Study on White Rabbit based sub-nanosecond precision timing distribution system for fusion related experiments

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Objectives

- More than 1 GHz high-speed sampling measurement is becoming popular in fusion plasma diagnostics, *e.g.* NI PXIe-5186 digital oscilloscopes running at max. 12.5 GS/s are already used in LHD.

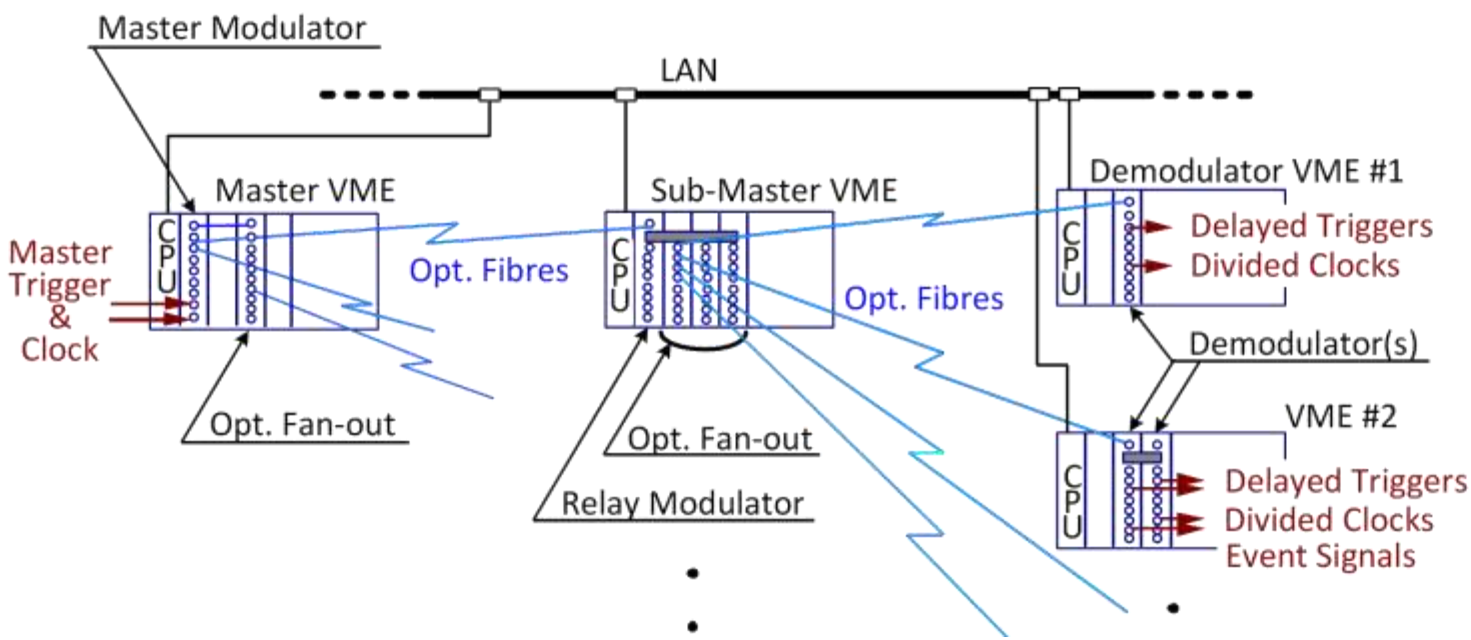
- High-accuracy time synchronization will be necessary.
  → Each sampling clock must be in phase with ≪ 1 nanosecond precision for multiple simultaneous measurements.

- Even in demo reactor designs, fast & highly synchronized diagnostics, *e.g.* reflectometry, may have to provide spatial correlations for plasma monitor.

- Large accelerator physics already developed < 1 ns synchronization method named White Rabbit at CERN. WR may possibly be applied for fusion related experiments if some missing functions added.
  → This study attempts the technical survey and conceptual design.

LHD Digital Timing System

- **LHD DTS has been using since the first plasma in LHD (1998).**
  - **Tree structured. Modulated trigger messages delivered on 10 MHz sync. clock.**



- **Weakness:**
  I. **One-way trigger/clock distribution by non-standard fiber link and protocol**
  II. **Lacks dynamic delay measurement & compensation mechanism**
  (Preset delay register can be set by 5 ns step up to 385 ns for static compensation.)
  III. **Lower time resolution (base clock = 10 MHz) $\ll$ 12.5 GS/s diagnostics**
  (Even 1-digit slower than popular Gigabit Ethernet using 125 MHz or 1.25 Gbps)

Precision Time Protocol (PTP) ver. 2

- **PTP v2 is a popular time sync. IEEE1588-2008 standard via Ethernet & IP**
  - **Deliver a reference clock over segments by Sync. Ethernet (SyncE).**
  - **Delay in delivering the timing information is measured between M/S to be compensated for sub-microsecond ($\leq$ 1μs) accuracy.**

