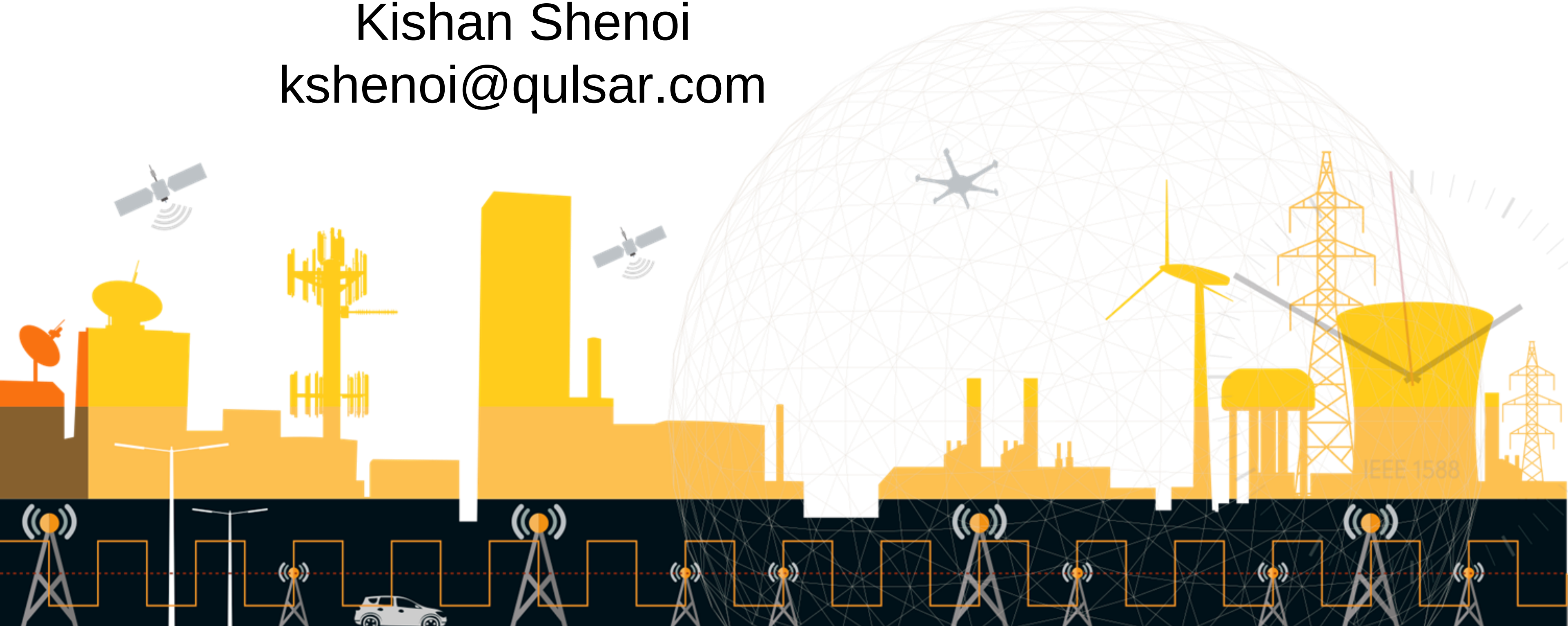
Fundamentals of Synchronization

WSTS 2019 Tutorial Session

San Jose, March 2019

Kishan Shenoi
kshenoi@qulsar.com



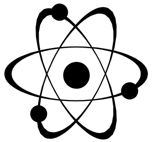
Fundamentals of Synchronization

- **Basic Principles**
  - **Time and Frequency**
  - **Clocks and Oscillators**
  - **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
- References for time/frequency
  - Transfer methods (one-way and two-way)
  - GNSS, Atomic Clocks (covered in the next section)
- Quantifying synchronization
  - Clock Model and timing signals
  - Time error, time interval error, jitter, wander, frequency offset
  - Classical metrics (MTIE, TDEV)

QULSAR

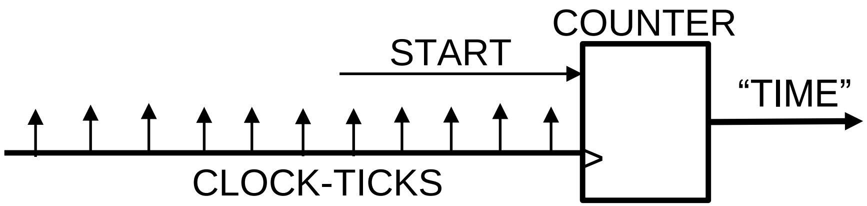
Time and Frequency

- 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)

Time and Frequency

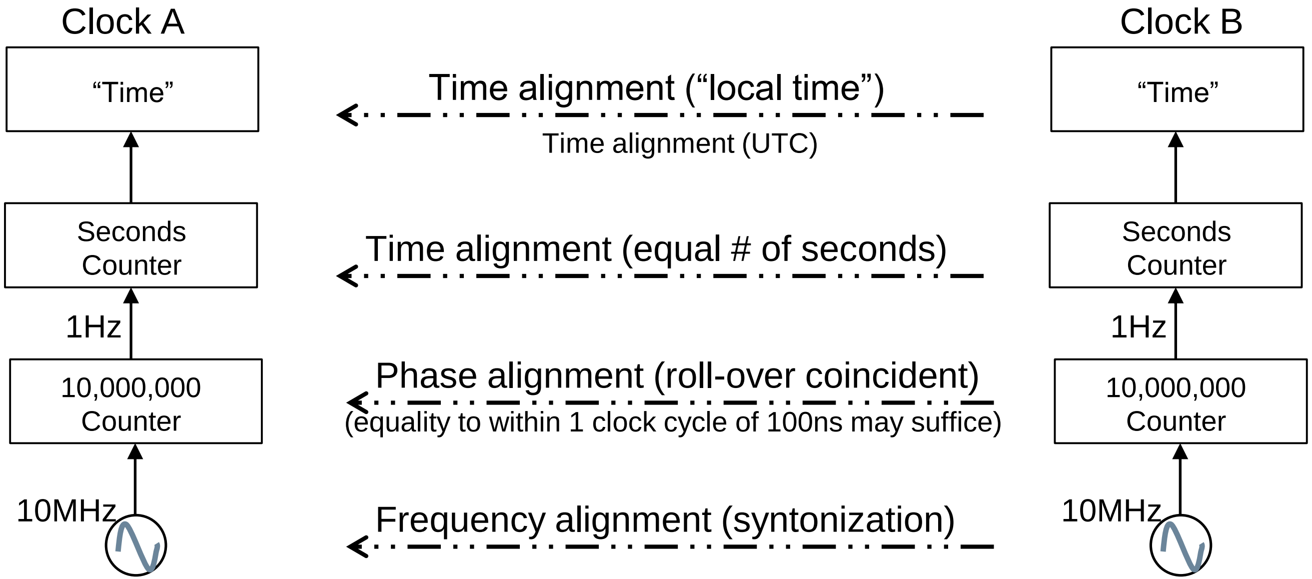
- *Time Interval* (e.g. 1 second) is based on a physical property of the Cesium atom
- *Time* is an artificial construct.
  - Choose an origin ("epoch") and consider *elapsed time interval* from the origin
  - Format (year/month/day/hour/min/sec…) [Time Zone]
- *Time Scales…*
  - Differ in terms of epoch…typically midnight (00:00:00hrs) Jan 1, 19xx; GPS is Jan 6, 1980
  - Continuous or discontinuous…"discontinuous" timescale allows for jumps related to leap seconds; "continuous" timescale does not have leap seconds
  - UT-1 which is based on the Earth's rotation around the sun (Jan. 1, 1958)
  - UTC : "Universal Time Coordinated" is the "standard" (discontinuous) (Jan. 1, 1972)
  - TAI : atomic clock based time based on count of seconds (continuous) (Jan. 1, 1958)
  - PTP : continuous time-scale (Jan. 1, 1970 00:00:00 TAI = Dec. 31, 1969 23:59:51.999918 UTC)
  - NTP : discontinuous and based on UTC (Jan. 1, 1900)

