White Rabbit Based Beam-Synchronous Timing Systems for SHINE

Yingbing Yan

Shanghai Advanced Research Institute

Chinese Academy of Sciences

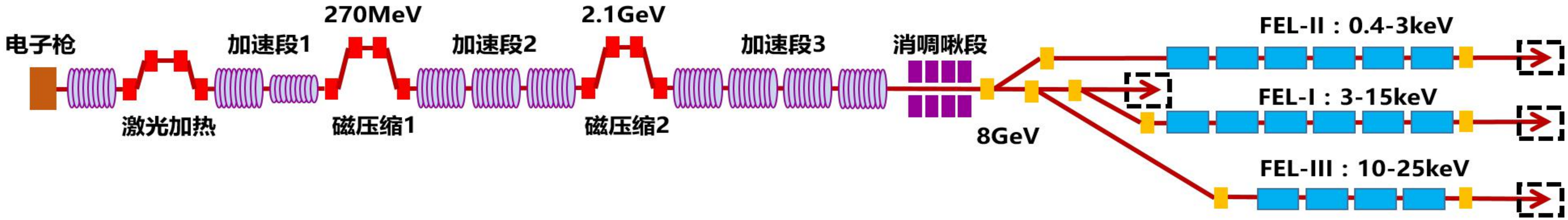
Outline

- SHINE Project Overview
- SHINE Timing System
- Standard Clock Transmission
- Random Trigger Distribution
- RF Signals Distribution
- Non-Standard Clock Transmission
- Prototypes Development
- Performance Test
- Summary
- Acknowledgment

SHINE

SHINE Project

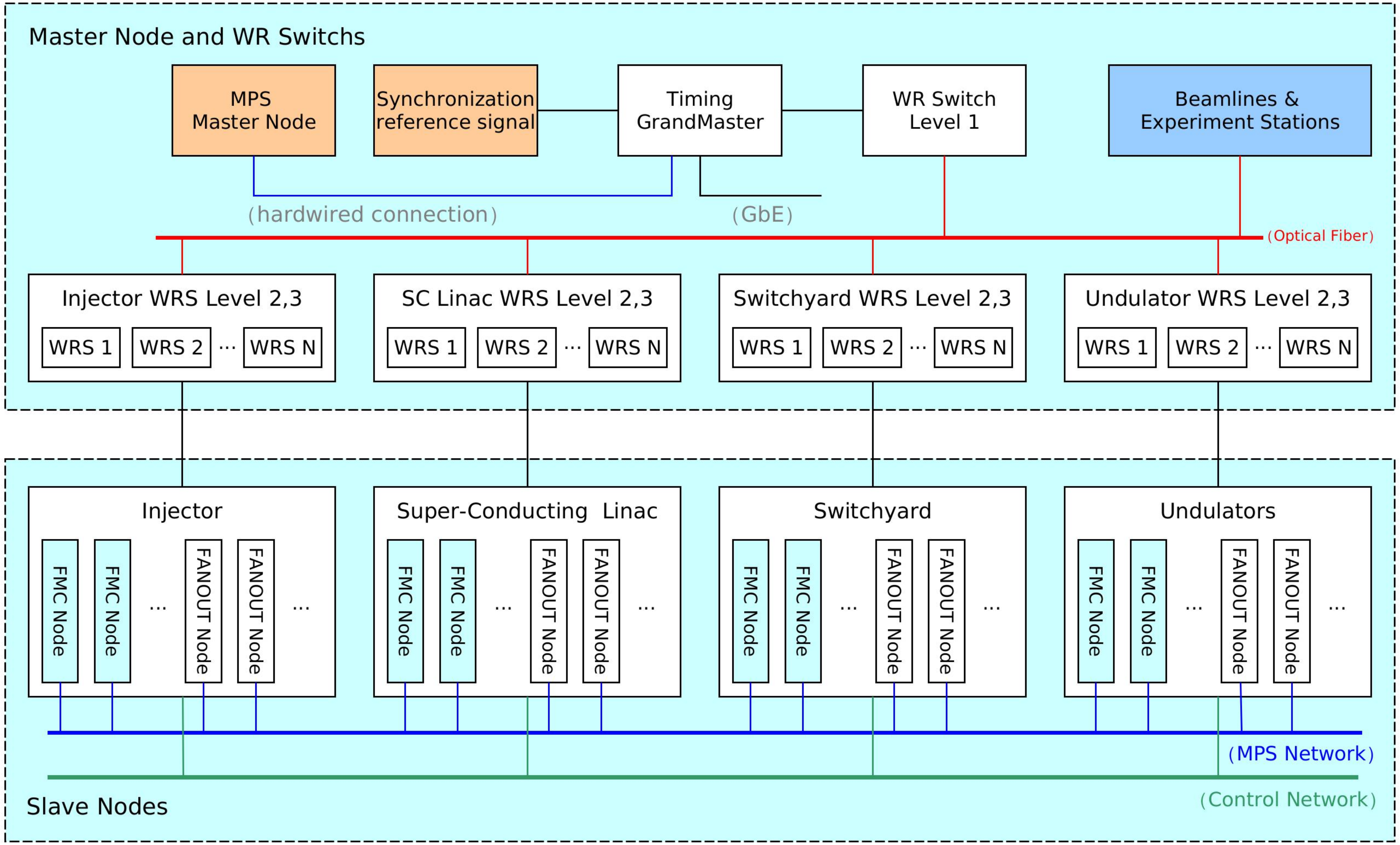
- Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE)
- First hard X-ray FEL facility in China



Beam energy : 8 GeV	**Photon energy : 0.4 - 25 keV**
Bunch charge : 100 pC	**Max repetition rate : 1.0030864 MHz**
Total length : 3.1 km	**Underground : ~ 29m**


SSRF
SXFEL
SHINE
Injector
SC Linac
Undulators
Beamlines
Near Exp. Hall
Beamlines
Far Exp. Hall

SHINE Timing System



1 Master Node, ~ 800 Slave Nodes, 3 Layers ~ 80 WRS

SHINE

SHINE Timing System

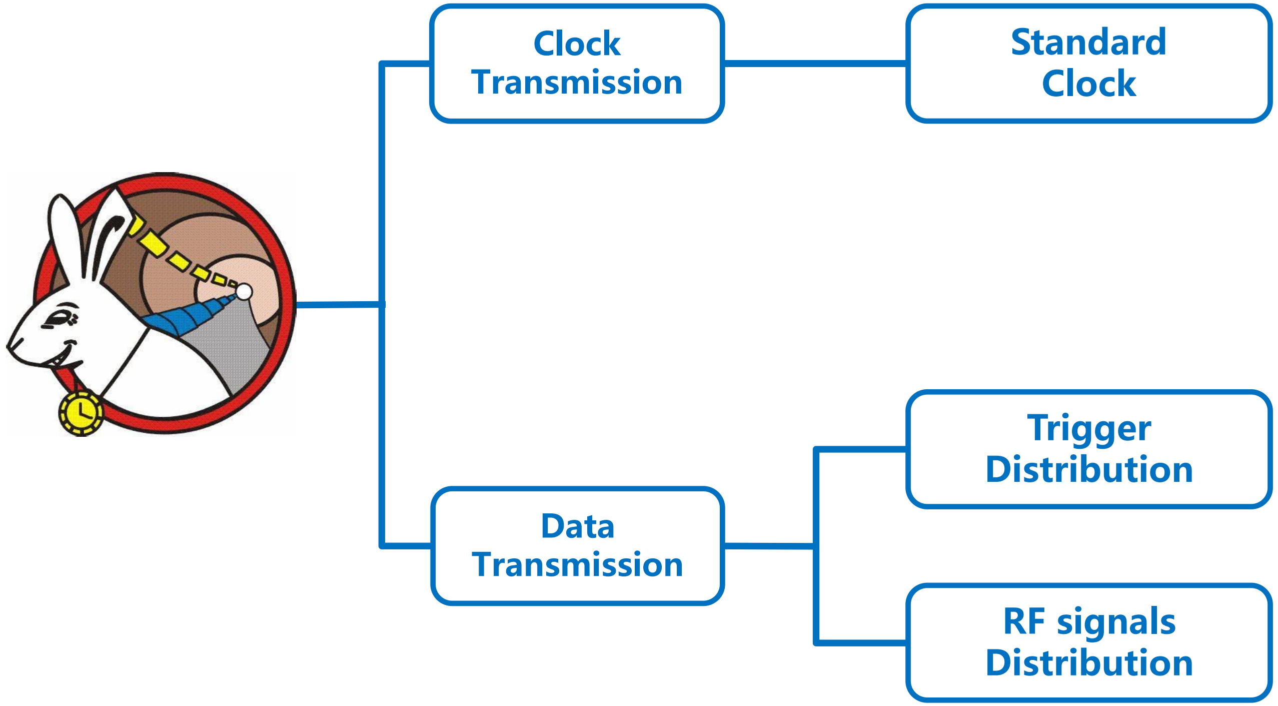
1) Beam-synchronous trigger signal distribution
   - Precise distribution and synchronization of the 1.003086MHz (1.3GHz/1296) timing signals over a long distance of about 3.1 km

2) Random-event trigger signal distribution
   - Extension function of the timing system
   - Various event signals, such as beam loss, machine snapshot, etc.

