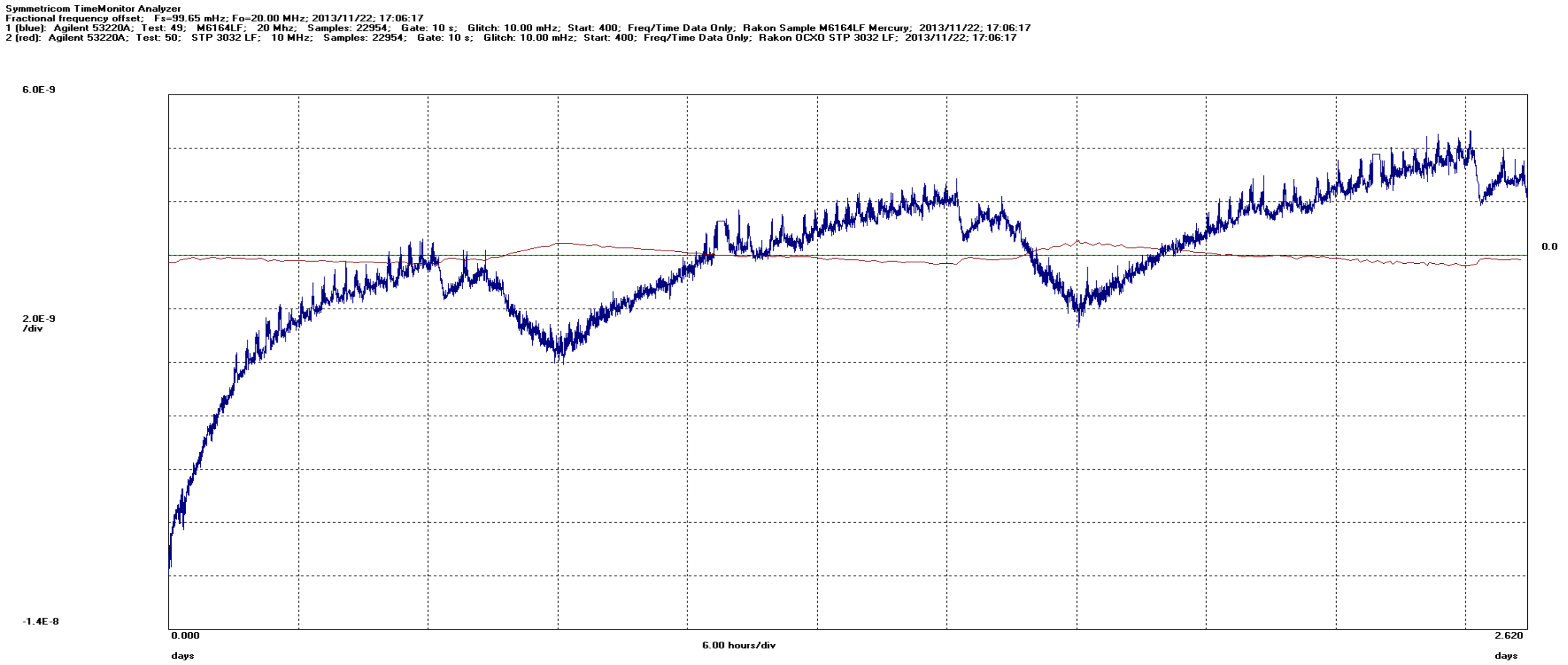
Time and Frequency

- 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.)