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 or “1-second”)
  - A clock is a “disciplined” oscillator plus counting capability
- Oscillator: Component providing periodic signals
  - Emphasis is on frequency stability (temperature, aging, other random processes) and waveform integrity (“phase noise”)
  - Oscillators are components of clocks

Alignment in Frequency, Phase, and Time

- 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.)



QULSAR

Fundamentals of Synchronization

- Basic Principles
  - Time and Frequency
  - Clocks and Oscillators
  - 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**
- References for time/frequency
  - Transfer methods (one-way and two-way)
  - GNSS, Atomic Clocks (covered in the next section)
- Quantifying synchronization
  - Clock Model and timing signals
  - Time error, time interval error, jitter, wander, frequency offset
  - Classical metrics (MTIE, TDEV)

QULSAR

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

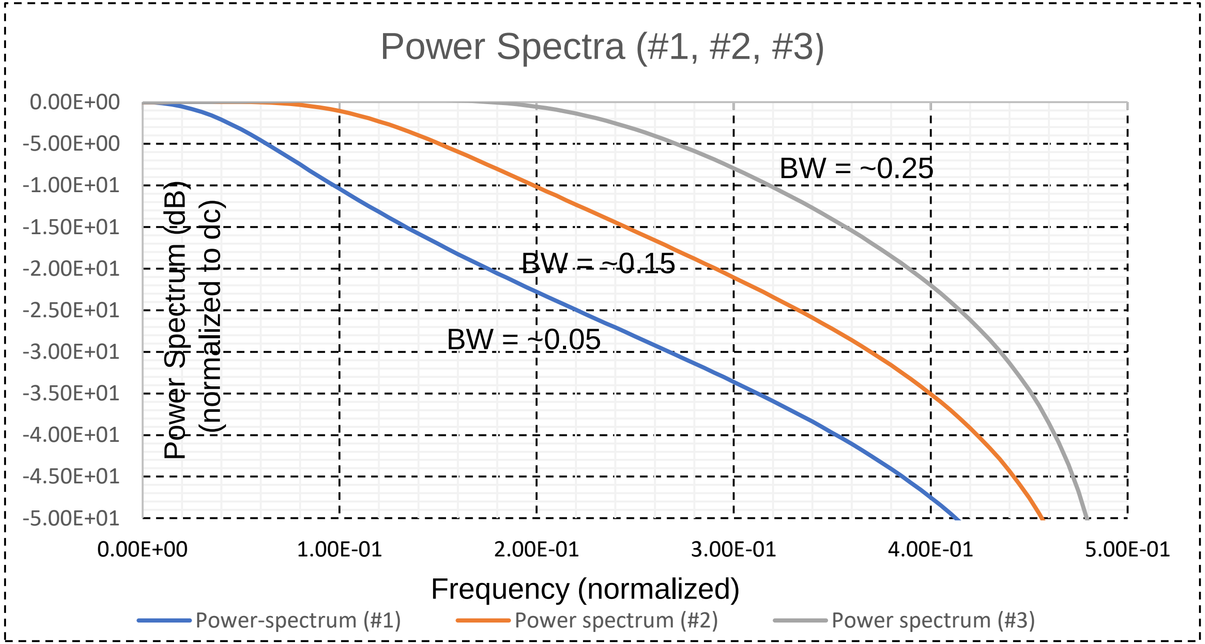
$$\epsilon(t) = x(t) - x(t + \delta)$$

QULSAR

Fundamental Need for Synchronization: Signal Processing

- Proper signal : $x(t)$; Synchronization error results in $x(t + \delta)$
- "Noise" resulting just from synchronization error is

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



Consider three cases:

1. BW ≈ 0.05·f_S
2. BW ≈ 0.15·f_S
3. BW ≈ 0.25·f_S

Sampling rate = f_S

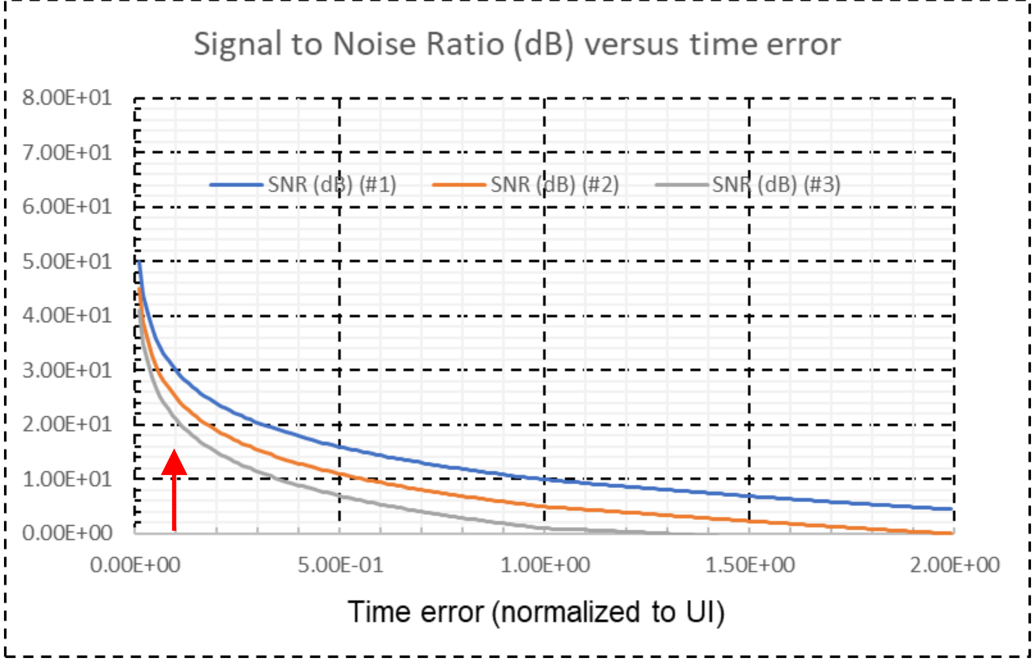
QULSAR

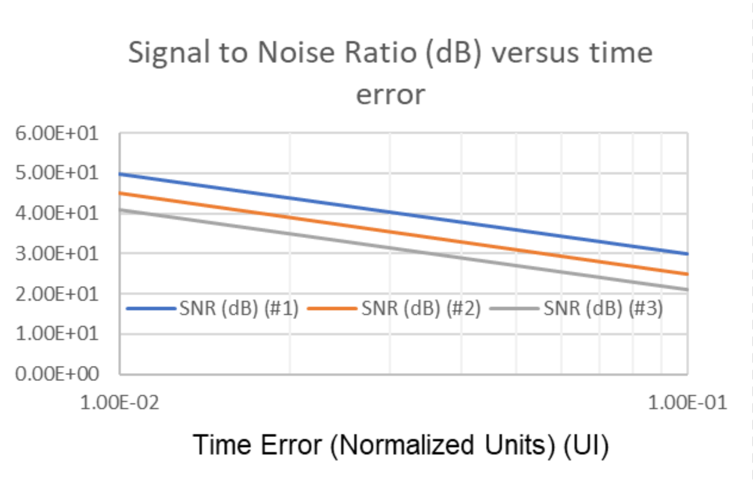
Fundamental Need for Synchronization: Signal Processing