3) Data exchange between nodes
   - May be used for local beam parameter feedback

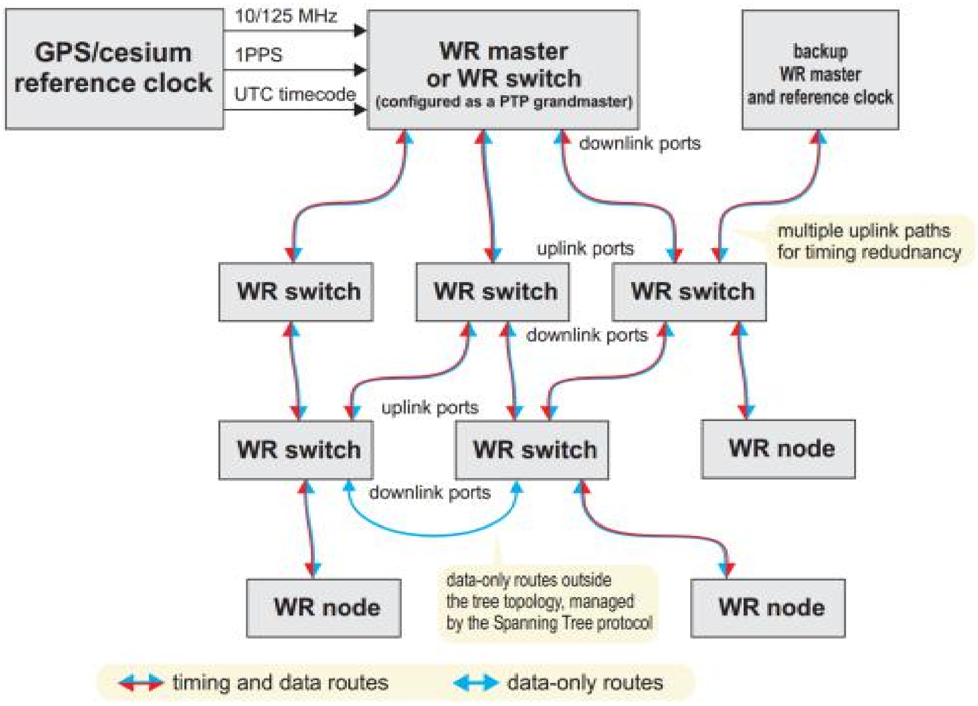
high priority

White Rabbit Technology



Standard Clock Transmission

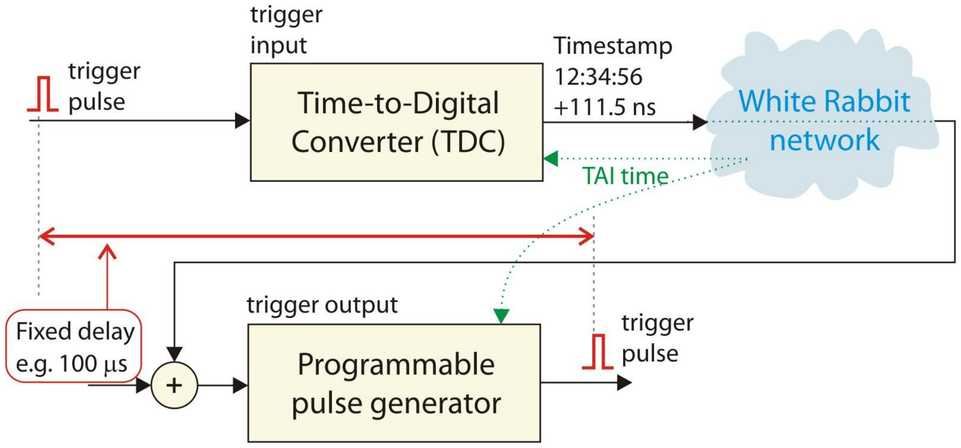
- Standard White Rabbit network operating clock 125/62.5MHz
- If the SHINE repetition frequency is 1.0MHz, 1.3GHz can be divided to 10MHz as the reference signal
- The salve node output the trigger signal at the specified time (1us, 2us, 3us, …)



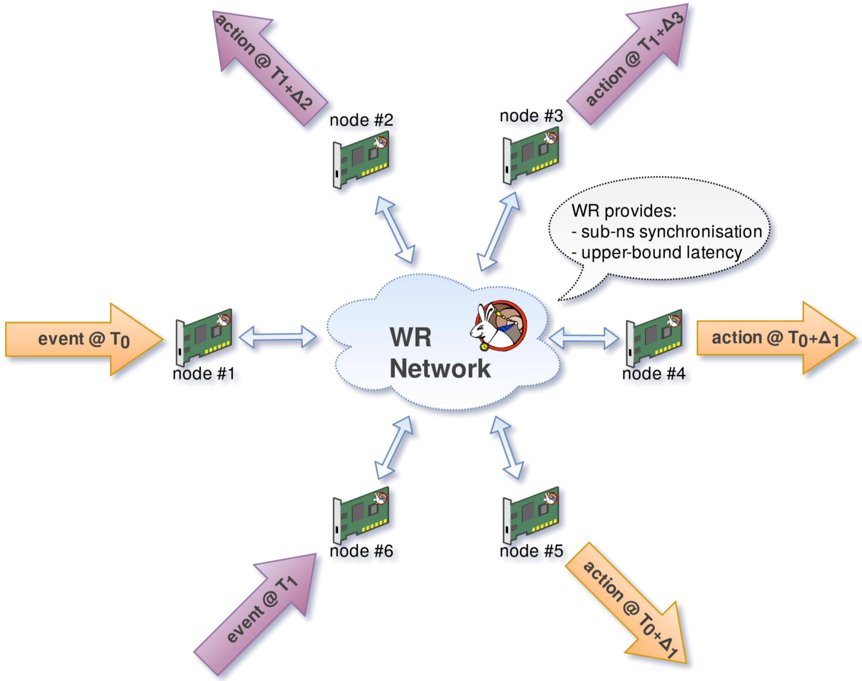
SHINE

Random Trigger Distribution

- White Rabbit Trigger Distribution (WRTD) is a generic framework for distributing triggers (events) between nodes over a White Rabbit network
- For SHINE, the network bandwidth is limited, the jitter will increase
- 10 Gigabit White Rabbit switch, no commercial product



