Current Experience with Precision Timing Distribution

Jeroen Hegeman

With many thanks to Jan Troska, Sophie Baron, and everybody else who recognizes their slides

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Currently there only a few *dedicated* and/or *precise* timing distribution systems in place in and around ATLAS and CMS and friends.

Of the above, not all have been understood and characterized well enough yet to publish figures or numbers.

I have taken some liberties with the original title, and tried to bring something informative nevertheless.
Overview

- A bit of background
- Dedicated clock distribution systems
  - TTC (from LHC RF to experiments)
  - TOTEM/CTPPS
  - ATLAS Forward Detectors
- Looking towards LHC Phase-2
Background
Where exactly does this precision clock matter?

Different ‘qualities’ matter in different places:

• Single sensors/channels: require reasonably low jitter and stable phase for optimal energy resolution
• Detectors: require low jitter, and coherent phase across channels for pileup suppression
• High-speed serial links: require stable clock frequency (esp. when multiplying clocks for Tx)

In the end it is the detector resolution and physics performance that matters. The clock system contribution just has to be (quadratically) sub-leading to the detector performance itself.

More detail, esp. on the detector side, in L. Gray’s presentation.
There are two things to be distributed:
(Ignoring the synchronization part of the timing, for the moment.)

- Clock frequency
- Clock (i.e., sampling) phase

Clock frequency precision/quality can be characterized in terms of *jitter*.

Phase alignment, absolute as well as between channels, in addition to low jitter also requires precise and careful distribution.

→ What is needed is both a precise clock and a precise distribution system.
• **Deterministic jitter** is defined as *bounded*, with a *well-defined minimum and maximum*.

• **Random jitter** is assumed to be (and it typically is) Gaussian-distributed.
Clock Quality - Jitter

- If there are many sources of deterministic jitter, the result can become random (Gaussian) jitter.
- The true shape of the overall jitter distribution will vary, but in many cases a Gaussian can be a good approximation. (Whether such an approximation is conservative or not depends on the case at hand.)
Clock Quality - Jitter

Time Interval Error (TIE): When do the edges arrive, compared to when they should arrive?
→ A fairly intuitive measure, supported by many oscilloscopes nowadays.

- Generate an ‘ideal clock’ with the same frequency as the input clock
- Calculate the deviations of the input clock edges w.r.t. their ideal positions
- The average $\bar{\Delta}_i$ is the Time Interval Error
Phase noise: Shows how much power is present in the signal at frequencies different from the desired frequency.

Phase noise integrated over an appropriate frequency window gives the RMS jitter.
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Phase Noise and RMS jitter


True spec must be defined in terms of frequency

\[ \text{rms} = 5-6 \text{ ps} \]
Timing Distribution – TTC
The Good Old TTC

- Sinusoidal optical signal at bunch clock frequency distributed from LHC RF at P4 to experiments. (CMS direct, others after regeneration at the CCC.)
- TTC machine interface electronics (RFRXD, RF2TTX):
  - Performs optical-to-electrical conversion
  - Allows selection and delay/phase adjustment
  - Performs fan-out (as AC-coupled ECL)
- TTCvi/TTCci, TTCex, etc. handle distribution throughout experiment as TTC stream (two-channel, biphase-Mark encoded)
- TTCrx ASIC handles decoding and clock recovery
- QPLL ASIC handles clock cleaning and serves as auto-locking PLL

More detail on TTC architecture in presentation by E. Brandao De Souza Mendes.
The Good Old TTC

RF Phase Jitter=2ps rms

Agilent SSA type E5052B lent by the BE/RF group and then by Agilent for a 2-weeks evaluation
The Good Old TTC

RF → Tx → CMS → Rx → RF

RF Phase Jitter = 2 ps rms
Rx Phase Jitter = 1.9 ps rms

S. Baron, TTC system and jitter in LHC experiments, https://indico.cern.ch/event/202454/
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The Good Old TTC

RF  Tx  Point 4  CMS  Rx  RF  2TTC  TTCvi/ ex  TTCrq

RF Phase Jitter=2ps rms
Rx Phase Jitter=1.9ps rms
RF2TTC Phase Jitter=10ps rms

S. Baron, TTC system and jitter in LHC experiments, https://indico.cern.ch/event/202454/
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ATLAS (and CMS Run-1)

CMS Run-2

- Current system jitter performance not degraded by TCDS system
  - Dominated by the receiver TTCrx/QPLL
  - where we care about low power, for example

S. Baron, TTC system and jitter in LHC experiments, https://indico.cern.ch/event/202454/

Review of capabilities of existing Clock Distribution System, https://indico.cern.ch/event/575572/contributions/2328970/
The TTC system as a whole is still performing admirably.