- "Noise" resulting just from synchronization error 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

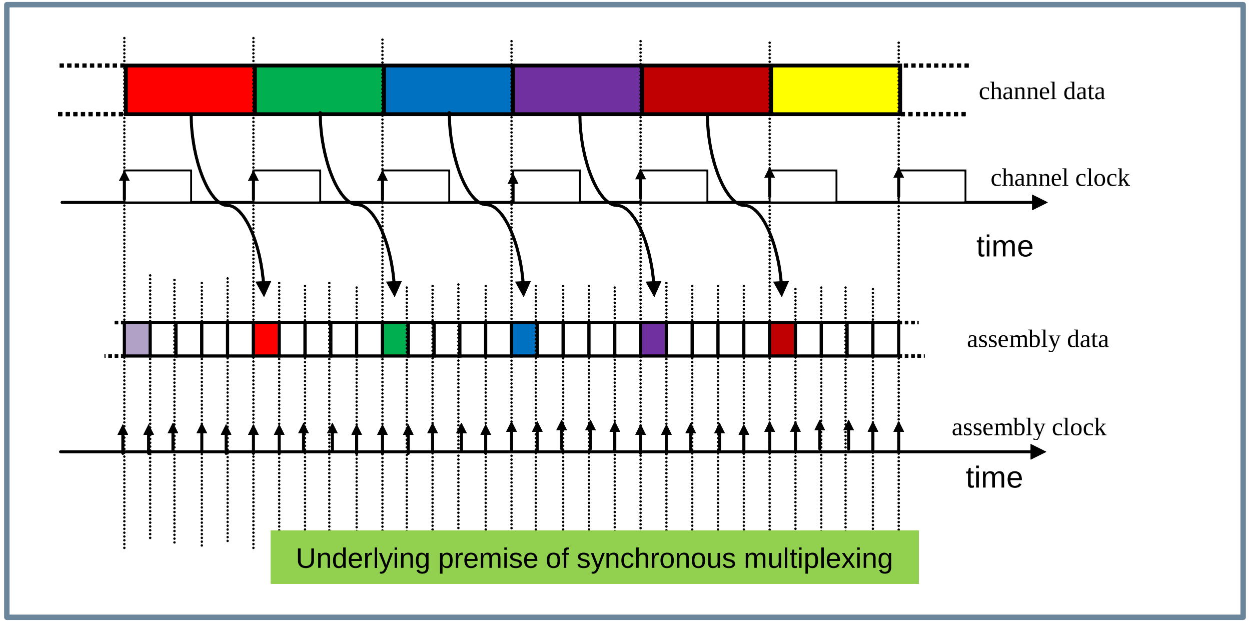
QULSAR

Fundamental Need for Synchronization – Time-stamping

- 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 (e.g. UTC or TAI or GPS, etc.).
  - Requires end-point synchronization to this common clock.
- 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
- Many examples (distributed database, shared documents, stock trades, sensor fusion, multi-player gaming, etc., etc.)

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

Buffer Write-Read – Synchronous Multiplexing



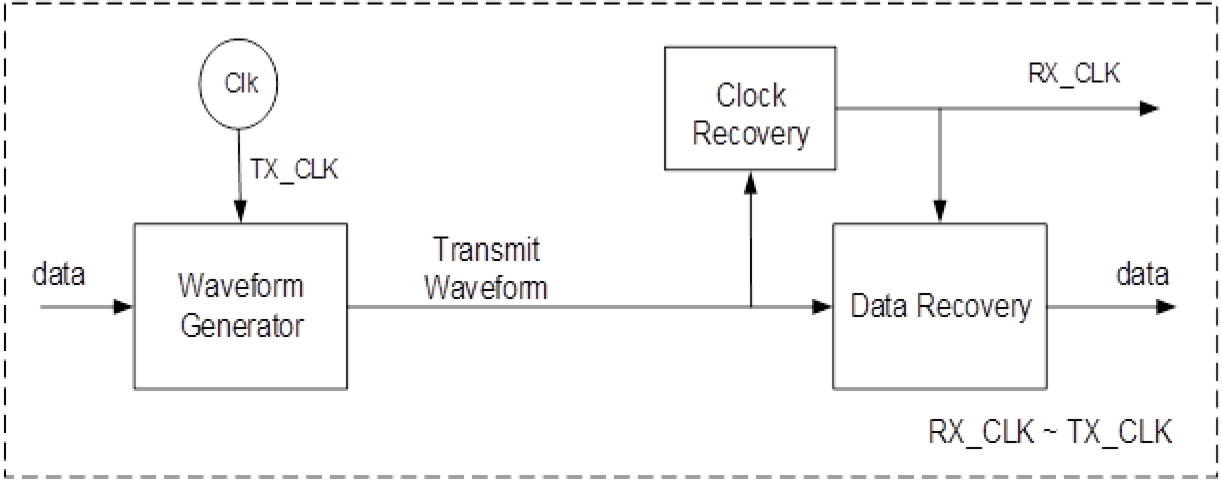
- Predetermined (rigid) ratio between channel clock and assembly clock
- 1-to-1 correspondence between channel bits and allowed bit positions
- *Fractional frequency difference between channel and assembly clocks = 0*

Fundamentals of Synchronization

- Basic Principles
  - Time and Frequency
  - Clocks and Oscillators
  - 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
- **References for time/frequency**
  - **Transfer methods (one-way and two-way)**
  - GNSS, Atomic Clocks (covered in the next section)
- Quantifying synchronization
  - Clock Model and timing signals
  - Time error, time interval error, jitter, wander, frequency offset
  - Classical metrics (MTIE, TDEV)