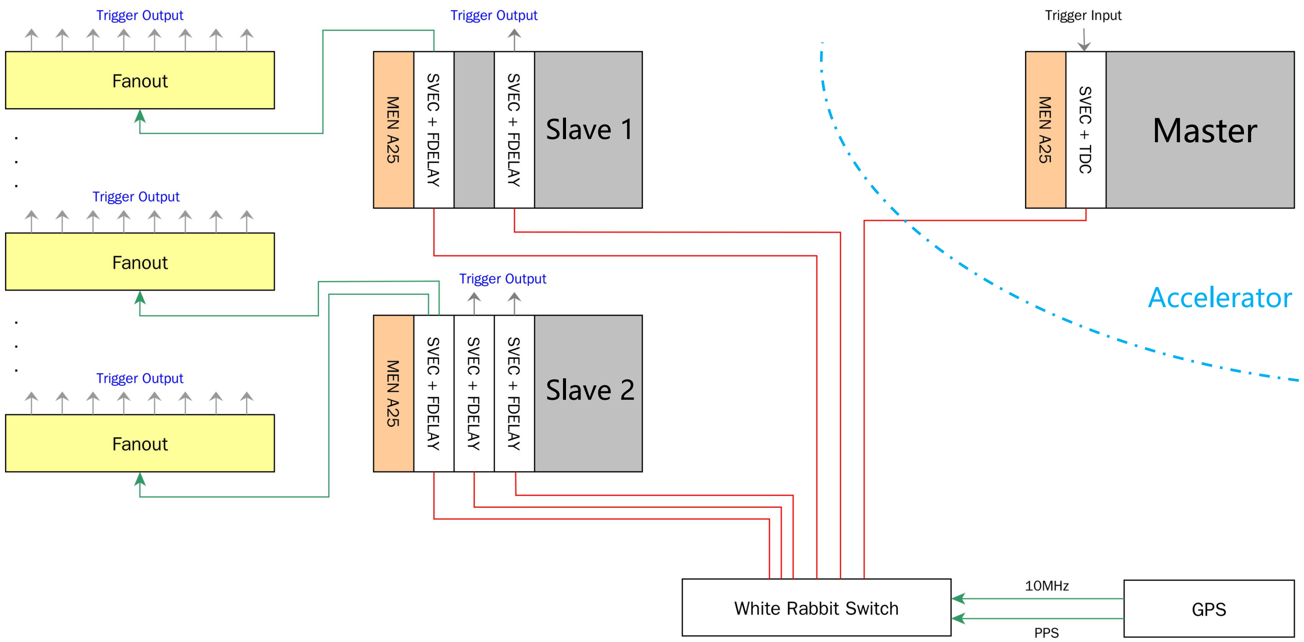
White Rabbit Trigger Distribution, ICALEPCS 2017

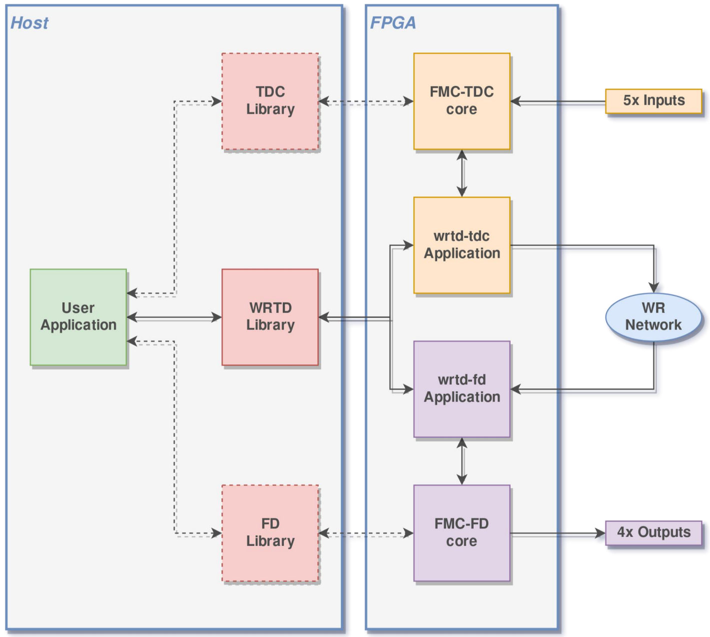


https://ohwr.org/project/wrtd/wikis

Random Trigger Distribution

- SXFEL-UF (Shanghai soft X-ray Free-Electron Laser User Facility)
- SVEC - VME with FMC TDC 1ns 5cha and FMC DEL 1ns 4cha





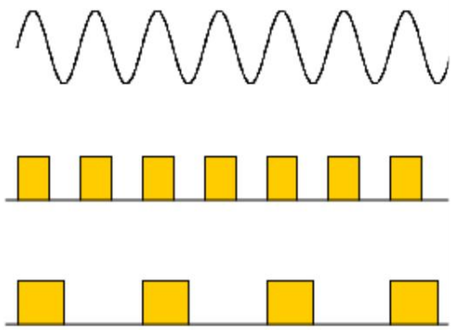
https://wrtd.readthedocs.io/en/latest/ref_svec_tdc_fd.html

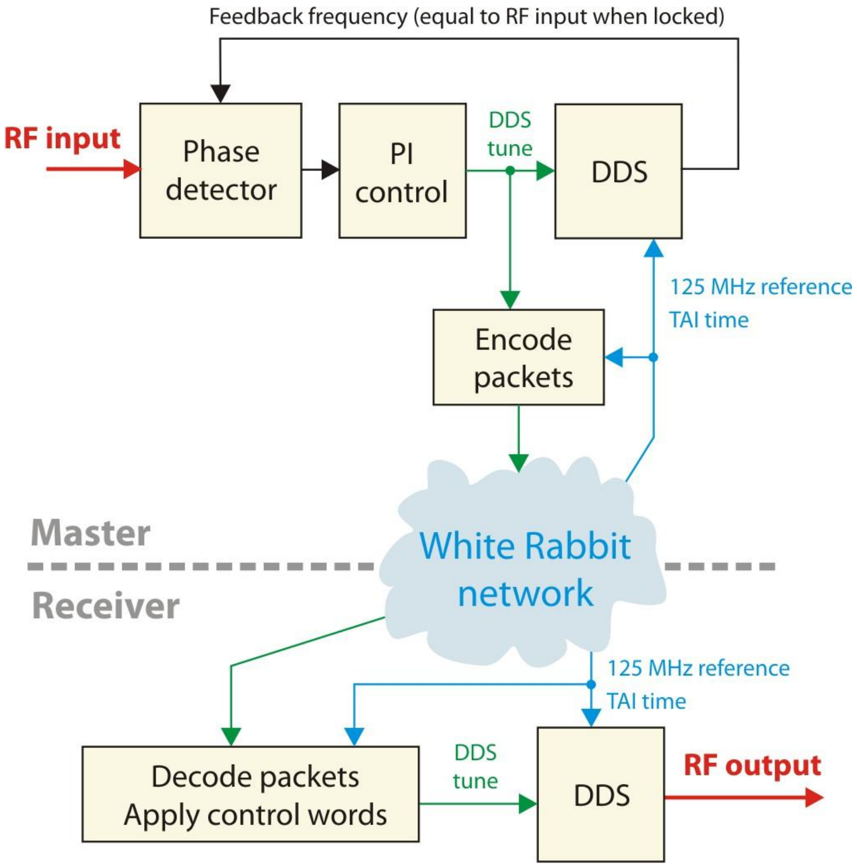
SHINE

RF Signals Distribution

- All nodes have the same reference frequency and time
- Master phase locks its DDS to the RF input
- Broadcast the DDS control words, including a TAI timestamp
- All receivers update their DDSes with the received control word at the same moment (+some fixed delay)

