Chasing Femtoseconds – How Accelerators Can Benefit from Economies of Scale in Other Industries

time-transfer & synchronization systems:
advantages, physical limitations and practical implementations

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Timing jitter

\[ \Delta t = \frac{T}{2\pi} \cdot \frac{U_N}{U_S} = \frac{1}{2\pi \cdot f} \cdot \sqrt{\frac{P_N}{P_S}} \]

Timing jitter as a function of signal-to-noise ratio
Thermal and quantum noise as function of frequency

Effective noise temperature
\[ \log(T) \]

Thermal noise:
\[ P_N = B \cdot k_b \cdot T \]
\[ N_0 = k_b \cdot T \]
\[ k_b = 1.38 \cdot 10^{-23} \text{ J/K} \]

Quantum (shot) noise:
\[ P_N = B \cdot h \cdot f \]
\[ N_0 = h \cdot f \]
\[ h = 6.626 \cdot 10^{-34} \text{ Js} \]

\[ T = \frac{h \cdot f}{k_b} \]
Microwave and optical timing jitter

Microwave timing jitter

Optical timing jitter

\[ P_N = B \cdot N_0 = \frac{f}{Q} \cdot N_0 \]
\[ \Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{N_0}{f \cdot Q \cdot P_S}} \]

\[ B \equiv \text{bandwidth} \]
\[ N_0 \equiv \text{noise spectral density} \]

\[ Q \equiv \text{resonator (filter) quality factor} \]

\[ N_0 = k_b \cdot T \]
\[ \Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{k_b \cdot T}{f \cdot Q \cdot P_S}} \]

\[ N_0 = h \cdot f \]
\[ \Delta t = \frac{1}{2\pi} \cdot \sqrt{\frac{h}{Q \cdot P_S}} \]
Military: Commercial Off The Shelf (COTS)!

Component grades: the distinction among consumer, industrial & military grades is disappearing!

Design: only high-volume parts may be used!
Specialized and/or custom components extremely expensive and rather unreliable!

Reliability: only high-volume production (million series) guarantees reliability in electronics!
Custom components very unreliable!

Availability: "obsolete" products dropped quickly!
Parts for commercially uninteresting frequencies, wavelengths and applications unavailable!

Recent trends in electronic-component technology
Technology SUCCESSES:

- Analog radio/microwave electronics
- High-speed digital electronics
- (Electronic) digital signal processing (DSP)
- Silica-glass optical fiber (waveguide)
- Semiconductor lasers, modulators and photo-detectors
- Erbium-doped fiber LASER amplifier (EDFA)

Technology FAILURES:

- Millimeter-wave electronics
- Micro-electro-mechanical devices (MEMS)
- Long-wave (thermal) IR optics
- Fiber-optic LASER sources (oscillators): CW, pulsed, mode-locked
- Optical signal processing (holography, nonlinear optics)
- Optical computing

Technology successes and failures
Silica-glass fiber attenuation & telecom windows

- 2dB/km
- IR resonances
- Rayleigh scattering
- Impurities (OH⁻)

Fiber attenuation

- 5dB/km
- 2dB/km
- 1dB/km
- 0.5dB/km
- 0.2dB/km
- 0.1dB/km
- 0.05dB/km
- 0.02dB/km

f [THz] 400 350 300 250 200 150

λ [μm] 0.8 1.0 1.2 1.4 1.6 2.0

I. window 850nm
II. window 1300nm
III. window 1550nm

UV resonances
IR resonances

Silica-glass fiber attenuation & telecom windows
Single-mode optical-fiber properties

**Single-mode glass fiber G.652**

- $n_1$ for silica + germanium oxide
- $n_2$ for core material
- $125\,\mu m$ diameter, $NA=0.1$
- $9\,\mu m$ cladding thickness

**Linear properties:**

- Chromatic dispersion: $D \approx 17\,ps/nm.km$
- PMD: $D_{PMD} \approx 0.02\,ps/\sqrt{\text{km}}$
- Temperature coefficient: $t_c \approx 40\,fs/m.K$
  - Much larger and unpredictable with improper (tight) cabling!
- Microphonics!

**Nonlinear properties:**

- Nonlinear refraction index
  - Kerr effect @ $P>100\,mW$
- Brillouin scattering $P>1\,mW$
  - (narrow-band CW only)
- Raman scattering $P>100\,mW$
- Connector breakdown $P>1\,W$
- Fiber breakdown $P>10\,W$

**Single-mode optical-fiber properties**
Optical timing systems

Optical CW system

Pulsed system

CW modulation system

Optical timing systems
All-optical (coherent) user

High-coherence optical clock (laser)

Single-mode fiber

Optical CW system

ADVANTAGES:
Highest resolution!
Highest accuracy!

DRAWBACKS:
5fs timing ambiguity?
Optical cycle slips?
Interferometric noise?
Brillouin scattering?
Polarization & PMD effects?
User-equipment availability?