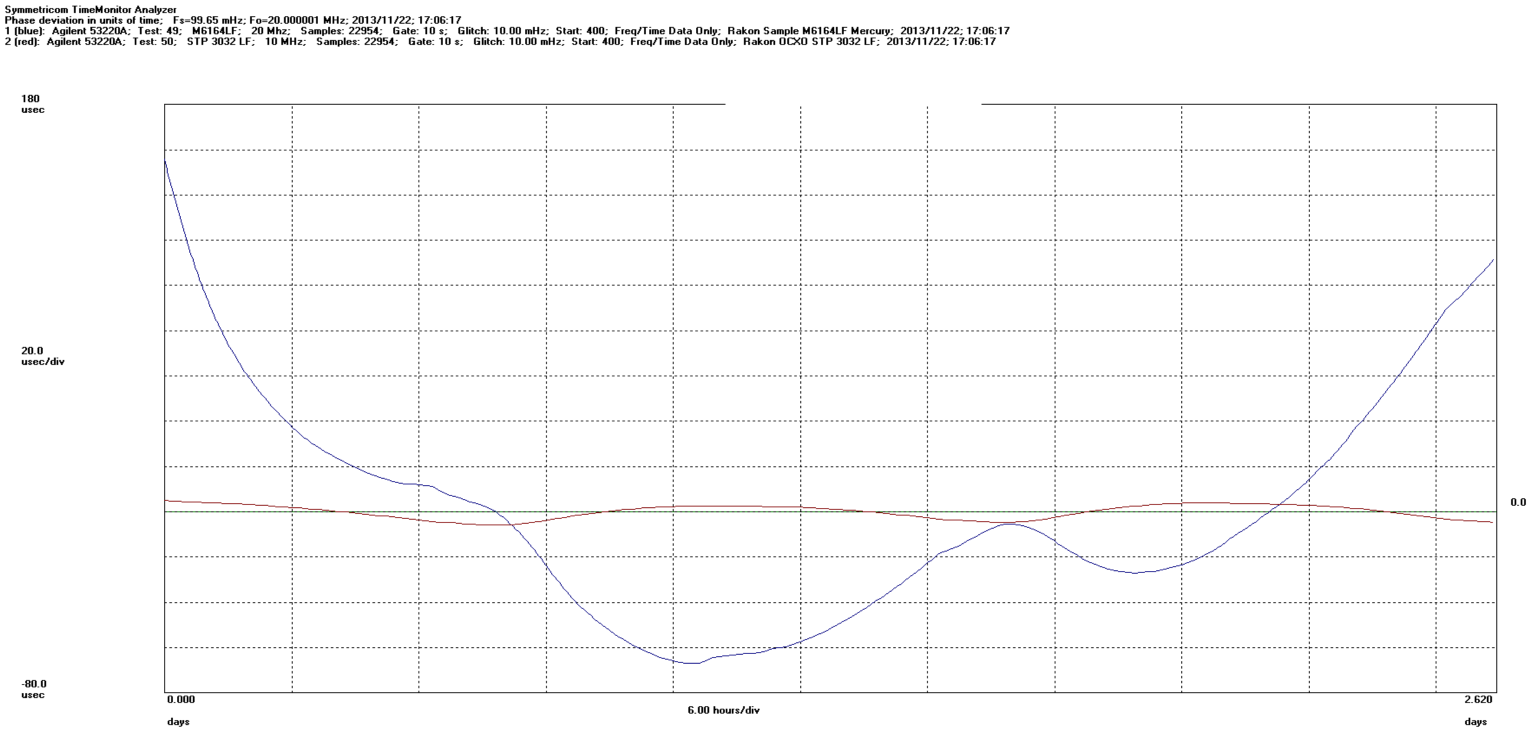
Time and Frequency

- 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

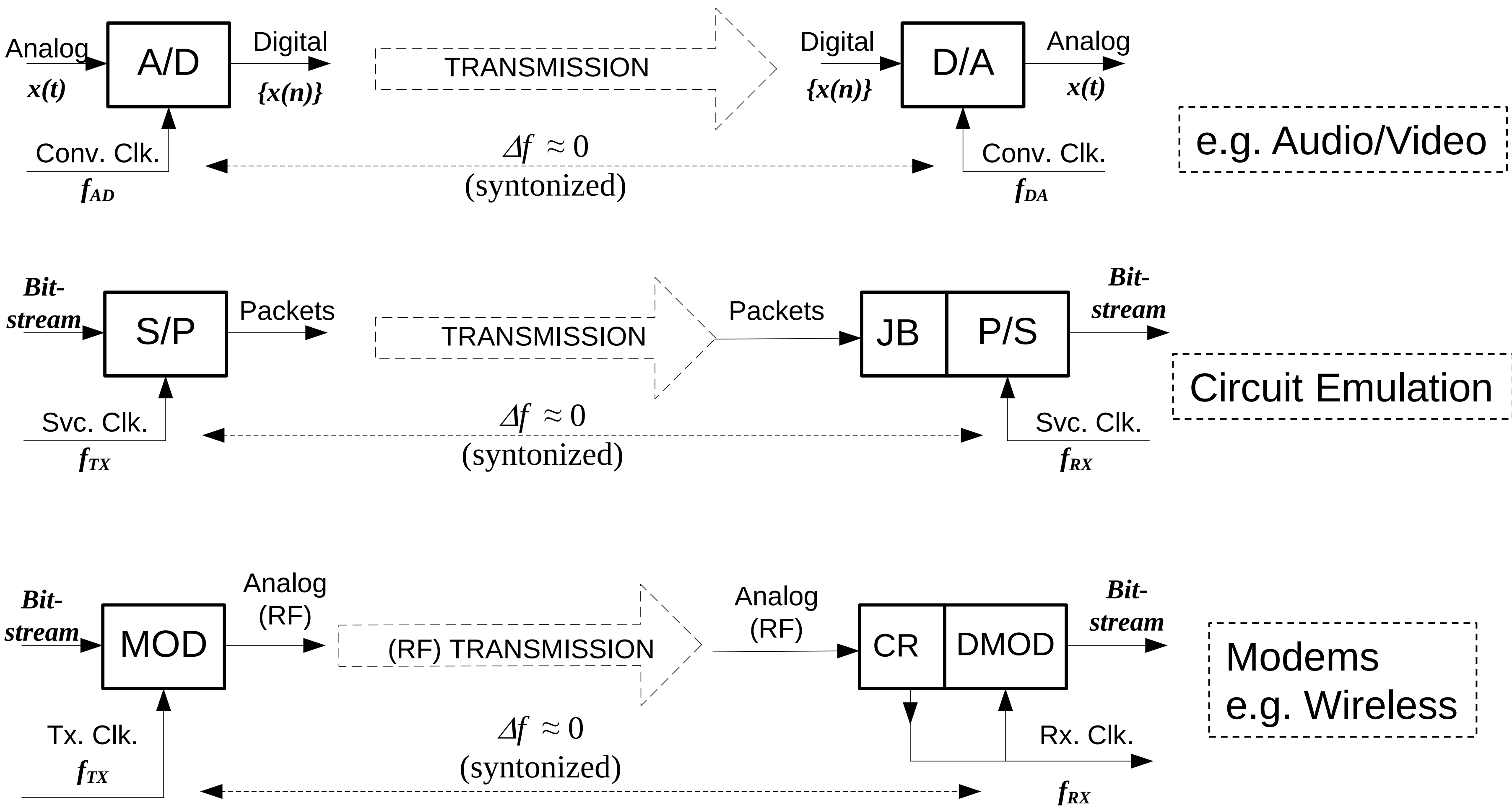


Fundamentals of Synchronization

- Time and Frequency
  - Clocks and Oscillators
  - Alignment (frequency, phase, time)
- Fundamental need for Synchronization
  - Coordinating Analog-to-Digital and Digital-to-Analog Conversions requires synchronization
  - Coordinating Signal Processing requires synchronization
    - Single source, single destination
    - Multiple sources, single destination
    - Single source, multiple destinations
    - Multiple sources, multiple destinations
- Examples in Telecommunications

Fundamental Need for Synchronization

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



Examples of single source, single destination

Fundamental Need for Synchronization

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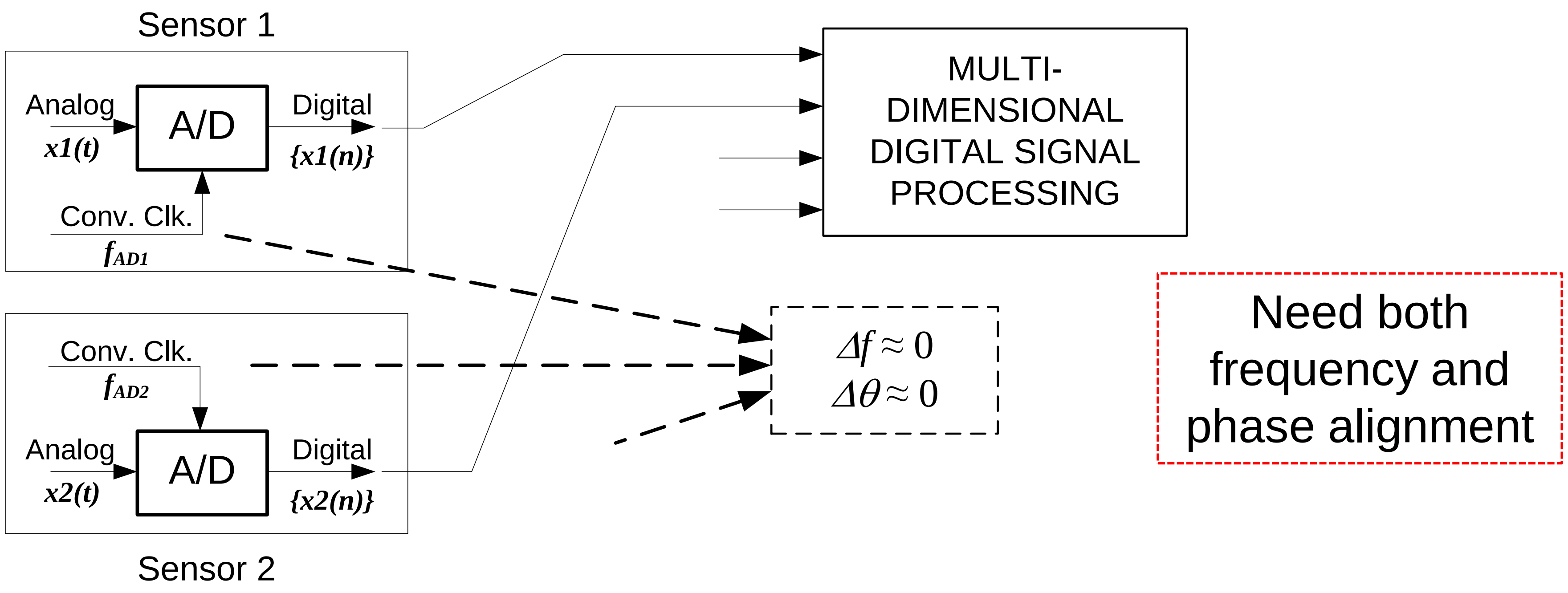
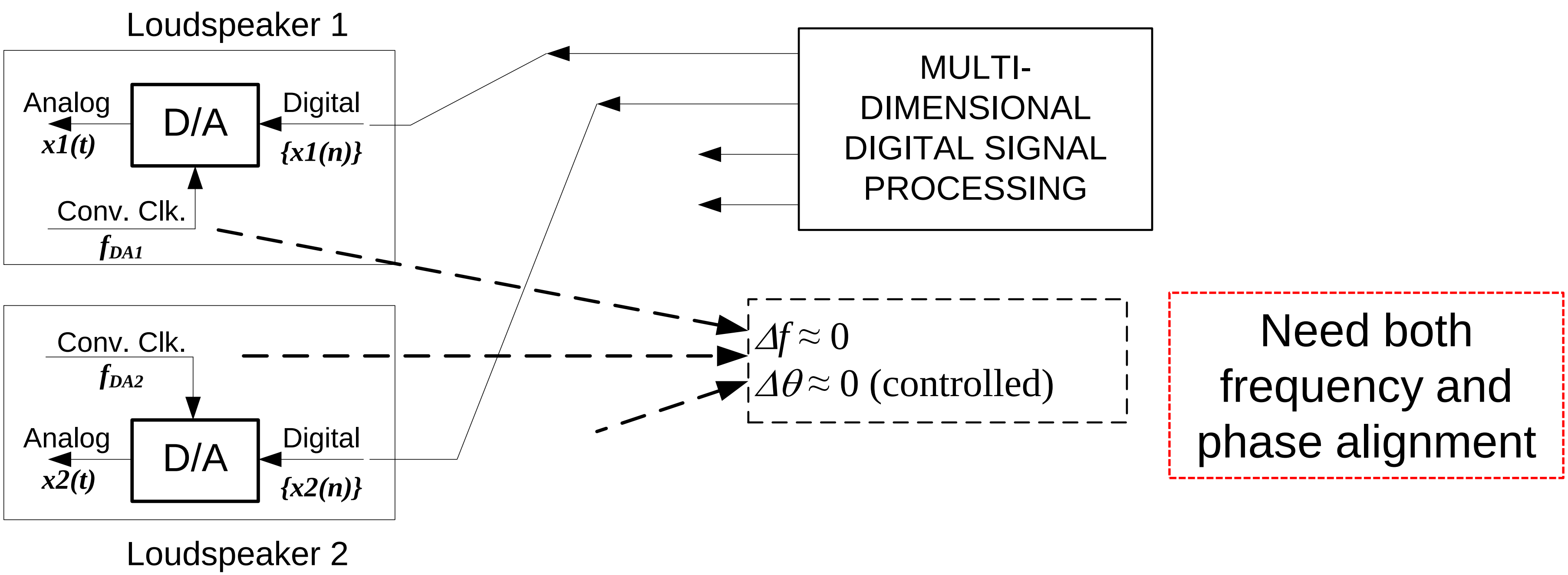