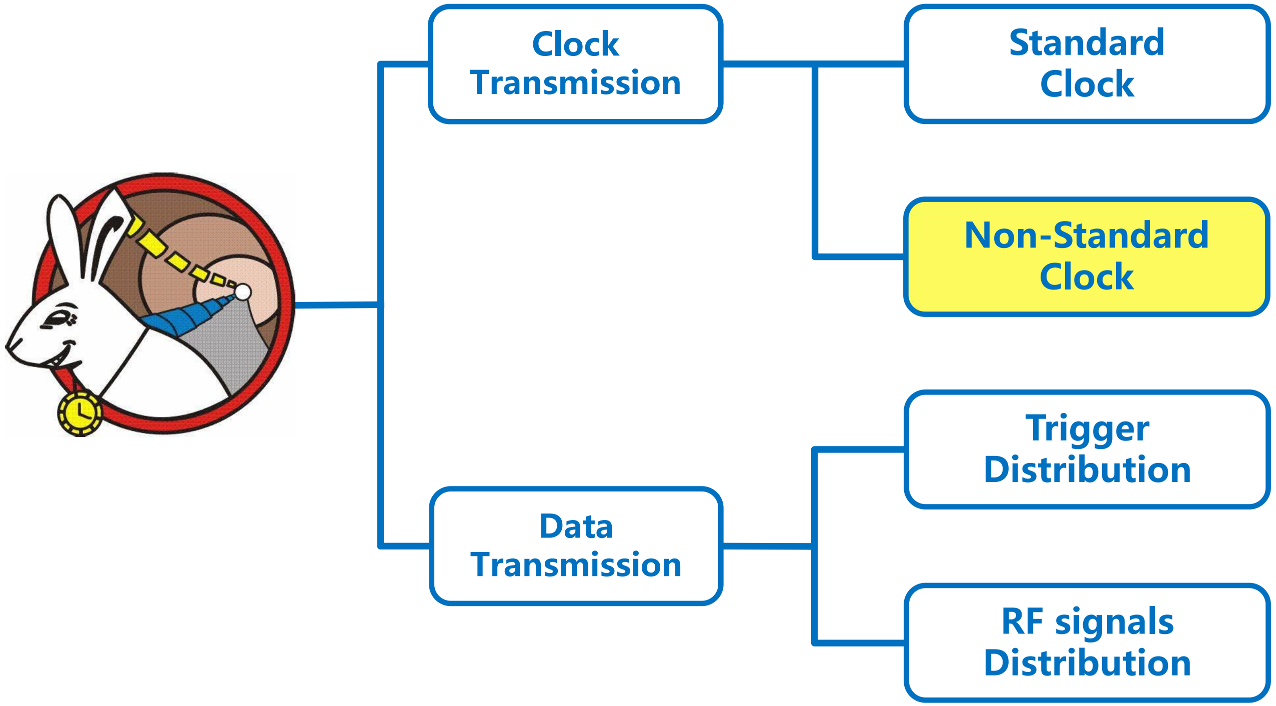
Can the sine be converted to editable and low jitter pulse signal ?





Distribution of RF signals using WR, ICALEPCS 2017

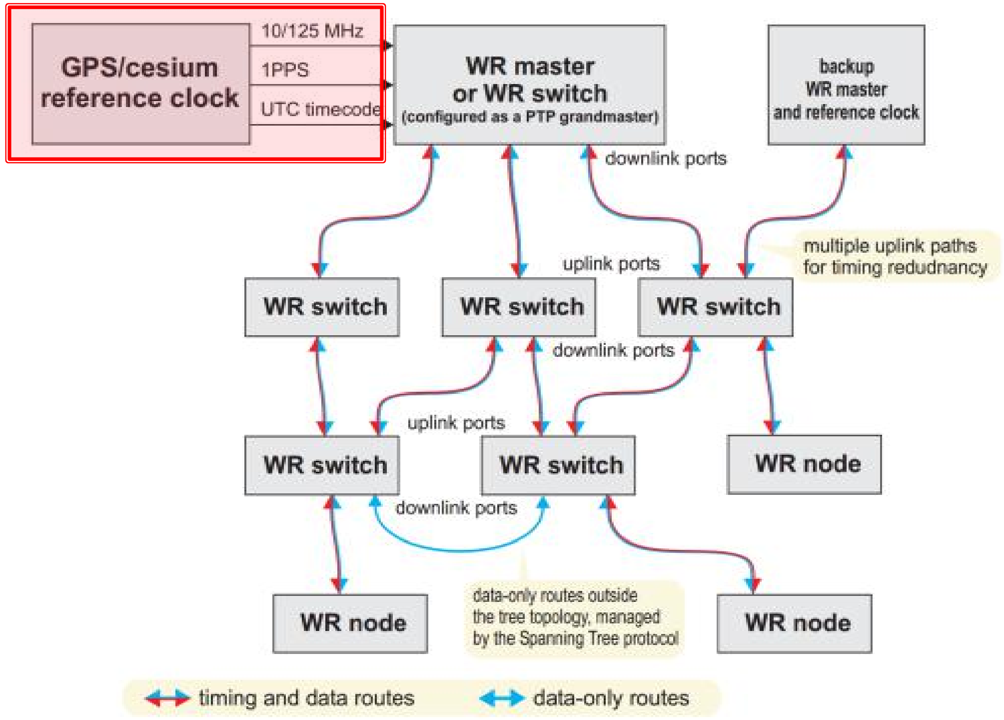
White Rabbit Technology



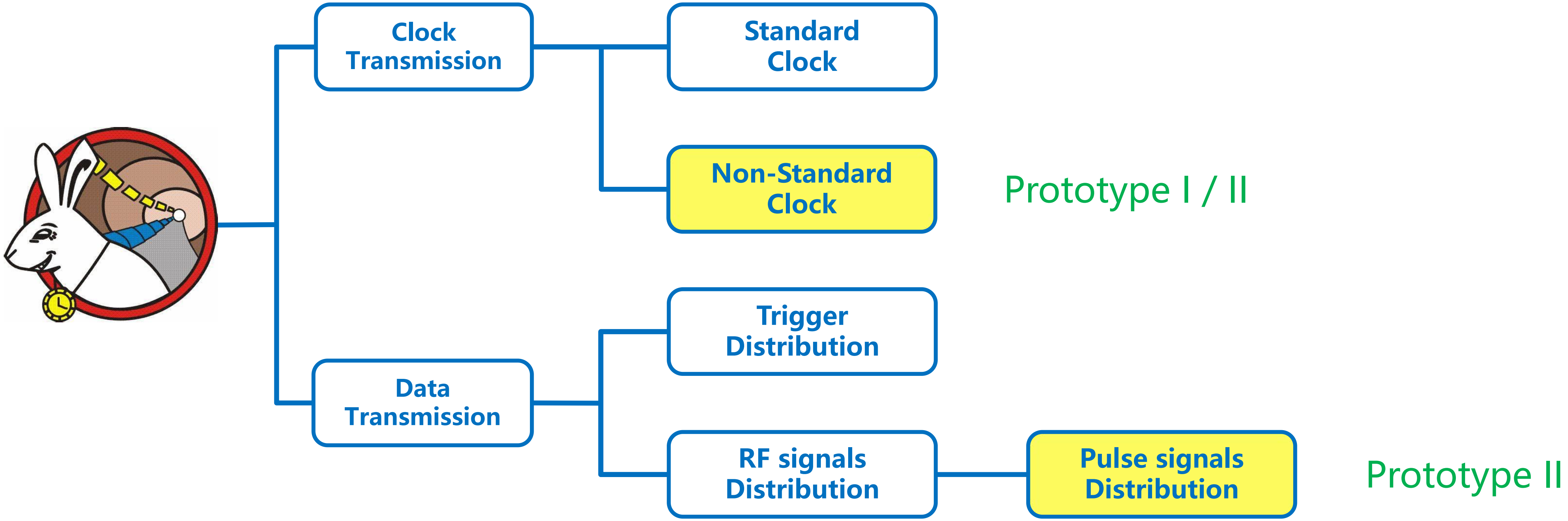
Non-Standard Clock Transmission

- The repetition frequency of SHINE is 1.0030864MHz (1.3GHz/1296)
- 1.3GHz RF reference signal can be divided to 10.030864MHz as a reference signal

Can the White Rabbit network operating clock be changed from 125/62.5MHz to 125.385/62.693MHz?