The top of the distribution tree is already cleaner than most of our sub-detectors can benefit from.

Remaining bottlenecks could probably be easily fixed.
Timing Distribution – TOTEM/PPS
• Hunting for Central Exclusive Production: a central event in CMS, together with coincidence of scattered protons in the very forward region
• Uses artificial single-crystal diamonds as timing detectors
  • to reject pileup, and
  • to identify the CEP vertex in CMS
Solves the problem of serving geographically distinct locations with phase-aligned clocks of different frequencies

*Universal picosecond timing system for the Facility for Antiproton and Ion Research*

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Universal picosecond timing system for the Facility for Antiproton and Ion Research
• Contrary to the FAIR original, the delay measurement is not used for correction, only for monitoring.

• Preliminary results indicate this approach provides sufficient stability.

F. Cafagna, *The TOTEM precision clock distribution system*, NSS/MIC 2017
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CTPPS/TOTEM timing

- RMS jitter at source $\sim 1\text{ps}$
- RMS jitter at receivers $\sim 2\text{ps}$
Diamond sensors (cvCVD) provide timing resolution of $\approx 55$ ps per detector arm.

Timing resolution completely dominated by sensors and front-end.

Timing Distribution – AFD
ATLAS Forward Detectors

- Physics compatriot of TOTEM/CTPPS
- Aiming for a timing resolution of $< 10$ ps
- Timing detectors based on Cerenkov radiator with a microchannel plate PMT:
  - QUARTIC (quartz) radiators, timing resolution $O(35 \text{ ps})$ per measurement
  - GASTOF (gas) radiators, timing resolution $O(20 \text{ ps})$
ATLAS Forward Detectors

- Timing system based on a design developed at SLAC, by Joe Frisch and Jeff Gronberg (LLNL)
- PLL stabilizing the 400 MHz LHC RF clock, then converting to 40 MHz
- Preliminary tests show:
  - a jitter of $\approx 150$ fs over a 100 m cable(!)
  - Temperature stability improved from $\approx 80$ ps/degree C to $\approx 4$ ps/degree C

Figure 5.3: (a) Schematic of the Reference timing system as described in text. (b) Results of temperature stabilization test showing a mild drift with temperature (about 4 ps for 10 degrees C).

AFP technical proposal,  
https://atlas-project-lumi-fphys.web.cern.ch/atlas-project-lumi-fphys/AFP_TP.pdf

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Both the TOTEM/CTPPS and the AFD timing systems are currently being commissioned, together with their detectors. Looking forward to seeing a comparison of their performance vs. expectations. Especially for long(er)-term stability.
Looking towards LHC Phase-2
Phase-2: lpGBT

lpGBT promises:

- 4 Programmable clocks:
  - Frequency and phase programmable
  - Frequencies: 40/80/160/320/640/1280 MHz
  - Clock jitter: < 5 ps
  - Phase resolution: 50 ps

- 28 eLink clocks:
  - Frequency programmable, phase fixed
  - Clock jitter: < 5 ps

The above is a very good start, but ‘the other half’ of the job remains:

- Careful system design, validation, and characterization
- Implementation of system-wide phase stability monitoring (and determining how to use the resulting data)

In the HEP community there is plenty of expertise around on precision timing, RF systems, high-speed data links, etc.

Precision timing, a somewhat niche subject until now, will be of utmost importance for the hi-lumi LHC experiments.

As is the case in many aspects, the timing requirements for the Phase-2 LHC detectors are challenging partly due to their lack of significant margins.

For future experiments, it is just as important to characterize the timing distribution performance as the sensors themselves.

For ultimate trust in system stability, timing distribution monitoring should be built in, just like sensor calibration.

→ Expect that everybody will benefit from participating in the common project on precision timing