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

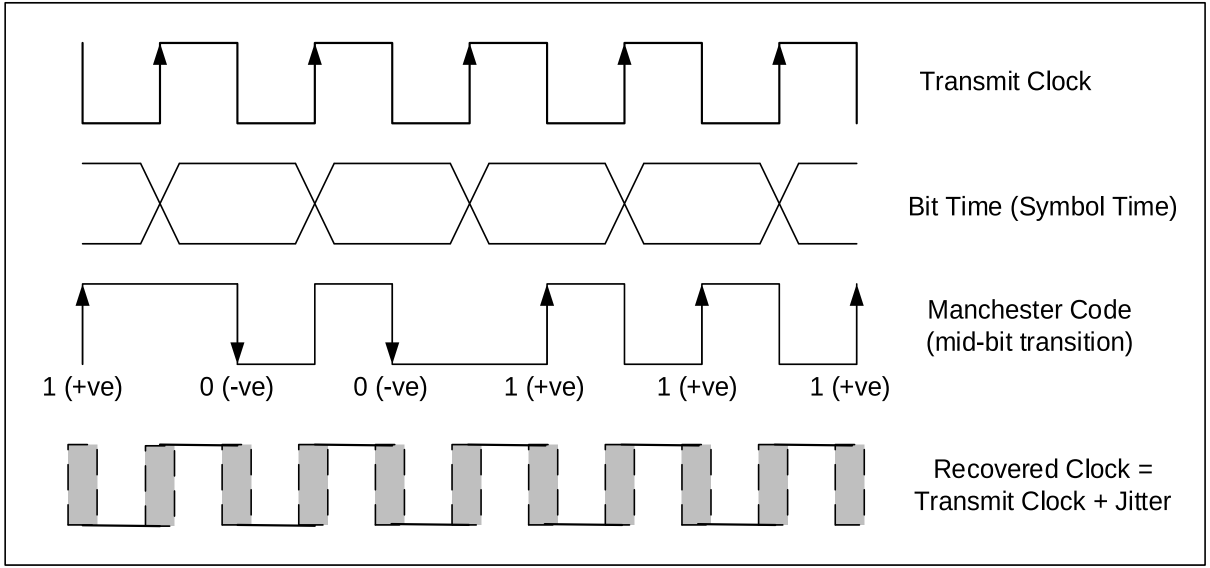
- A timing signal is a signal that inherently includes the clock properties of the source, allowing the destination to extract a timing reference
- Using this timing reference the destination can construct a (near) replica of the source clock
- Example: the transmit waveform used to deliver digital information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



QULSAR

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

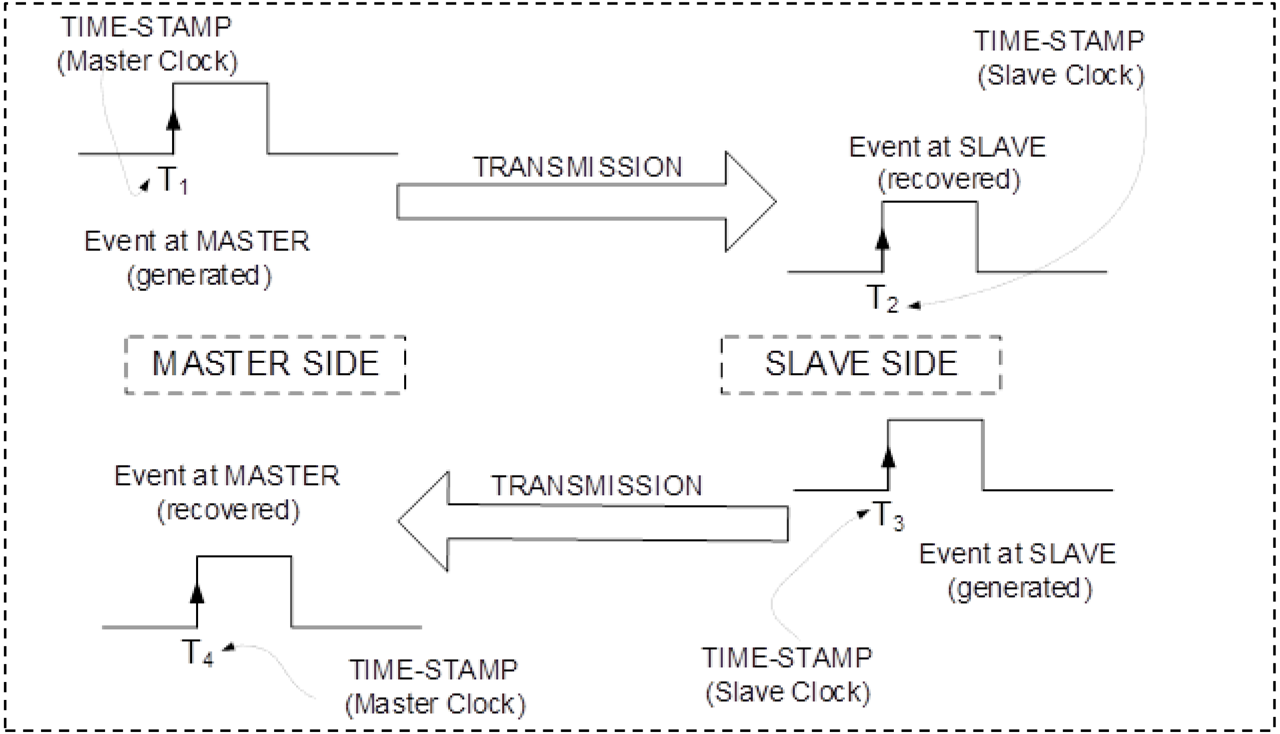
- Example: Manchester encoding of data provides a signal transition every bit-time
- Clock Recovery "fills" in the edges… recovered clock ~ transmit clock
- Phase is unknown because of unknown transmission delay (one-way suitable for frequency but not phase/time transfer)
- Jitter in recovered clock can be filtered out (lowpass filter function of a PLL)



QULSAR

Transfer of time – *Timing Signal (two-way)*

The timing signal could be the combination of an event plus a message (“time at”)



Note:

1. PTP utilizes time-stamped packets to provide a timing reference.
2. Transfer of time and/or phase requires two-way exchange to determine round-trip delay.
3. $RTD=(T_4-T_1)+(T_2-T_3)$
4. Usually assume one-way delay is (1/2) round-trip delay.

QULSAR

Fundamentals of Synchronization

- Basic Principles
  - Time and Frequency
  - Clocks and Oscillators
  - 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
- References for time/frequency
  - Transfer methods (one-way and two-way)
  - GNSS, Atomic Clocks (covered in the next section)
- **Quantifying synchronization**
  - **Clock Model and timing signals**
  - **Time error, time interval error, jitter, wander, frequency offset**
  - **Classical metrics (MTIE, TDEV), etc.**

QULSAR

Quantifying Synchronization (Performance)

- Mathematical Model
- Fundamental Clock Concepts and Metrics
  - Time Error (TE) and Time Interval Error (TIE)
  - MTIE
  - TDEV

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"