SHINE Timing System

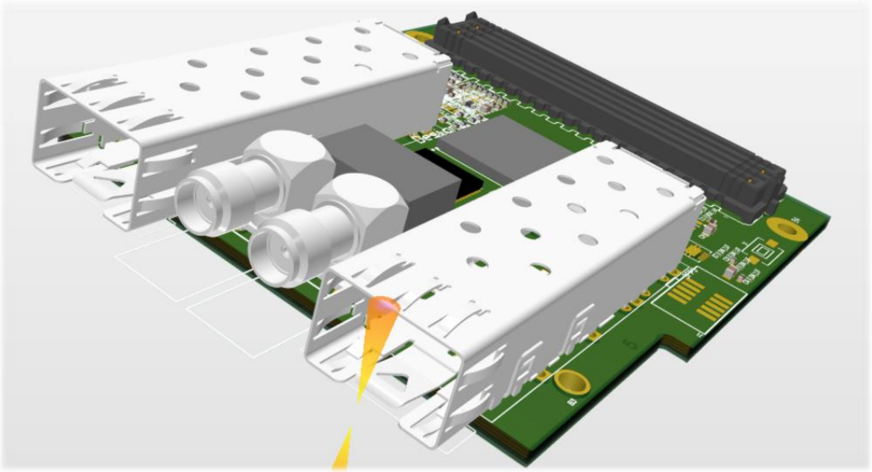


SHINE Timing System

1) Beam-synchronous trigger signal distribution
   – Non-standard clock or pulse signals distribution
   – Master node : reference signal and PPS signal
   – Slave node : adjustable delay and pulse width

2) Random-event trigger signal distribution
   – Standard White Rabbit Trigger Distribution (WRTD)
   – Master node : 4 channals pulse inputs < 1 kHz
   – All slave nodes output at the same time (+ fixed delay)

3) Data exchange between nodes



Slave node (FMC)

SHINE

SHINE Timing System

2018
- Technical route selection
- Potential vendor selected

2019
- Non-standard clock verification
- Pulse signals distribution verification

2020
- Hardware v1 & v2 design and test
- Parameters adjustment and optimization

2021
- Integration debug and performance test
- Firmware and software development

2022
- Design finalized and production

2023
- Site installation

Prototype I (Non-Standard Clock)

- Minimize modifications to the standard White Rabbit Protocol
- Replace the VCXO using customed 27.083MHz oscillator
- Operating frequency is 67.708MHz (1.003086MHz x 135/2)

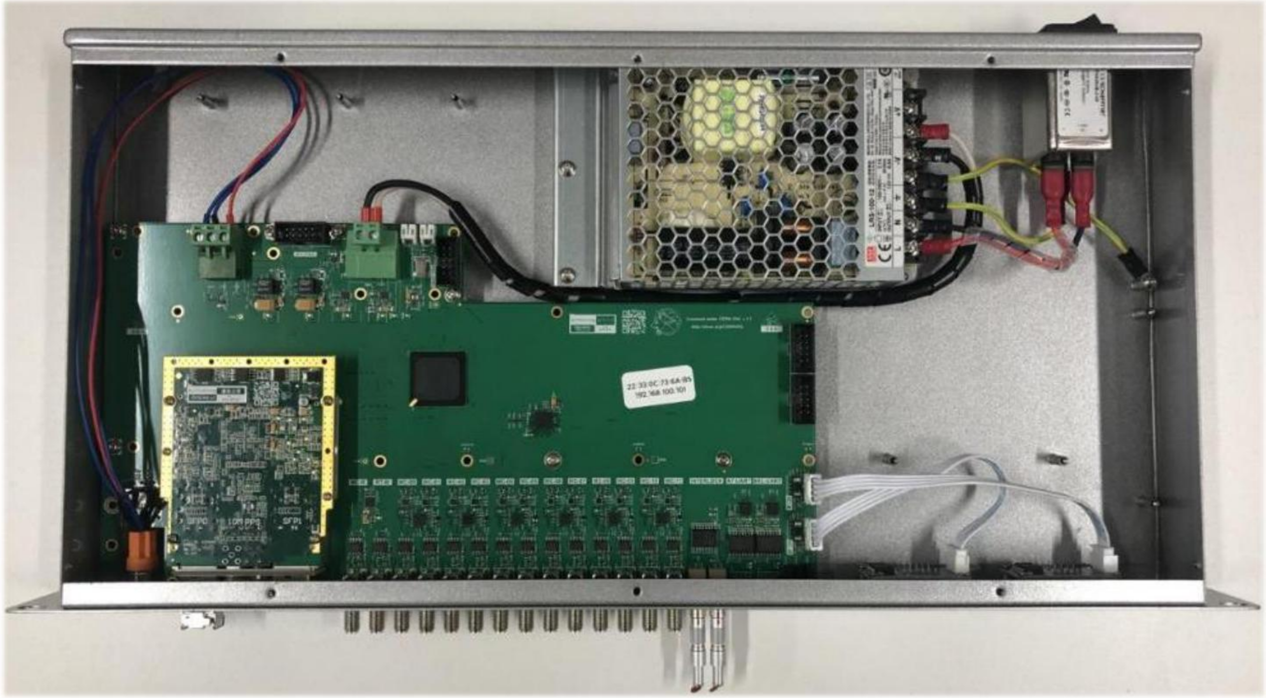
- Change the frequency to 64.197530MHz (1.0030864MHz x 64, 52/81 x 25MHz x 4)
- Easy to generate 2^N divisions and obtain beam-synchronous clocks
- Clear proportional relationship between the pseudosecond and the standard second

Standard time : [seconds : nanoseconds : subnanoseconds]

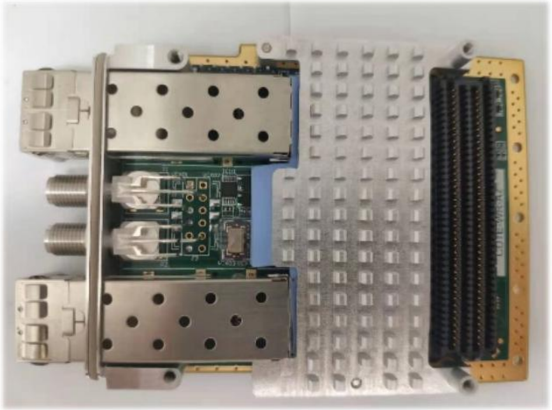
Non-standard time : [pseudo-seconds (~0.9969s) : clock integer period (~15.5769ns) : phase]

SHINE

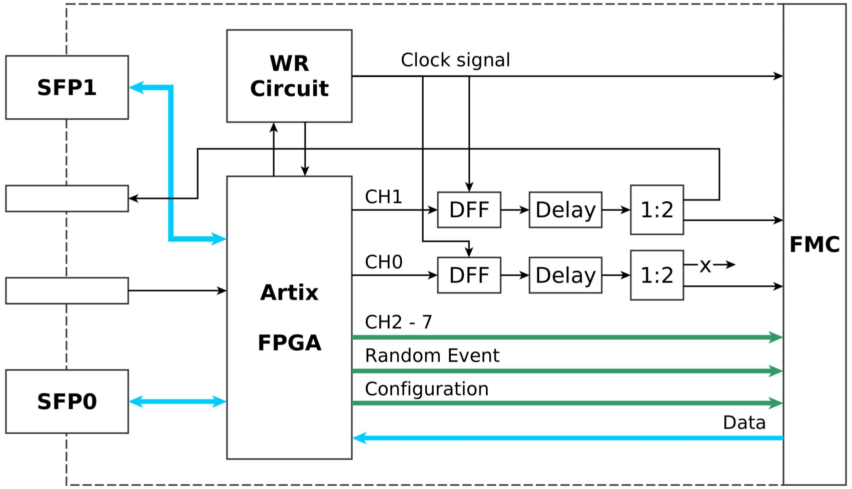
Prototype I (Non-Standard Clock)