- Multiple sources, single destination (many, many, examples)
- Wireless: MIMO, eICIC, CoMP, etc., etc.
- Multimedia: audio/video, surround-sound, 3D video, etc., etc.
- Power: synchrophasors
- Geophysical applications (e.g. mapping strata for oil exploration)

Fundamental Need for Synchronization



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

Fundamentals of Synchronization

- Time and Frequency
  - – Clocks and Oscillators
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- Fundamental need for Synchronization
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Fundamental need for Synchronization

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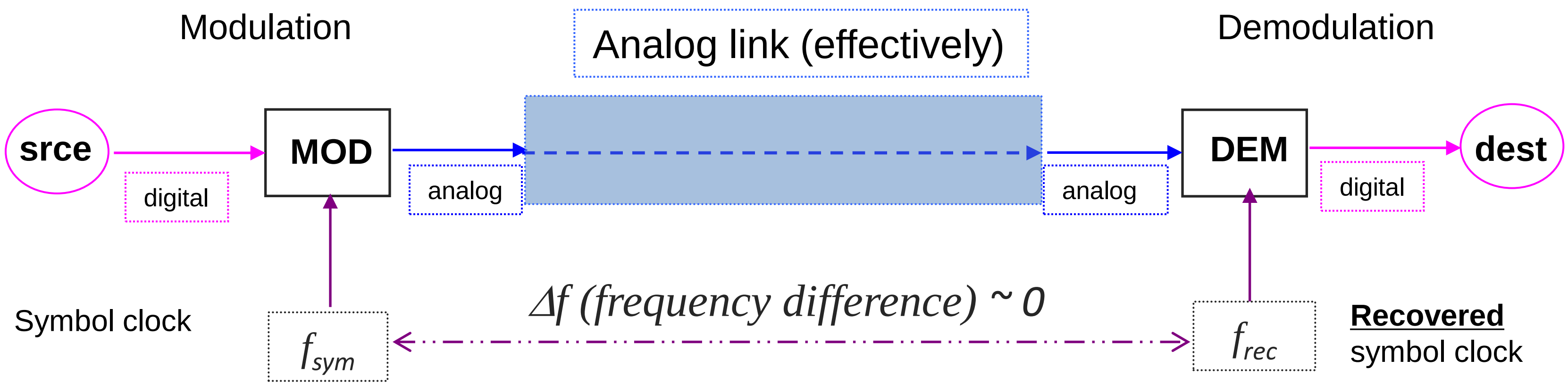
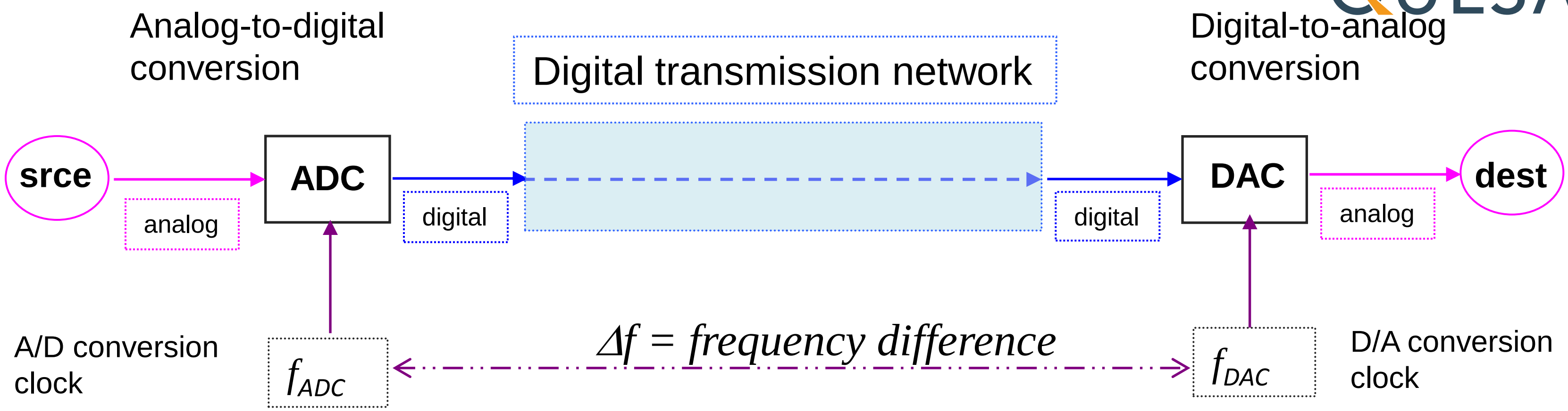
- Timing Alignment is Fundamental in Telecommunications
  - Digital transmission requires symbol-timing alignment
  - Digital network require synchronization to emulate analog channels
  - Circuit Emulation (CBR over packet) requires timing alignment
  - Wireless (Cellular) requires timing alignment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

Data transmission schemes require synchronization



- 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



$\Delta f \neq 0$ 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 (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 implicit in Circuit Emulation