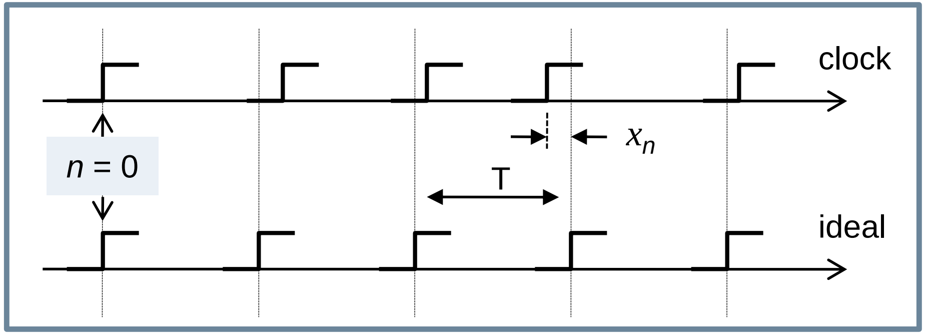
- A: Amplitude of signal. Does not figure in timing metrics.
- ϕ_0: Initial phase. Depends on choice of time origin. Usually assumed to be 0.
- $\varepsilon(t)$: Can be further decomposed into different categories such as frequency error, frequency drift, and random noise components
- ideal periodic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

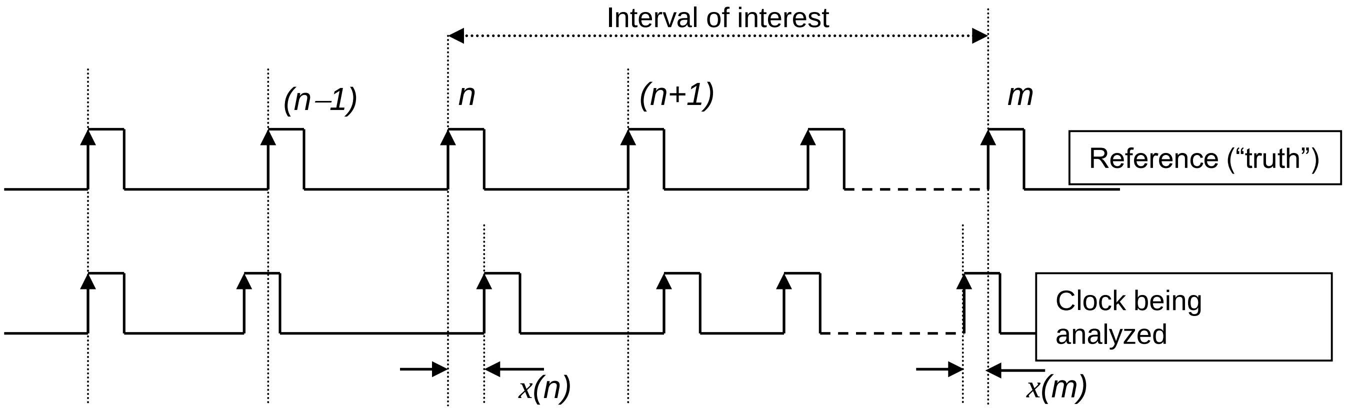
Clock Metrics – Basics: Time Error



- 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: $x_0 = 0$.

QULSAR

Time Interval Error

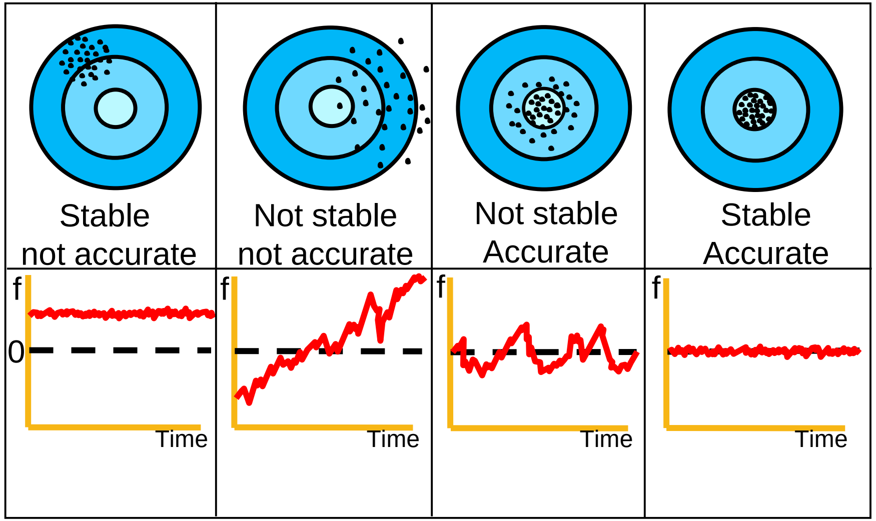


- Consider an interval of interest (e.g. 100m dash):
- Start: "n" ; Stop: "m"
- Duration measured by ideal clock ("truth") : $(m - n)\cdot T_S$
- *Error* in measurement of same interval by clock being analyzed:

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

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.)



Samples of measurements of frequency offset

Clock Metrics – MTIE and TDEV

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 $\{x(k);\ k=0,1,2,\ldots,(N\text{-}1)\}$, 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:

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

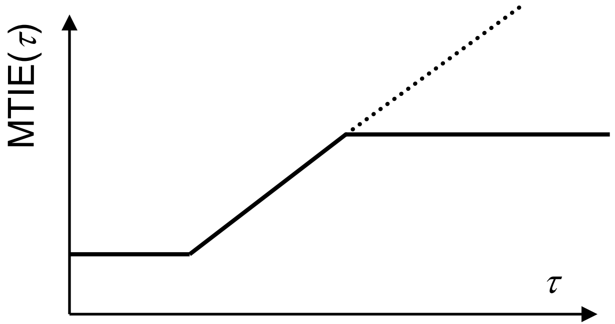
Clock Metrics – MTIE and TDEV

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” (zero-slope)

QULSAR

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

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

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

Conventional Definition

Note: $x(k) \Leftrightarrow x_k$

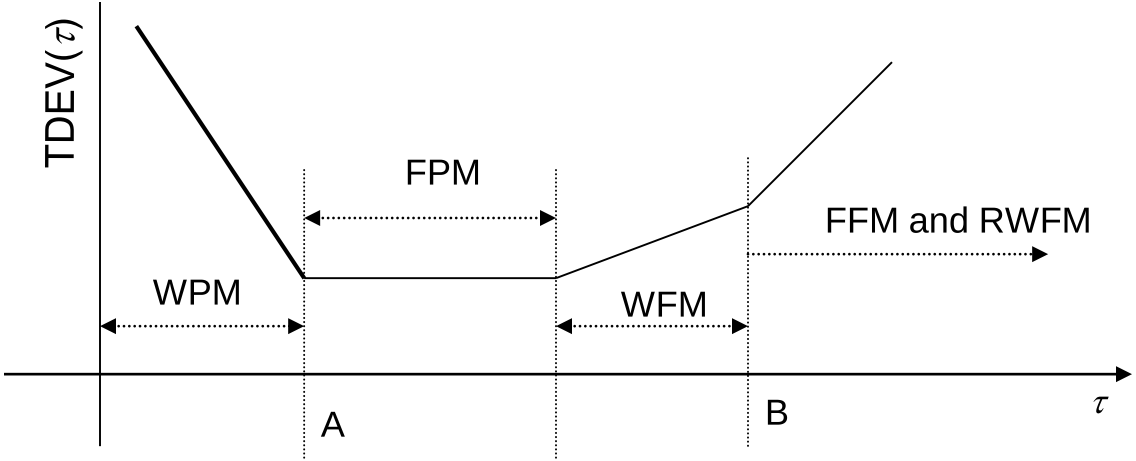
TVAR = square of TDEV

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.