Salve Node Crate



FMC LPC, ANSI/VITA 57.1-2019

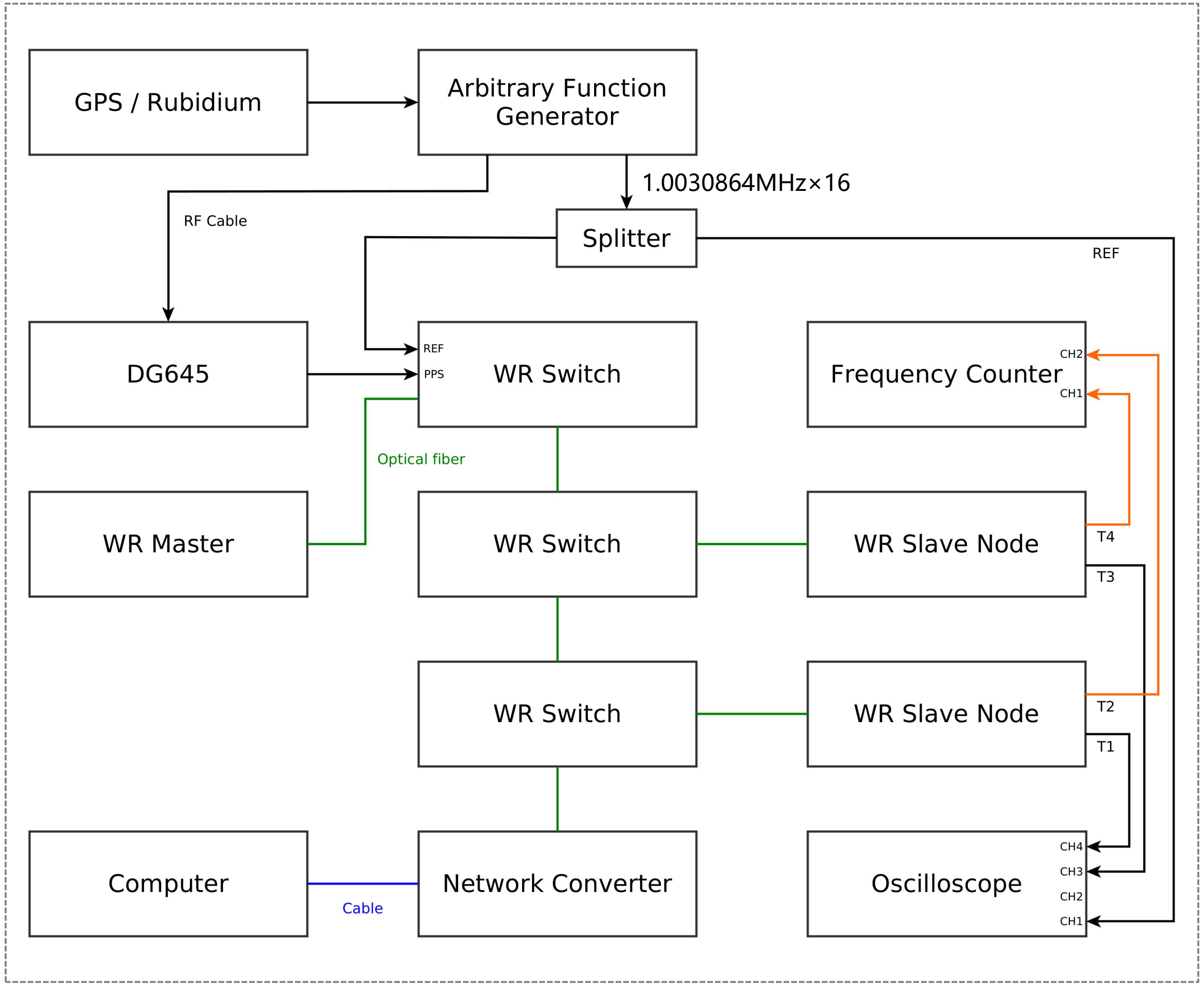


Prototype I (Non-Standard Clock)

- GPS-Disciplined Rubidium Clock, MT6000-XPRO
- Digital Delay/Pulse Generator, DG645
- Tektronix Arbitrary Function Generator, AFG31252, 2-Ch 250MHz Bandwidth, 2GSa/s sample rate, Rise/fall time ≤2 ns, Jitter (rms) 2.5ps
- Keysight MSOS604A Oscilloscope, Infiniium S Series, 6 GHz Bandwidth, 20GSa/s sample rate, 10bits
- Siglent SDS6204 Oscilloscope, 2 GHz Bandwidth, 10GSa/s sample rate, 12bits
- Keysight Frequency Counter/Timer, 53230A

SHINE

Prototype I (Non-Standard Clock)



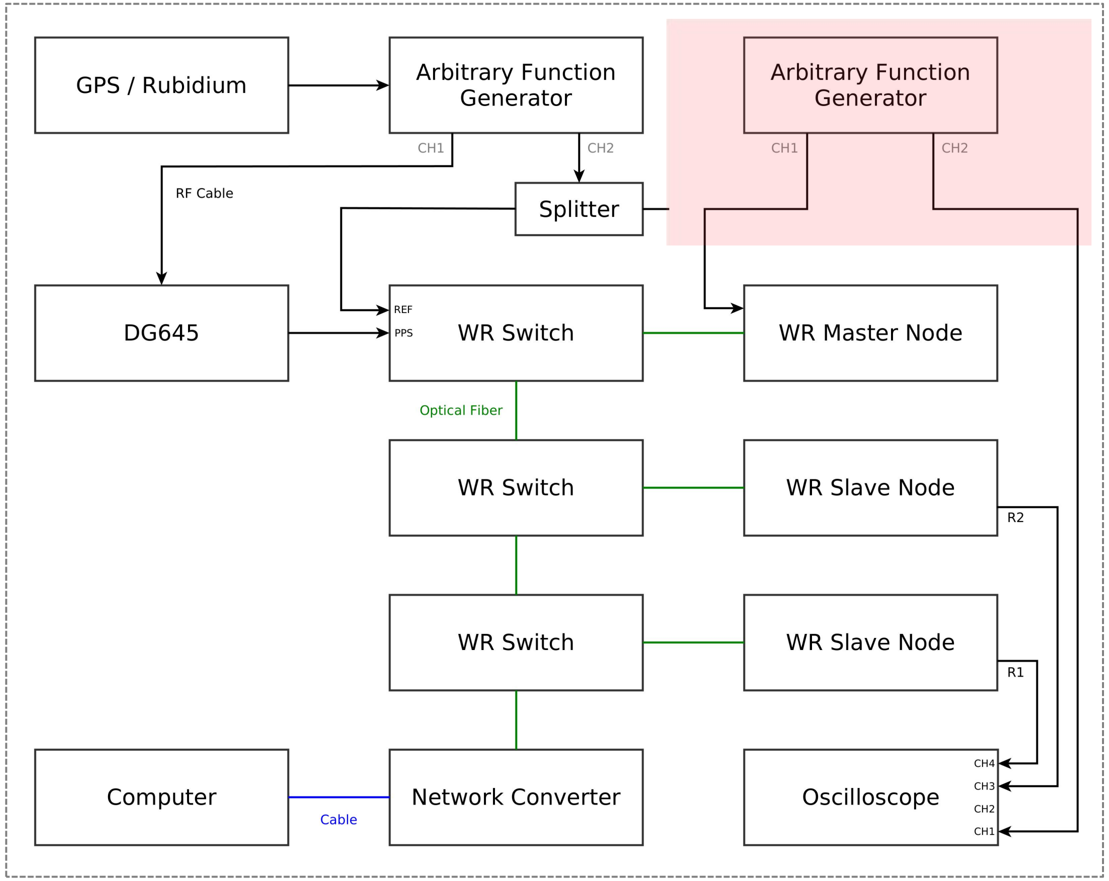
- GPS-Disciplined Rubidium Clock, MT6000-XPRO
- Digital Delay/Pulse Generator, DG645
- Tektronix Arbitrary Function Generator, AFG31252, 2-Ch 250MHz Bandwidth, 2GSa/s sample rate, Rise/fall time ≤2 ns, Jitter (rms) 2.5ps
- Keysight MSOS604A Oscilloscope, Infiniium S Series, 6 GHz Bandwidth, 20GSa/s sample rate, 10bits
- Siglent SDS6204 Oscilloscope, 2 GHz Bandwidth, 10GSa/s sample rate, 12bits
- Keysight Frequency Counter/Timer, 53230A

SHINE

Prototype I (Non-Standard Clock)

- Beam-synchronous trigger signal distribution
  - Jitter between the slave node output and reference signal <10ps
  - Jitter between slave nodes outputs <5ps