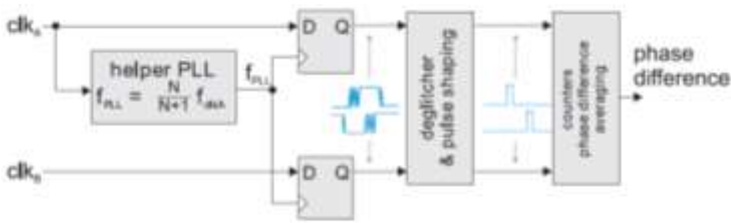
- **Industries prefer IEEE802.1AS Time-Sensitive Networking (TSN).**
  - **PTPv2 and TSN are similar, but TSN is more deterministic than PTP.**
  - **Machine automation, IoT, robotics, mobile comm., …**

- **Most of Ethernet switch products are in conformity to IEEE1588-2008 PTP v2 standard.**
  - **When a GNSS (GPS) receiver connected to PTPv2 switch, it can be the PTPv2 grand-master clock (GMC) providing the Int'l Atomic Time (TAI).**
  - **ITER Time Communication Network (TCN) has also adopted PTP v2, *i.e.* IEEE1588-2008. → Another talk on Tue. (RFX)**

White Rabbit

- **WR (IEEE1588-2019) is an extension of PTP v2 for sub-nanosecond ($\leq$ 1ns) accuracy, which consists of :**
  1. Synchronous Ethernet (SyncE) to share a common clock
  2. Finer phase delay detection by Digital Dual Mixer Time Difference (D-DMTD)
  3. Link asymmetry can be precisely evaluated. (not in PTPv2)

- **The network switch & node interface must conform to WR.**
  - Otherwise, time accuracy would be degraded down to PTPv2.



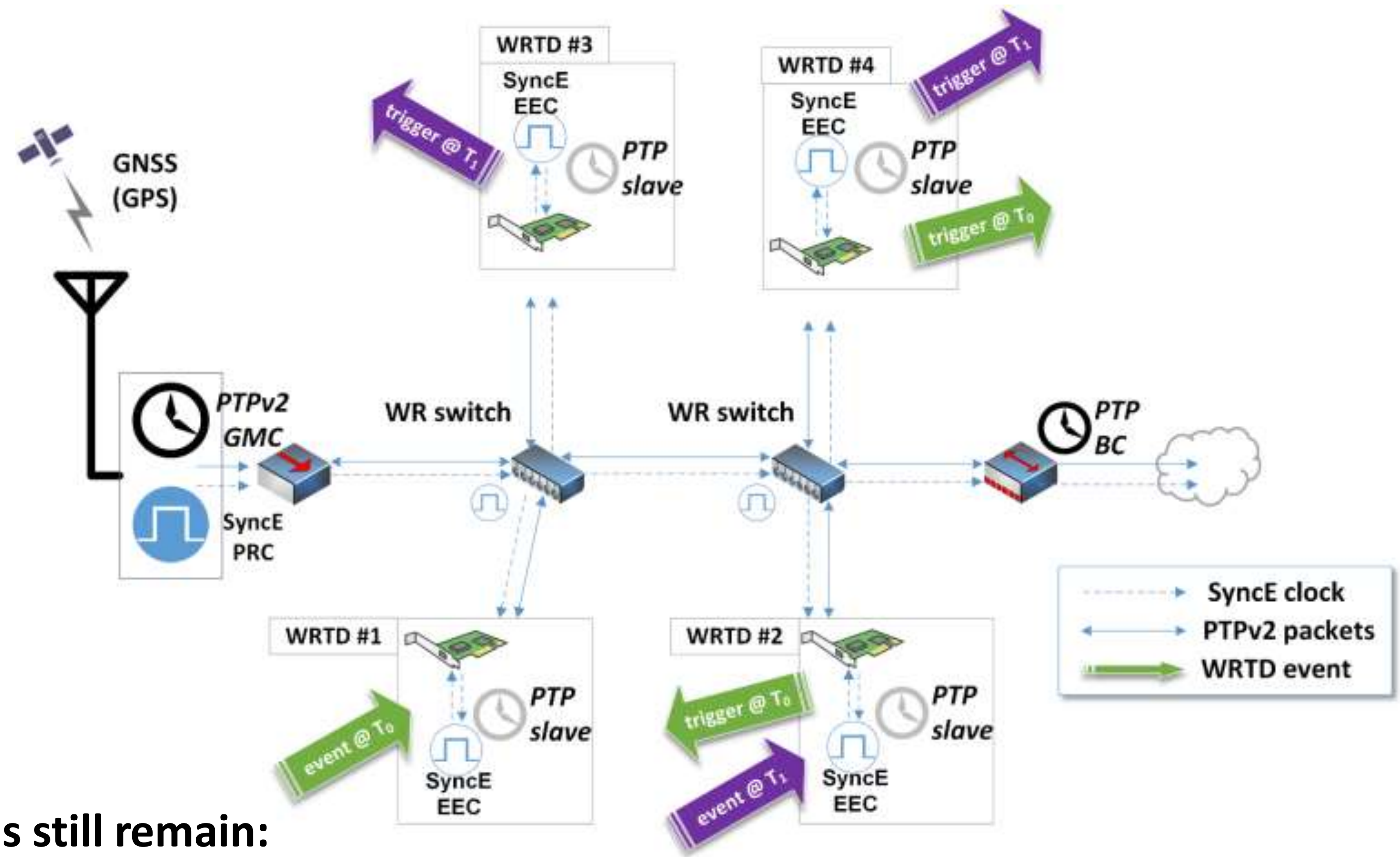
Dual-Mixer Time Difference circuit
T. Wlostowski, M.Sci. thesis (2011)