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

Phase Flicker Floor

Frequency Flicker Floor

Concluding Remarks

- Basic Principles
  - Time and Frequency
  - Clocks and Oscillators
  - 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
- References for time/frequency
  - Transfer methods (one-way and two-way)
- Quantifying synchronization
  - Clock Model and timing signals
  - Time error, time interval error, jitter, wander, frequency offset
  - Classical metrics (MTIE, TDEV), etc.

QULSAR

Thank you …

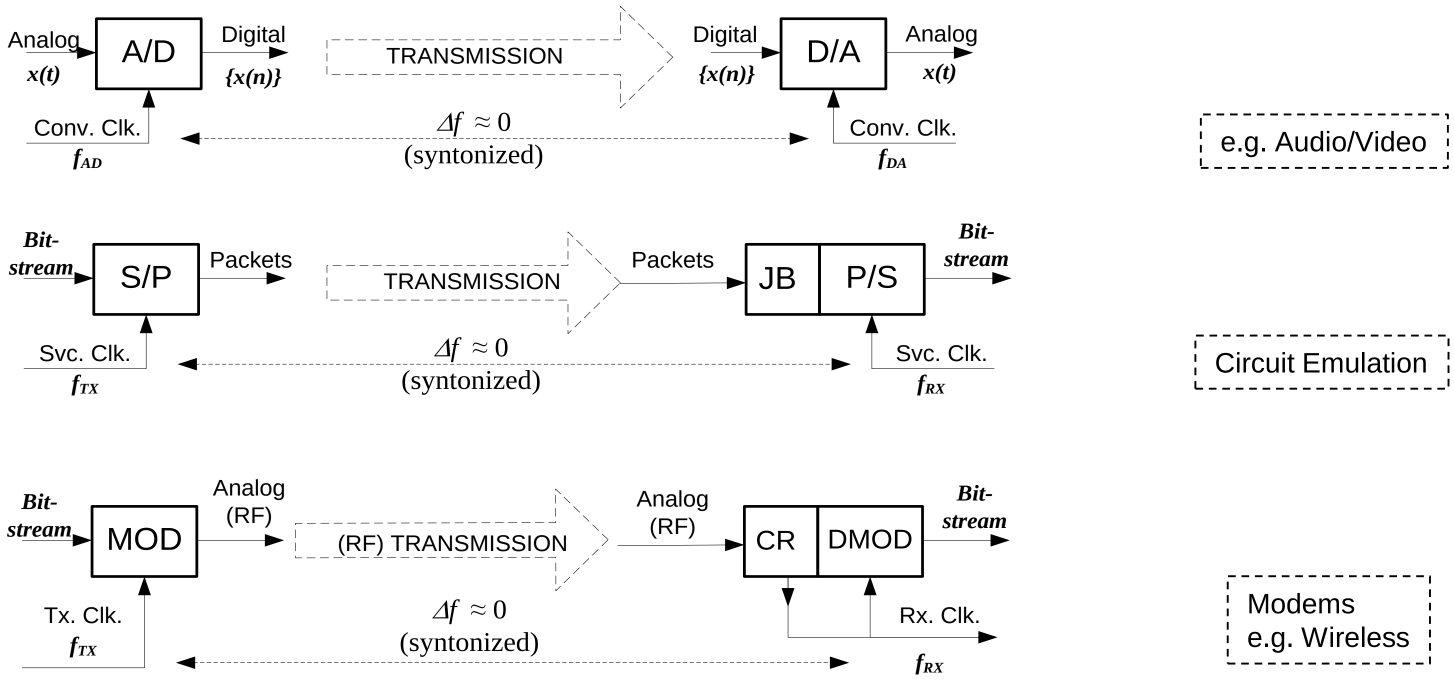
Questions?

Kishan Shenoi
CTO, Qulsar, Inc.
Email: kshenoi@qulsar.com
www.qulsar.com
@qulsar

BACKUP SLIDES

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

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

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

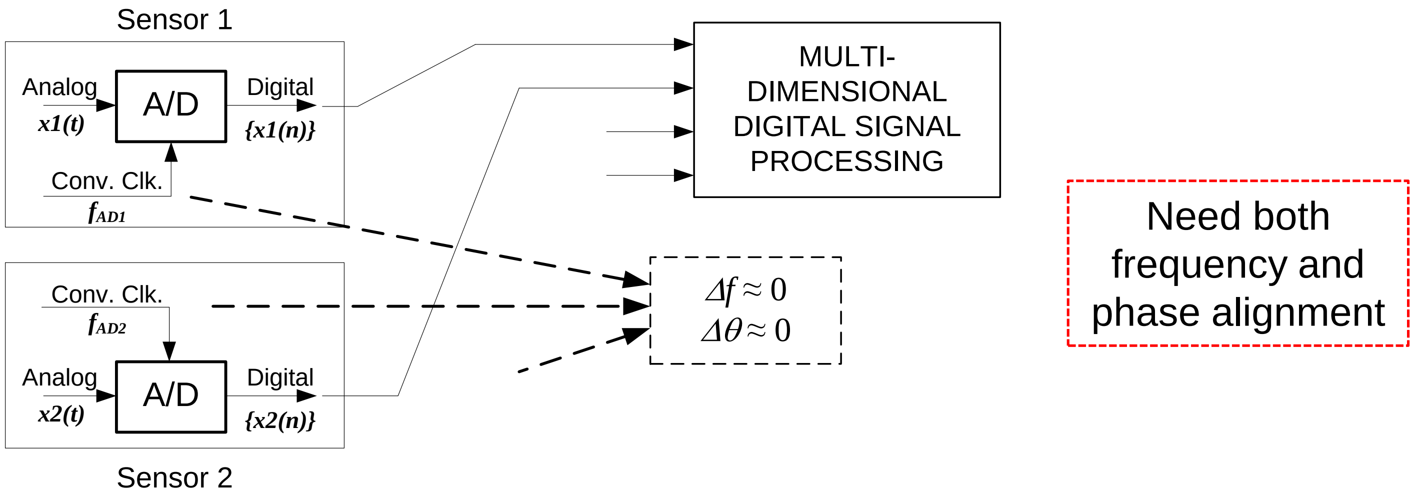
- Device has a “copy” of the interference $b(t)$ *but*….error in synchronization results in an effective time-shift of copy
- Device subtracts the “copy” from its receive signal
- What could go wrong?