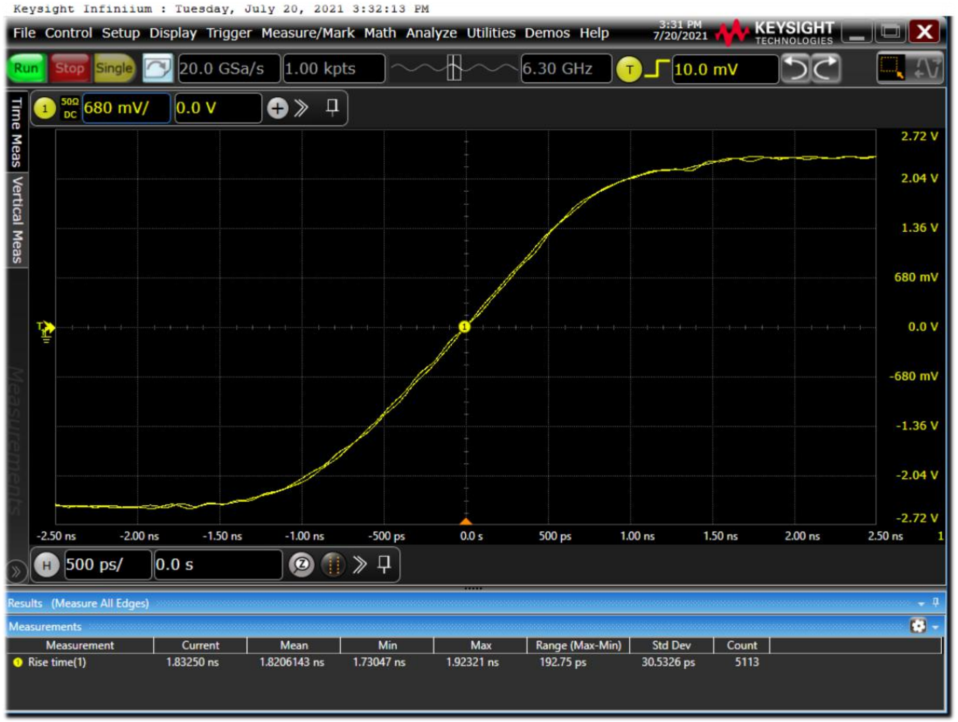
- Random-event trigger signal distribution
  - Jitter between the slave node output and input trigger <60ps



SHINE

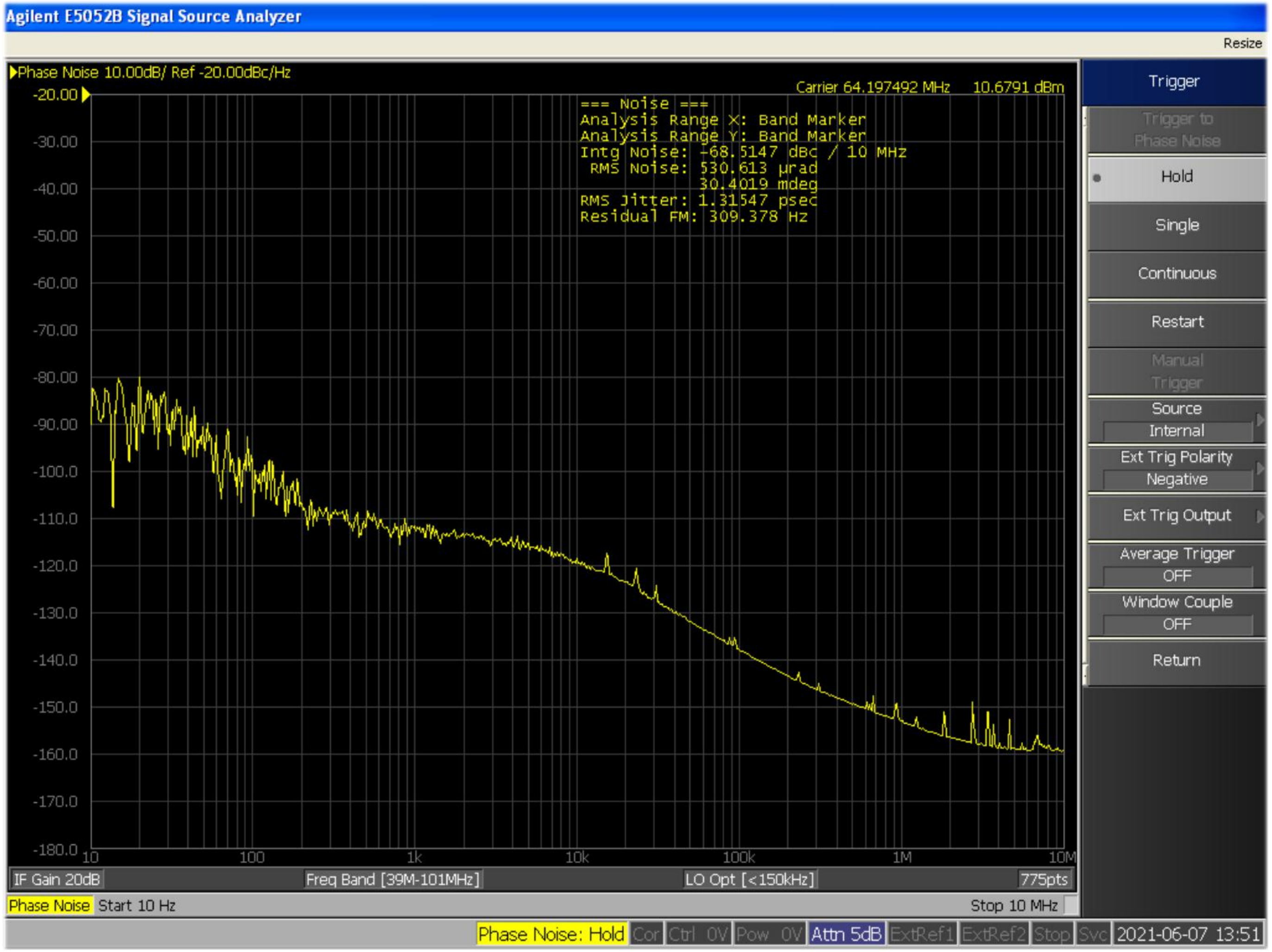
Prototype I (Non-Standard Clock)

- The sine signal is better as the reference signal, but it is difficult to measure the jitter.
- There is jitter between the square wave cycles, which affects the system performance.



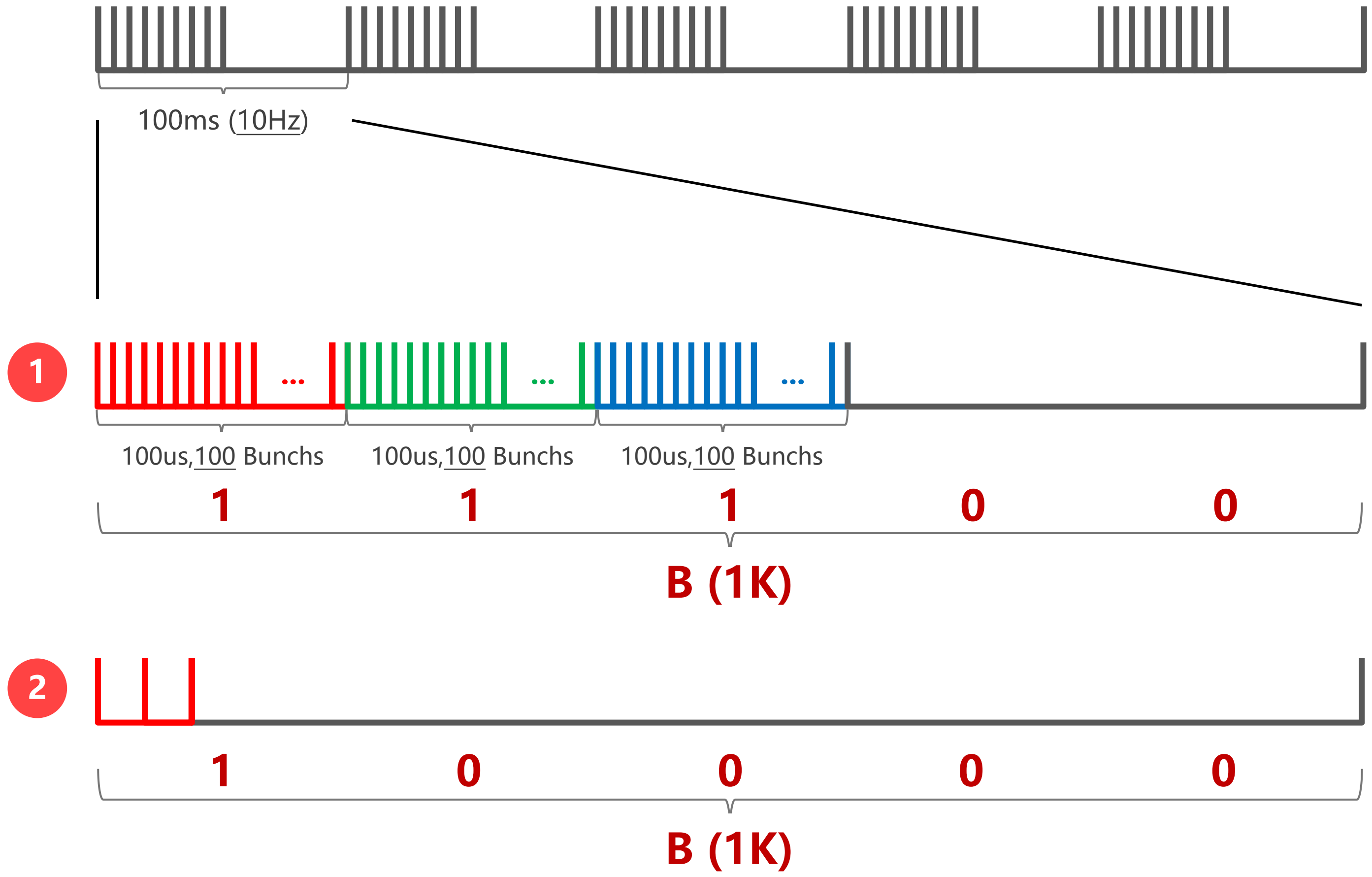
Prototype I (Non-Standard Clock)