- **Advantage: WR is an open hardware project.**
  - Design specifications and related source codes are publicly available via open hardware repository → Easy to export to other applications

- **However, WR PTP Core has no mechanism to generate various clock frequencies, nor to distribute triggers, in original functions.**

White Rabbit Trigger Distribution (WRTD)

- **WRTD can distribute "trigger events" bi-directionally over WR network.**

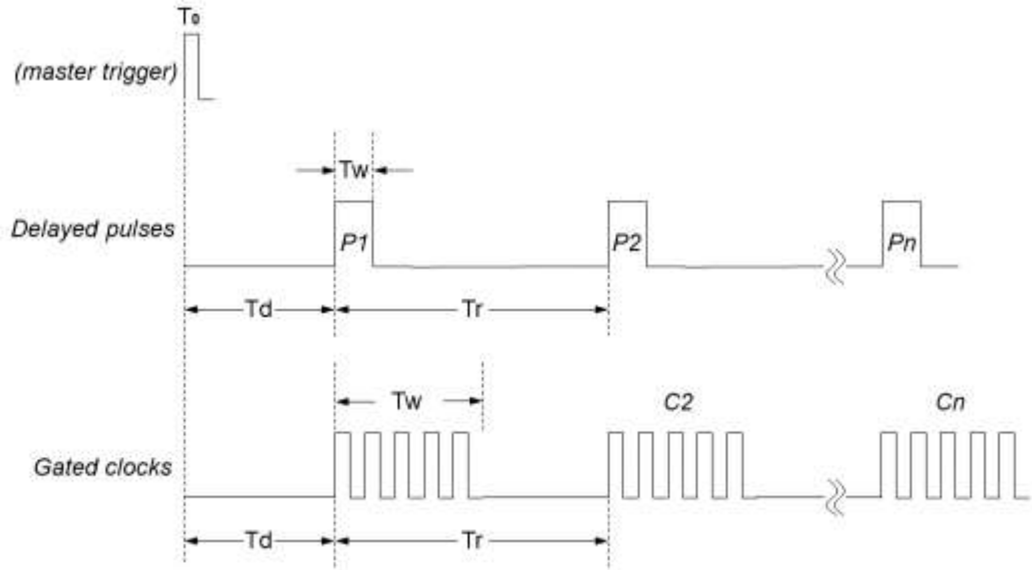


- **Problems still remain:**
  - **No idea for (structured) trigger/event grouping in WRTD**
  - **No divided clocks. WRTD can only deliver triggers.**

Expected trigger & clock for fusion exp.

- **LHD DTS can output pre-programmable delayed triggers and divided clocks independently at each demodulator (8 ch).**

- **Operation parameters:**
  - Delay time (Td)
  - Pulse (gate) length (Tw)
  - Repetition period (Tr)
  - Repetition count (n)
  - (clock) Frequency := X × 10^{Y}



  - 8 Trigger Groups are operable independently in parallel.
    Each group is coupled with the master trigger channel from No. 1 to 8.

- **Discussions:**
  1. Can we use "a series of (burst) triggers" instead of "divided clocks" → No.
  2. Fusion related plants may need "trigger groups" for limited delivery

Conclusion

- Technical surveys and functional verifications have been made on White Rabbit (WR) to study the feasibility applying to fusion related experiments.

- If some deficient functionalities, such as divided clocks and group operations of multiple nodes, would be additionally implemented, WR is found to be applicable for diagnostic and control systems of fusion related experiments.

- For the next step of this study,
  we plan to implement some extensions for trigger grouping and divided clocks on WR(TD), together with some performance tests.

- A test plant or practical applications should be found.
  Any interest for collaborative development?