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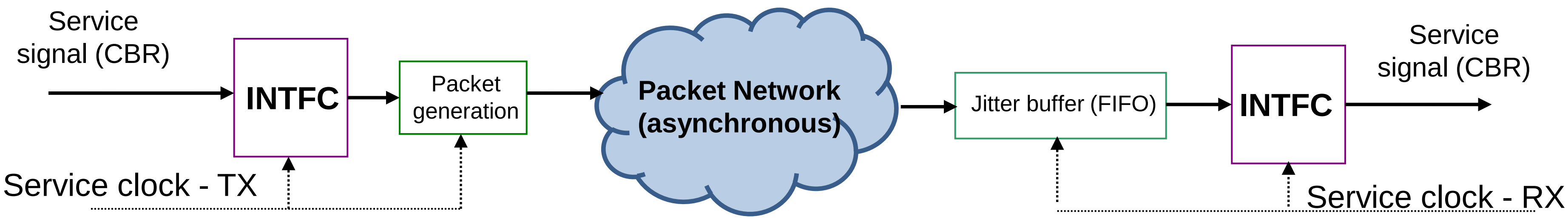
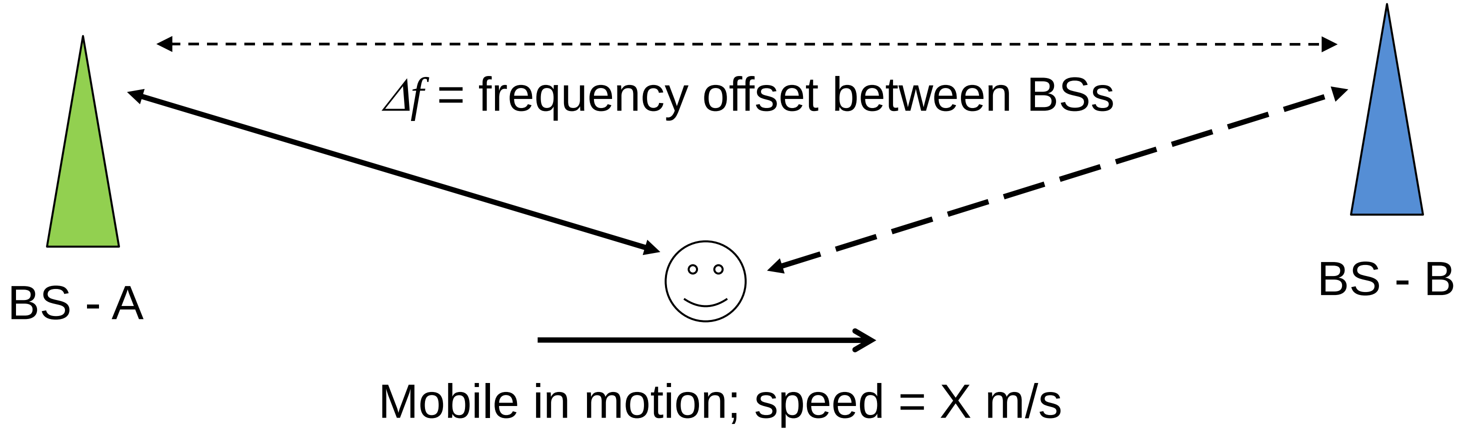


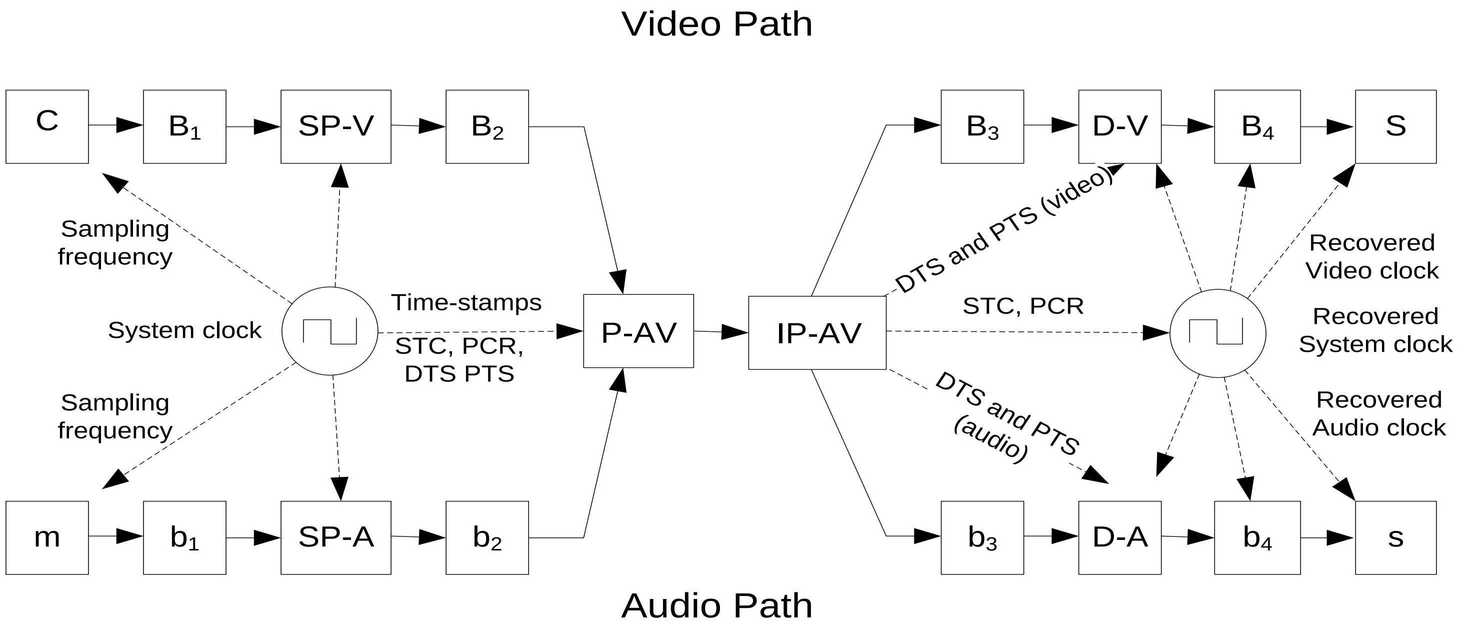
- Network impairments: delay, packet-delay-variation (PDV), discarded packets
- Jitter buffer size: large enough to accommodate greatest (expected) packet-delay-variation. Packet loss concealment is not an option.
- Causes of packet "loss":
  - Network drops packets (bit errors, congestion)
  - Jitter 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