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

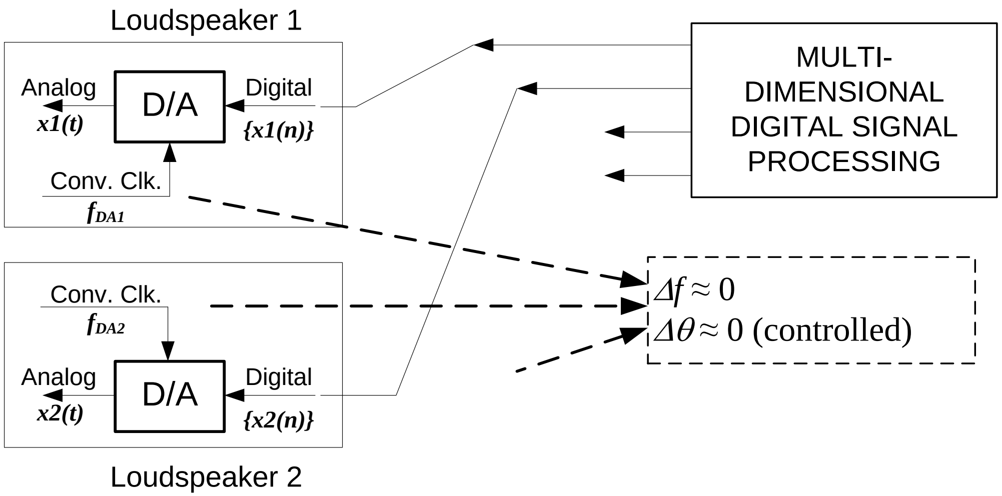
Fundamental Need for Synchronization



- 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)

QULSAR

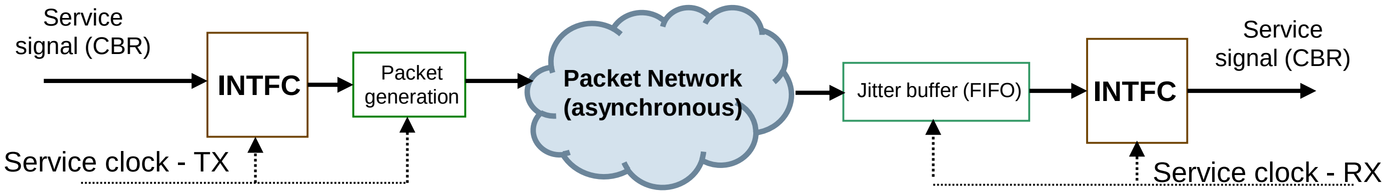
Fundamental Need for Synchronization



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

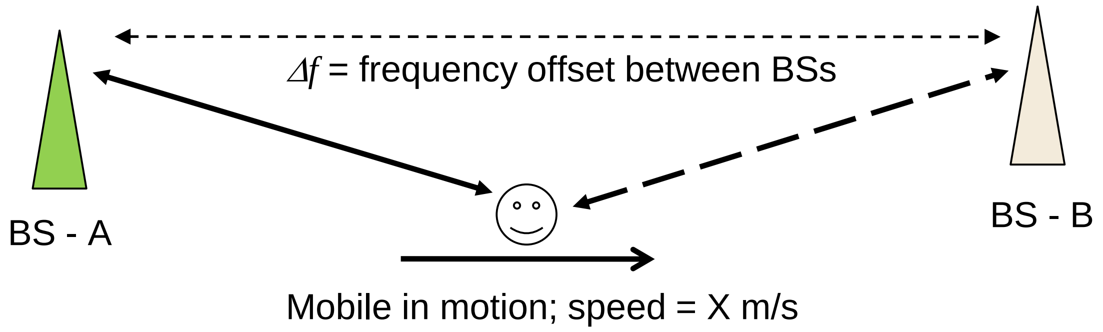
Timing alignment implicit in Circuit Emulation



- 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

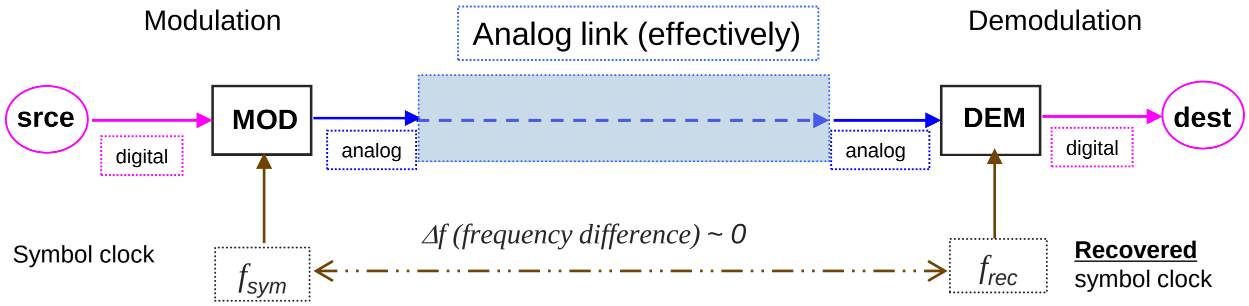
QULSAR

Timing Alignment in Wireless



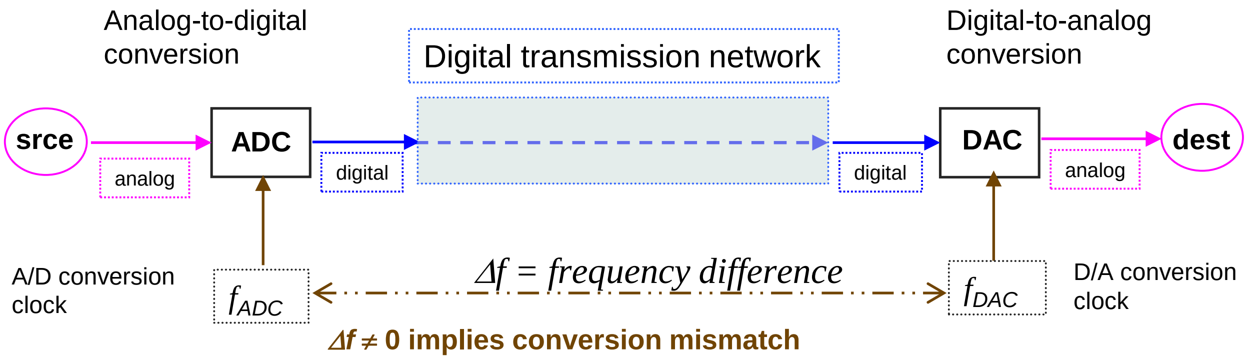
- Mobile in motion (X m/s) introduces a Doppler shift (X/c)
  - When hand-over occurs, the mobile must reacquire carrier frequency
  - Large Δf compromises the reliability of hand-over
- Modern Wireless (LTE) requires stringent timing to support special services/functions
  - BS-A and BS-B can cooperate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

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)

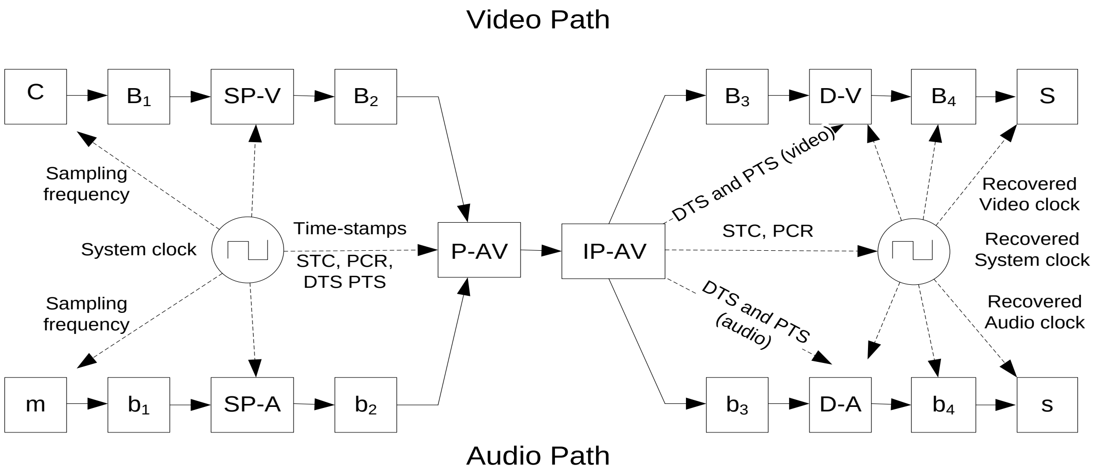
Timing Alignment required in Voice-Band Transmission