Optical CW system

\[ f = 194 \text{THz} \]
\[ \lambda = 1.55 \mu\text{m} \]
\[ T \approx 5.16 \text{fs} \]
Femtosecond pulsed laser

Optical and/or electrical user

Single-mode fiber

\[ f_{\text{carrier}} = 194\text{THz} \]
\[ T_{\text{pulse}} = 100\text{fs}-10\text{ps} \]

Electrical pulse source

ADVANTAGES:
- Reasonable resolution and accuracy!
- User-community understanding!

DRAWBACKS:
- Fiber nonlinearity?
- Fiber chromatic dispersion?
- PMD pulse distortion?
- Fiber thermal compensation?
- Electrical SNR?
- Optical pulse processing?
**CW modulation system**

- LASER → EOM → Single-mode fiber → AMP
  - $f_{\text{carrier}} = 194\text{THz}$
  - $f_{\text{modulation}} = 1-30\text{GHz}$

**Electrical clock source**
- 1-30GHz +15dBm

**Electrical clock user**
- 1-30GHz +15dBm

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**ADVANTAGES:**
- Simple temperature compensation!
- Standard electrical interfaces!
- Standard hi-rel telecom components!

**DRAWBACKS:**
- High photodetector electrical noise: jitter 1-10ps?
- Low timing resolution?
Photodiode: $P_o \approx 1\,\text{mW} < 10\,\text{mW}$

Electrical output: $P_e \approx 1\,\mu\text{W} \approx -30\,\text{dBm}$

Electrical amplifier: $P_e \approx 30\,\text{mW} \approx +15\,\text{dBm}$

Photodiode electrical noise:

\[ U_{Neff} = \sqrt{P_N \cdot R} \]
\[ P_N = B \cdot k_b \cdot T \]
\[ B = \frac{1}{2\pi \cdot R \cdot C} \]

Photodiode electrical noise:

\[ U_{Neff} = \sqrt{\frac{k_b \cdot T}{2\pi \cdot C}} = 25.7\,\mu\text{V}_{\text{eff}} \quad @ \quad C=1\,\text{pF}, \ T=300\,\text{K} \]
LASER → EOM → Single-mode fiber

\[ f_{\text{carrier}} = 194\text{THz} \]

\[ f_{\text{modulation}} = 1-30\text{GHz} \]

Electrical clock source
1-30GHz +15dBm

Flywheel: very narrow band-pass filter:
high-Q cavity or VCXO PLL

FLYWHEEL ADVANTAGES:

- Bandwidth reduction factor \(10^4\) to \(10^6\) (Q)!
- Jitter reduction factor 100 to 1000!
- Remaining jitter 10fs to 100fs!

Electrical clock user
1-30GHz +15dBm

CW modulation system with flywheel
Delay-variation compensation techniques

COMPENSATION TECHNIQUES:
- DFB LASER electric tuning +/-0.2nm
- DFB LASER temperature tuning +/-2nm
- Compensation fiber temperature tuning

Transmission fiber with chromatic dispersion $D \approx 17 \text{ps/nm.km}$

Flywheel

Electrical clock source 1-30GHz +15dBm
LASER

Single-mode fiber pair $l \approx 300m$

EOM

AMP

TRANSMITTER

Electrical clock source 1-30GHz +15dBm

RECEIVER

AMP

Electrical clock user 1-30GHz +15dBm

CW modulation system with temperature compensation
Measured 3GHz CW-modulation-system phase noise & jitter
Measured 3GHz CW-modulation-system long-term drift
CW modulation system with PMD compensation

- **LASER**
- **Single-mode fiber** $l \approx 3\text{km}$
- **EOM**
- **Faraday mirror**
- **TRANSMITTER**
- **Electrical clock source** 1-30GHz +15dBm
- **RECEIVER**
- **Electrical clock user** 1-30GHz +15dBm
Multi-point chain clock distribution

- Master TX
- End-point RX
- Tap RX
- Electrical clock source 1-30GHz +15dBm
- Electrical clock user #M 1-30GHz +15dBm
- Electrical clock user #N 1-30GHz +15dBm

uncorrected error $\pm \Delta \Phi$

$d_1 \neq d_2$

Vector sum

$-\Delta \Phi = +\Delta \Phi - \Delta \Phi - \Delta \Phi$

$+\Delta \Phi$

$-\Delta \Phi$

$+\Delta \Phi$

$-\Delta \Phi$
Electro-optical master oscillator

LASER | EOM | Photodiode

Fiber delay line 1-30km | Flywheel

PA | AGC | LNA

Electrical clock

output 1-30GHz +15dBm

Shielded & temperature-controlled environment

Fiber delay + flywheel >>> equivalent $Q \approx 10^5 - 10^7$

Electro-optical master oscillator
Sincrotrone Trieste, Elettra laboratory: initial system requirements initial experiments

University of Ljubljana, Faculty of Electrical Engineering, Laboratory for Radiation and Optics: initial research

Center of Excellence for Biosensors, Instrumentation and Process Control (COBIK): current research & development

Instrumentation Technologies: initial sponsoring & management, co-development, industrialization & production