Timing Alignment in Multimedia

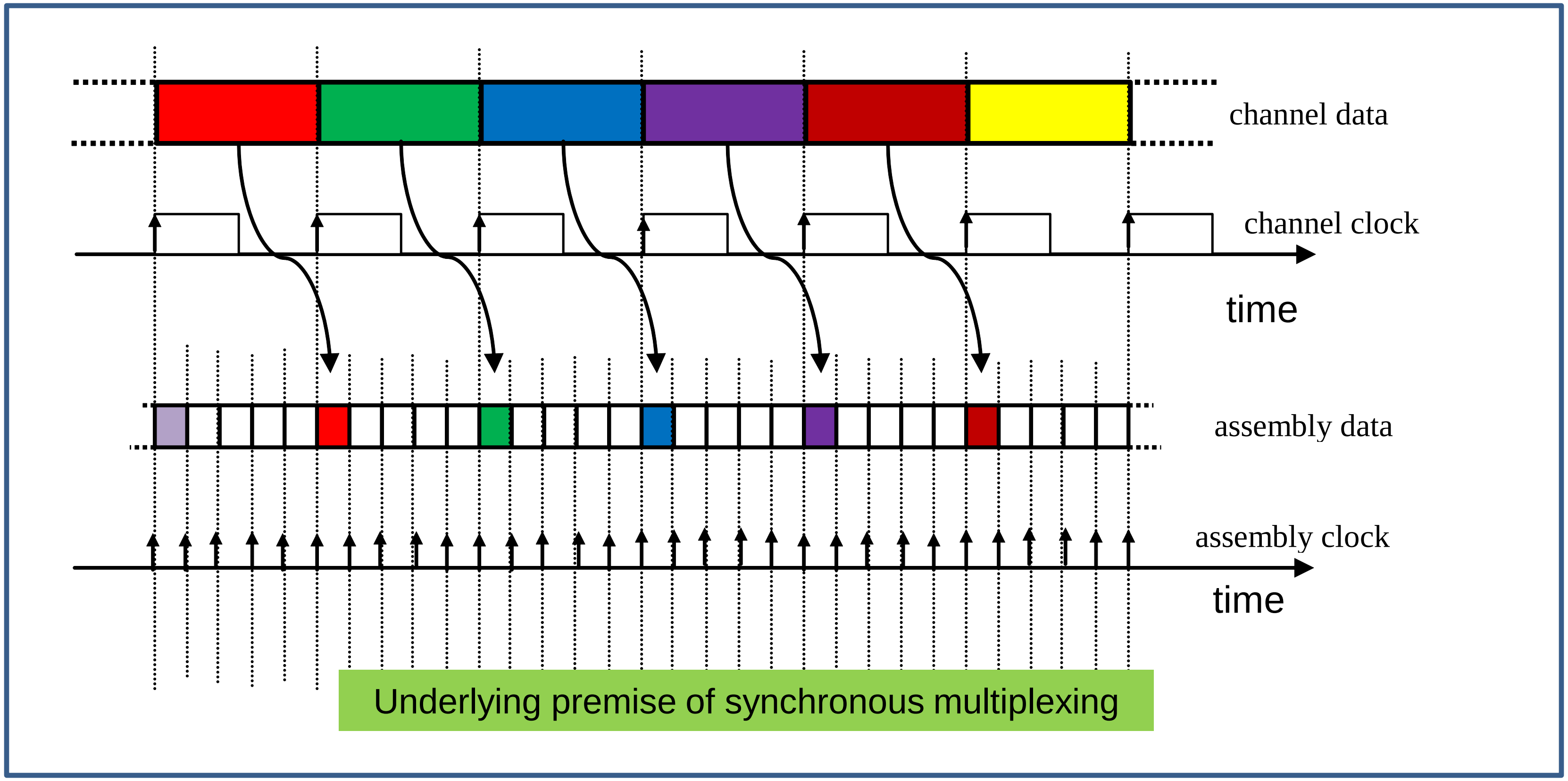


- Frequency offset (wander) between audio and video sampling results in loss of lip-sync
- Frequency offset (wander) between send-side and receive-side system clock results in freeze (video), breaks (audio), and possible loss of lip-sync

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 not 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

Synchronous Multiplexing



- 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*

Distribution of timing (frequency)

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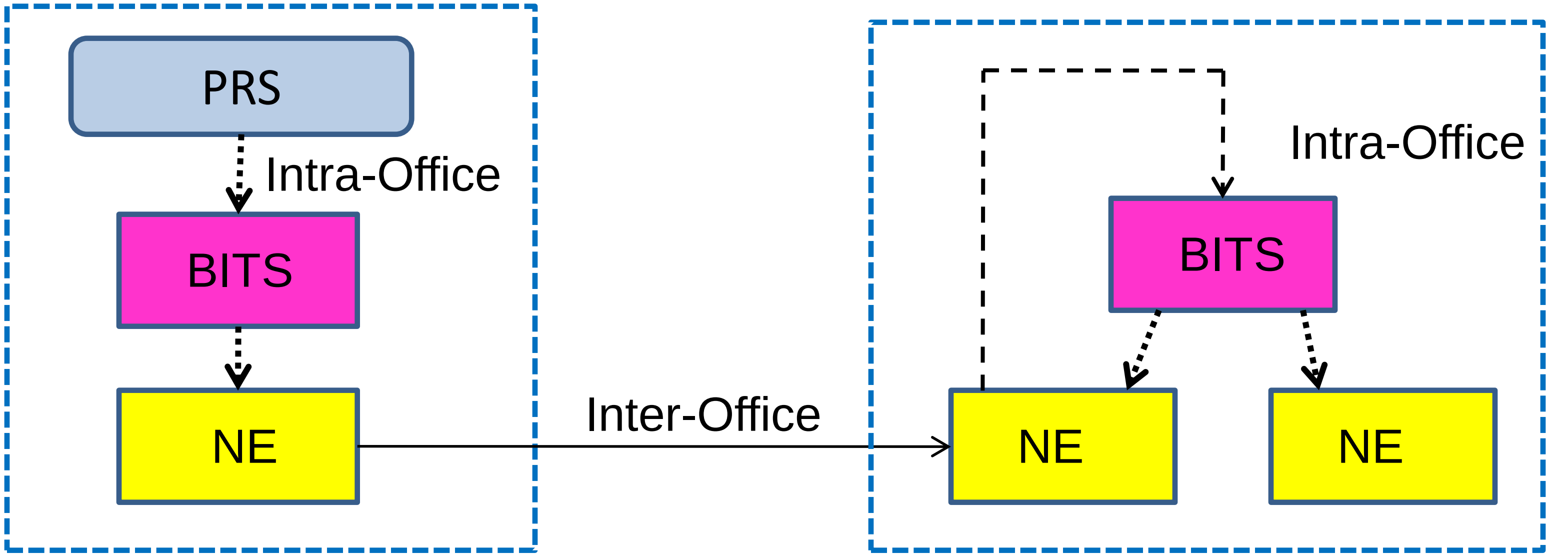

- PRS: *Primary Reference Source* – provides stratum-1 quality output signal
- BITS: Building Integrated Timing Supply (also TSG – Timing Sig. Gen.)
  - Provides clock reference to the different NEs in the CO
  - Accepts a reference input and performs clock-noise filtering (removes jitter/wander)
- NE: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

Stratum Levels - Telecom

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- Stratum level represents the intrinsic accuracy of a clock
  - Stratum-1: $1x10^{-11}$ (one part in 10^{11})
  - Stratum-2: $1.6x10^{-8}$ (16 parts per billion, ppb)
  - Stratum-3: $4.6x10^{-6}$ (4.6 parts per million, ppm)
  - Stratum-4: $32x10^{-6}$ (32 parts per million, ppm)
- Implication:

  output frequency is <u>always</u> 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!