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



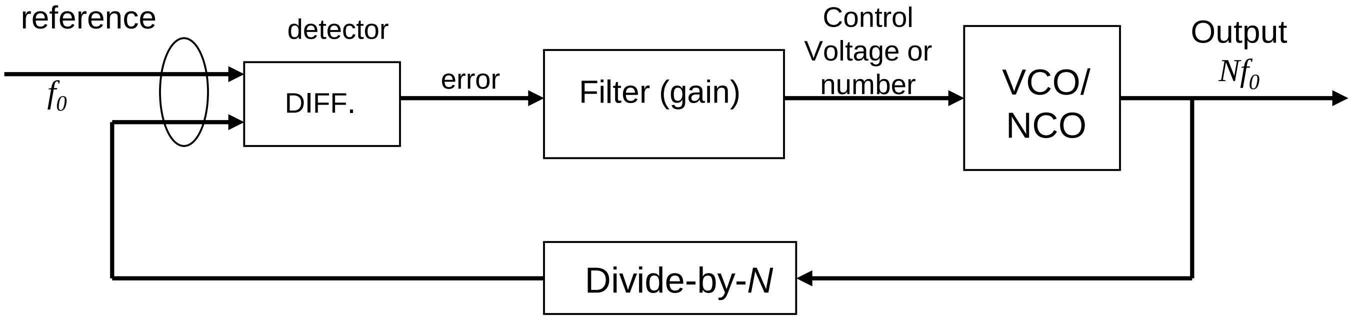
- Frequency offset (wander) between audio and video sampling results in loss of lip-sync
- Frequency offset (wander) between send-side and receive-side system clock results in freeze (video), breaks (audio), and possible loss of lip-sync

QULSAR

Timing in TDM Networks

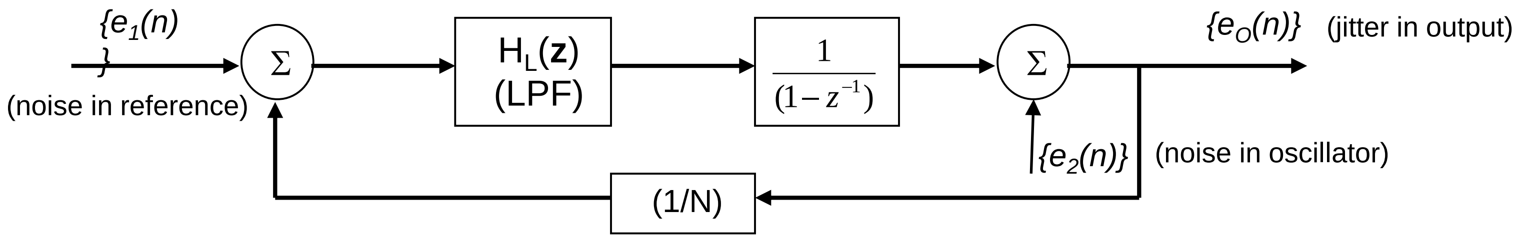
- Synchronization is essential for synchronous multiplexing
  - To avoid information loss
- Synchronous multiplexing assemblies are used as carriers of timing information (DS1/E1, SONET/SDH)
  - The recovered clock is used as a reference for the BITS
  - The transmit signals must meet the “sync” mask 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

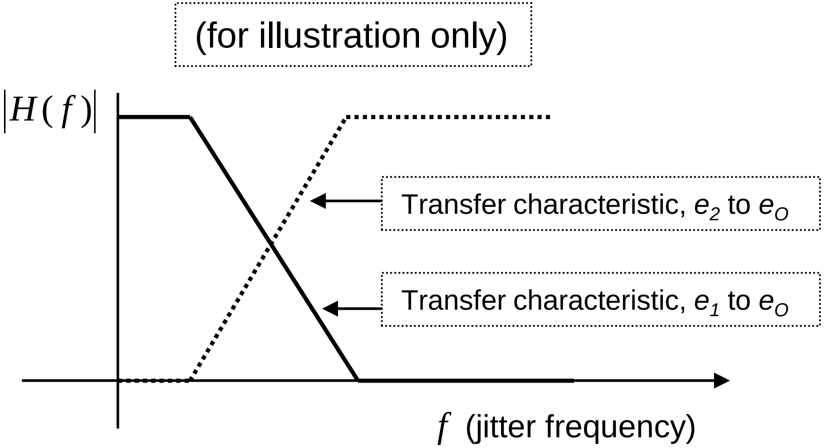
Loops and Holdover



- 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

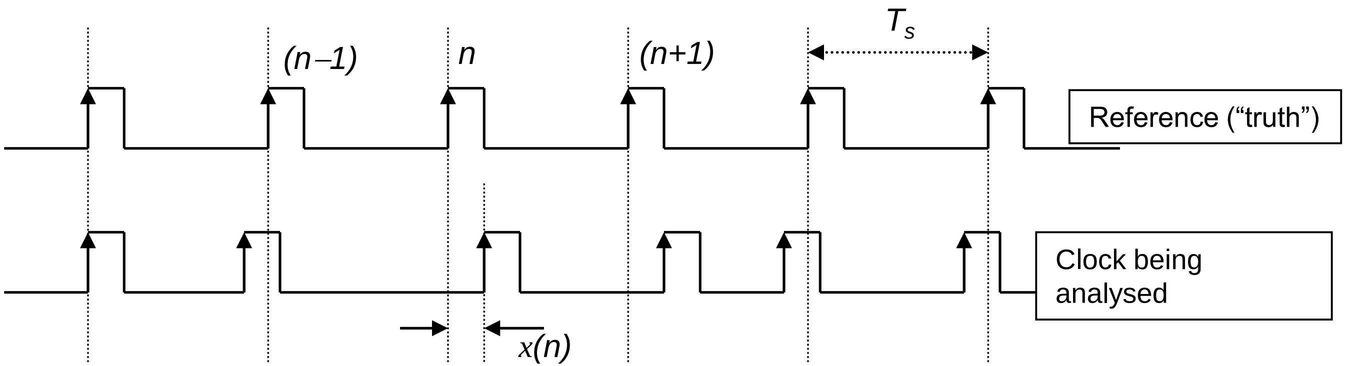
Analytical Model of Locked Loop





- 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 the time-constant can be is governed by TDEV(τ) of oscillator and reference (flicker floor)

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]

QULSAR