INTRODUCTION TO CLOCKS

Introduction to Clocks

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

Clocks and Oscillators

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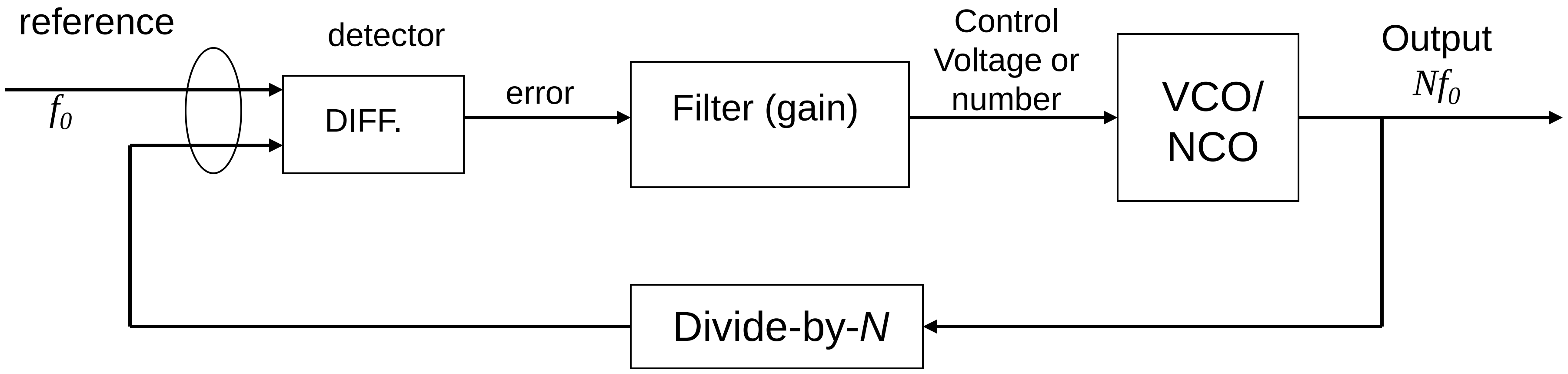
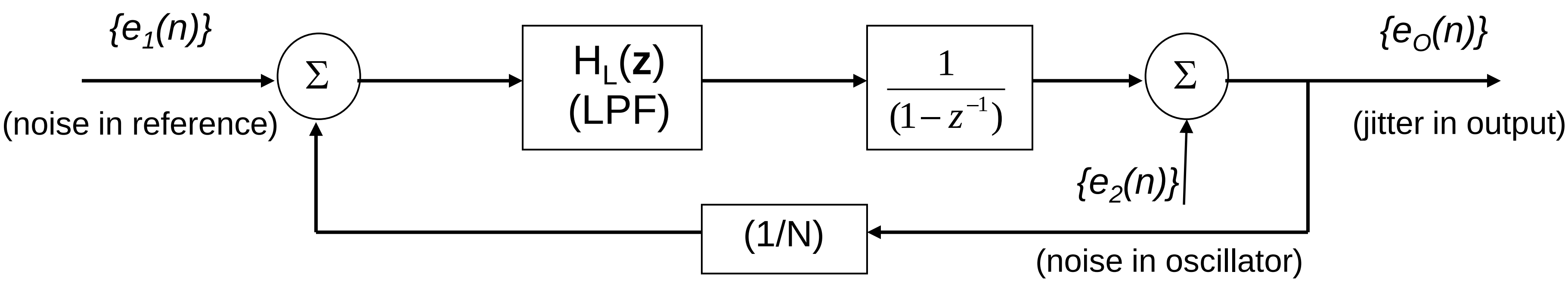
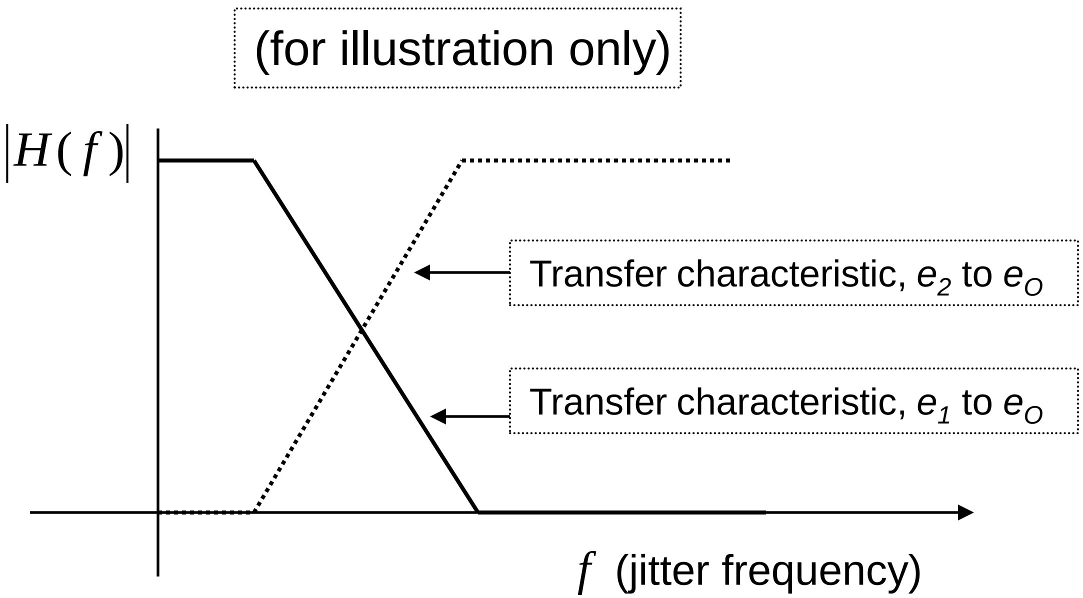
Loops and Holdover



- 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 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)

Common Mathematical Models

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

signal

Mathematical time

Phase function

(radian) frequency

"Clock Noise"

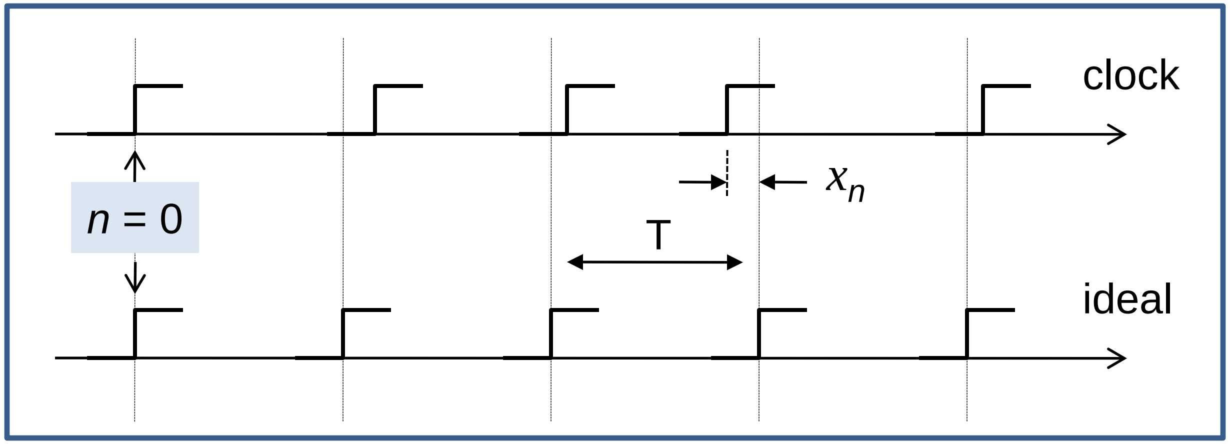
- A: Amplitude of signal. Does not figure in timing metrics.
- ϕ_0: Initial phase. Depends on choice of time origin. Usually assumed to be 0.
- $\varepsilon(t)$: Can be further decomposed into different categories such as frequency error, frequency drift, and random noise components
- ideal periodic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

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

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

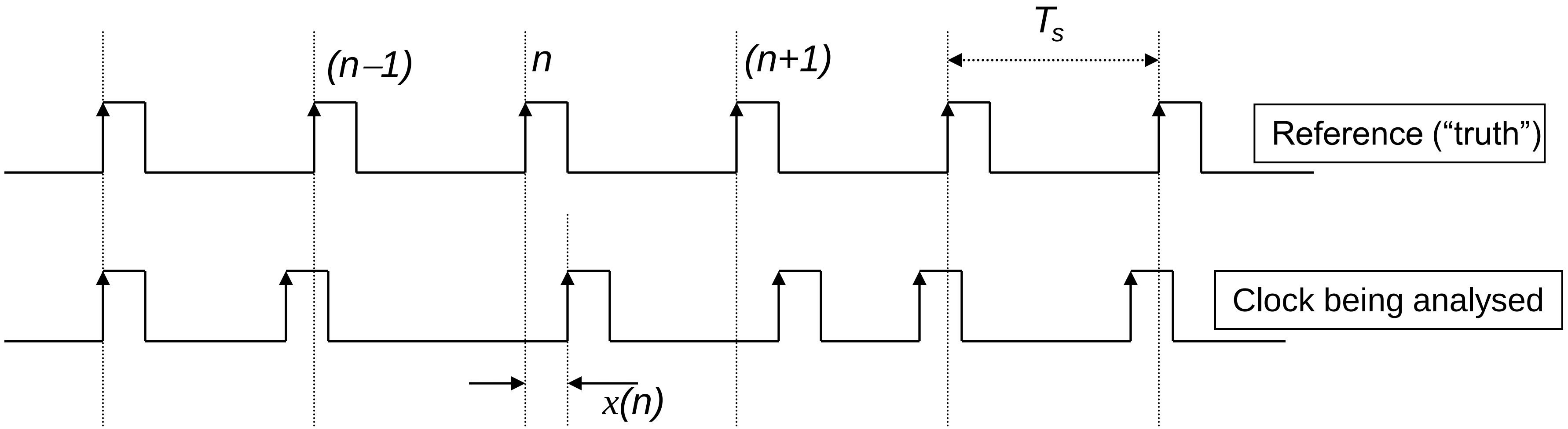
Time Error Models

Clock Metrics - Basics



- 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 Error



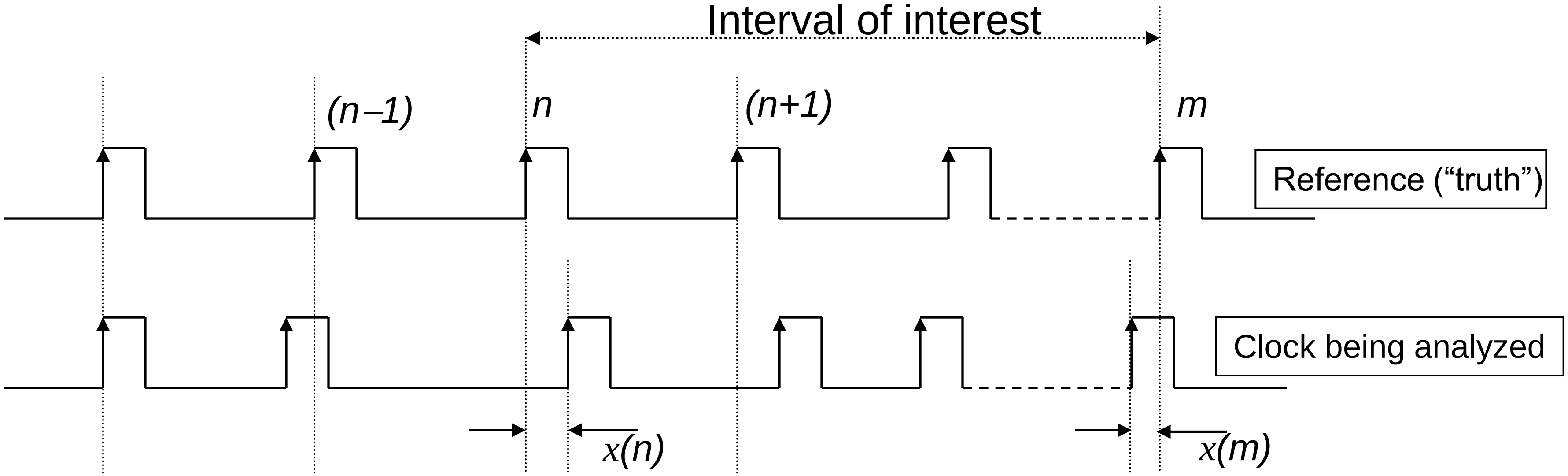
Basic premises:

- 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 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]

Time Interval Error

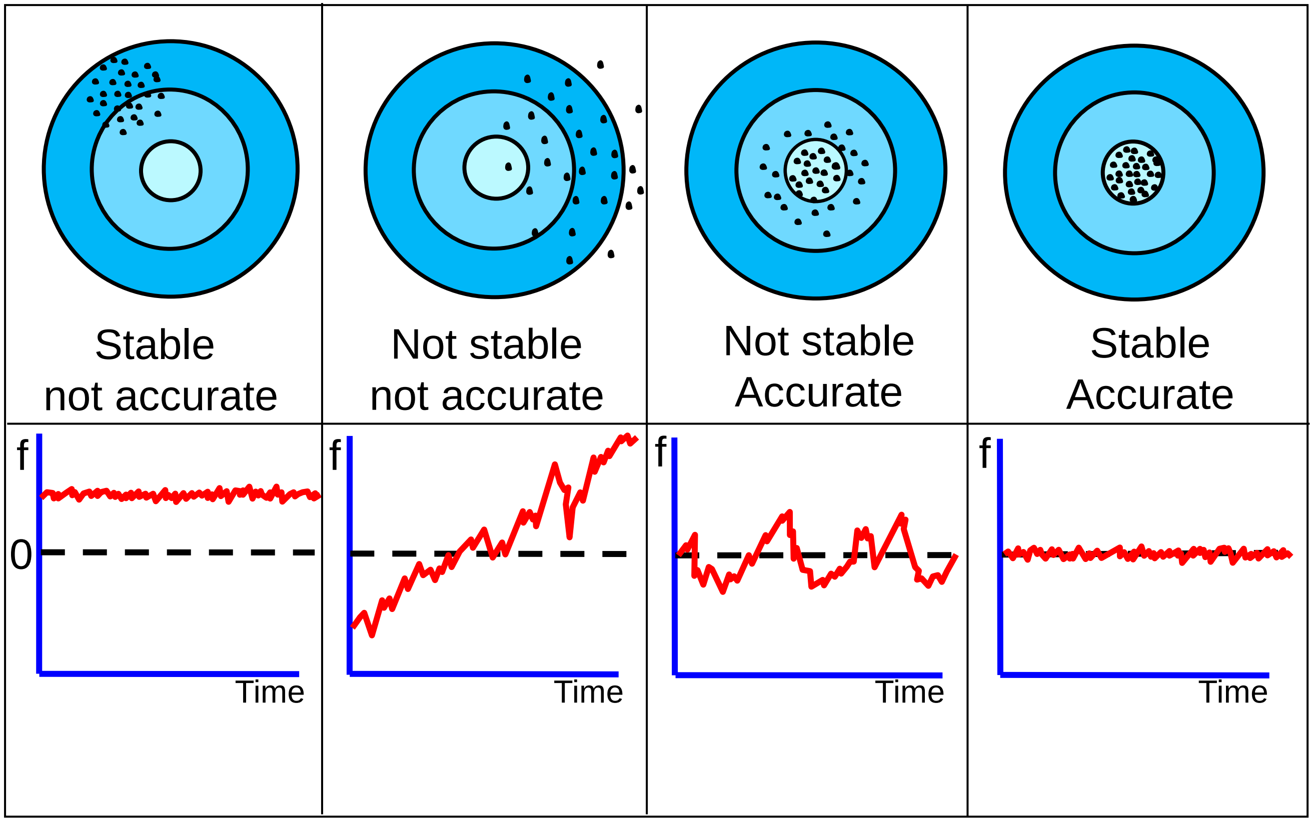


- Consider an interval of interest
- Duration measured by ideal clock ("truth") : $(m - n) \cdot T_S$
- *Error* in measurement of same interval by clock being analyzed:

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

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:

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

Clock Metrics – MTIE and TDEV

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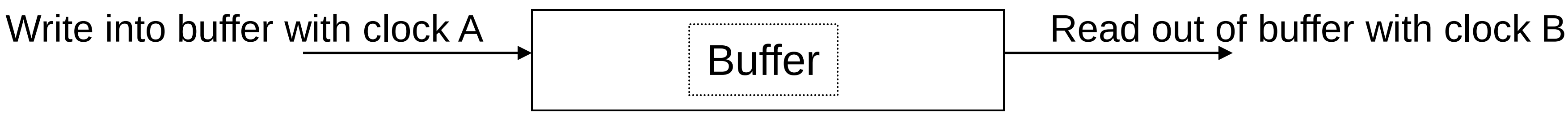
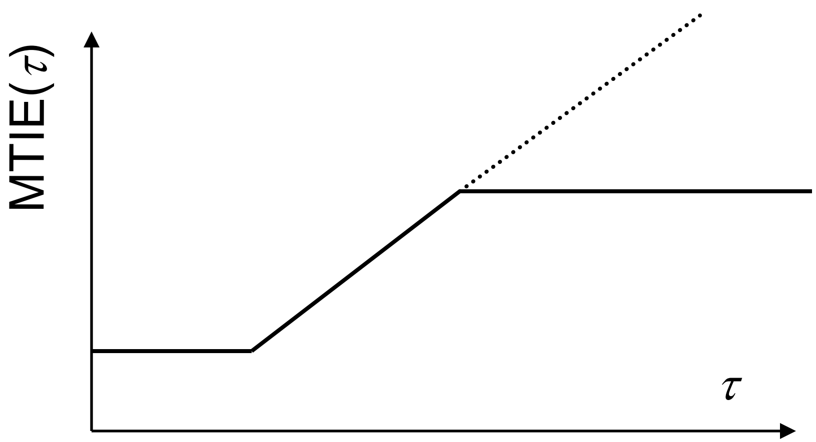
MTIE

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

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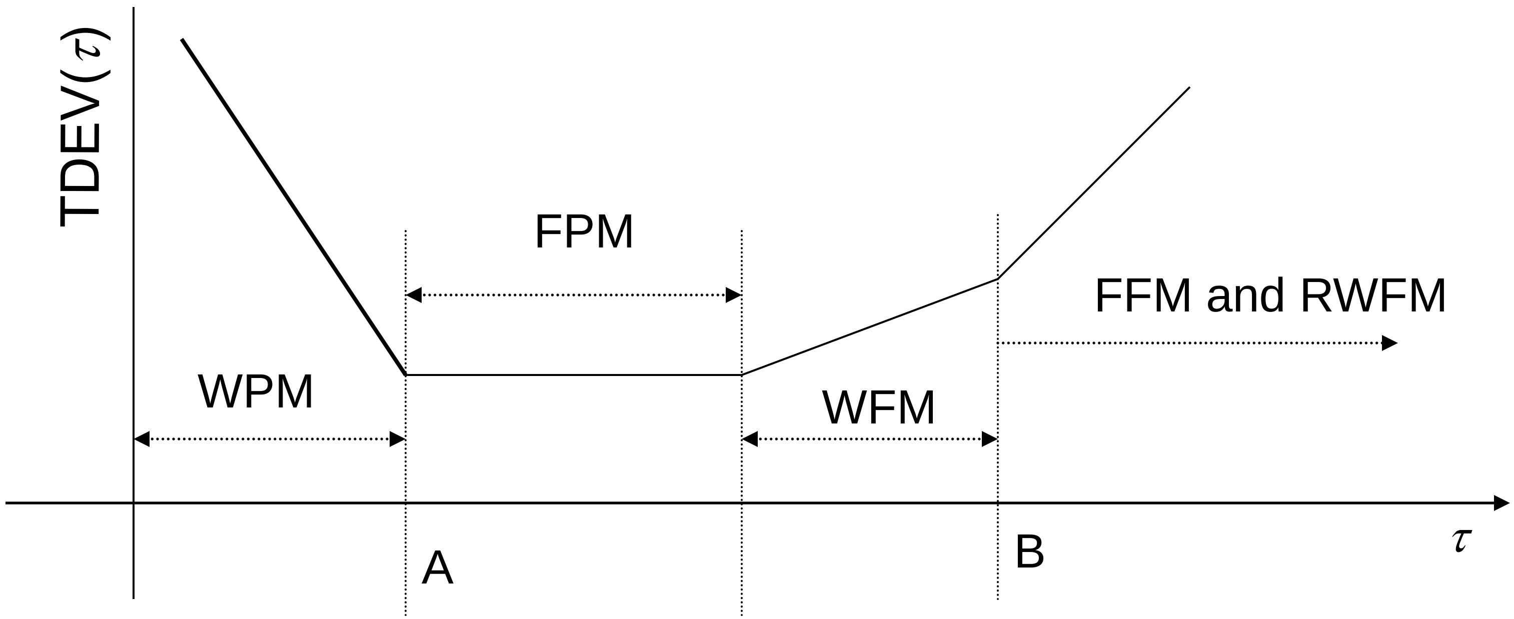

"Phase coherence" for up to A sec.
$\Rightarrow$ Keep PLL time constants less than A sec.

Phase Flicker Floor

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

Frequency Flicker Floor

Thank you …

Questions?

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TIMING REFERENCE SOURCES
&
ATOMIC CLOCKS

MARC WEISS

PHASE-LOCKED LOOPS AND OSCILLATORS

GREG ARMSTRONG

MEASURING AND CHARACTERIZING NETWORK TIME

LEE COSART

TIMING IN PACKET NETWORKS

STEFANO RUFFINI

STANDARDS

SILVANA RODRIGUES

CONCLUDING REMARKS

What did we cover?

QULSAR

- Fundamentals of Synchronization & Introduction to Clocks (Kishan Shenoi)
- Timing Reference Sources (Marc Weiss)
- Phase-Locked Loops and Oscillators (Greg Armstrong)
- Measurement Methods (Lee Cosart)
- Packet-based Timing (Stefano Ruffini)
- Standards (Silvana Rodrigues)

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- Examples in Telecommunications

Introduction to Clocks

- Clocks and Oscillators
- Model of a Locked Loop
- Fundamental Clock Concepts and Metrics
  - Time Error (TE) and Time Interval Error (TIE)
  - MTIE and TDEV

Quartz Crystal Oscillators and Phase Locked Loops

- 1. Quartz Crystal Oscillator (XO) Technology
  - Quartz Crystal Overview
  - Ageing and Temperature
  - XO, TCXO, OCXO, DOCXO
- 2. Phase Locked Loops (PLL)
  - PLL Overview
  - Response To Injected Noise
- 3. PLL with 2 inputs

Greg Armstrong (IDT)
Dominik Schneuwly (Oscilloquartz)

Timing in Packet Networks

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

Standards

- 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
  - 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

Thank You