- Clock Phase Noise
- Agilent E5052B Signal Source Analyzer, Frequency Range 10 MHz to 7.5GHz
- 10Hz - 10MHz jitter <2ps



SHINE

Prototype I (Non-Standard Clock)



Bunch Train (Preliminary)

A x B x C

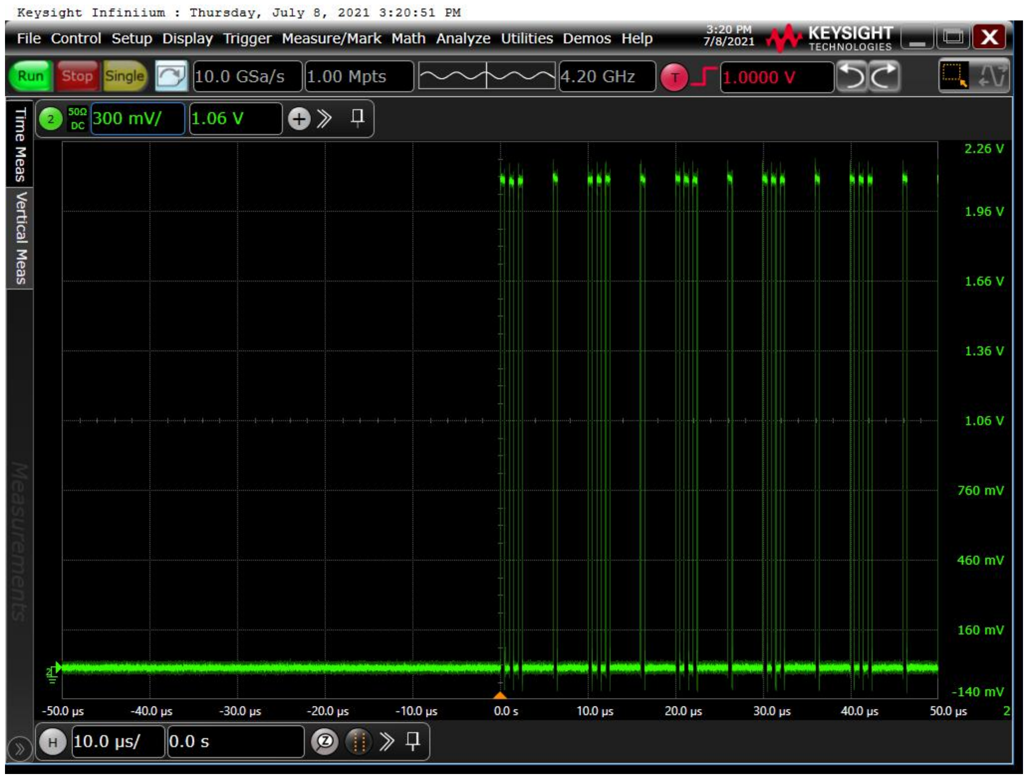
For example： 10Hz x 1K x 100

- A (10Hz)： Train Repetition Rate
- B (1K)： Sequential Editable Unit

  10000 …， 11000 …
- C (100)： Arbitrary Editable Unit

SHINE

Prototype I (Non-Standard Clock)

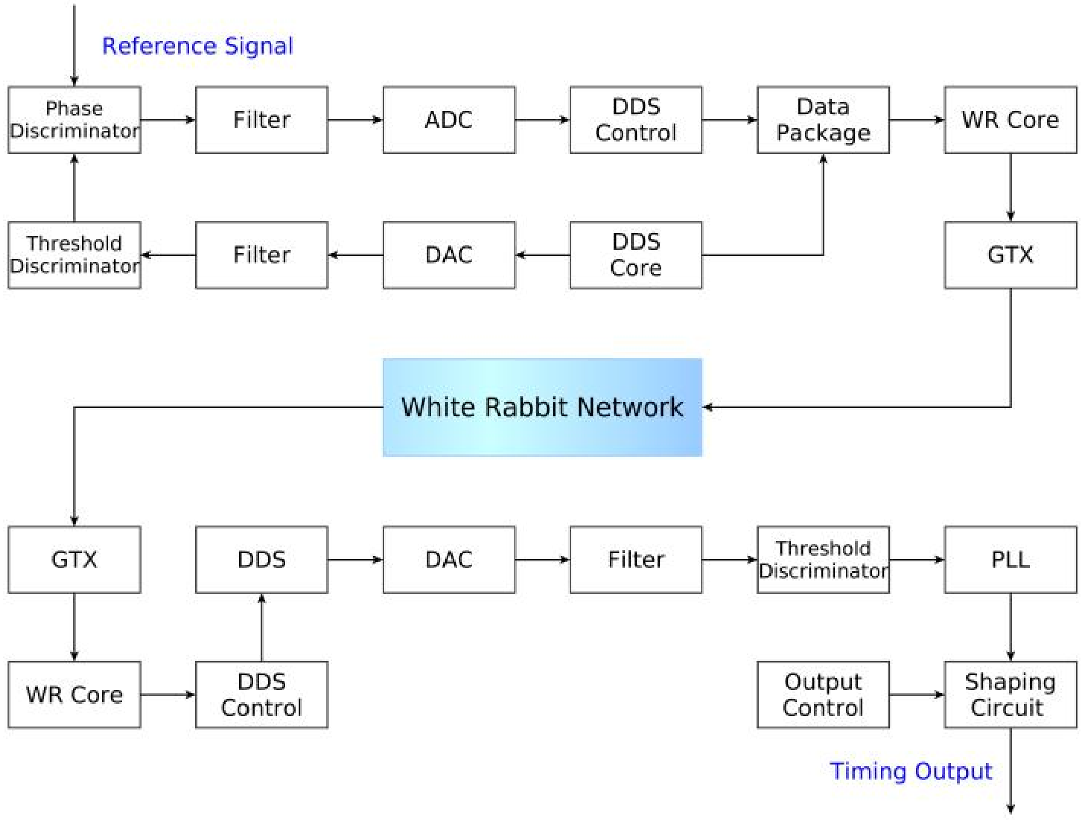


A=500Hz, B=111 ··· 000 ··· , C=1110001000 1110001000 ···

Prototype II (Pulse Signals Distribution)

- Clock (125/62.5MHz) distribution and synchronization based on standard White Rabbit network

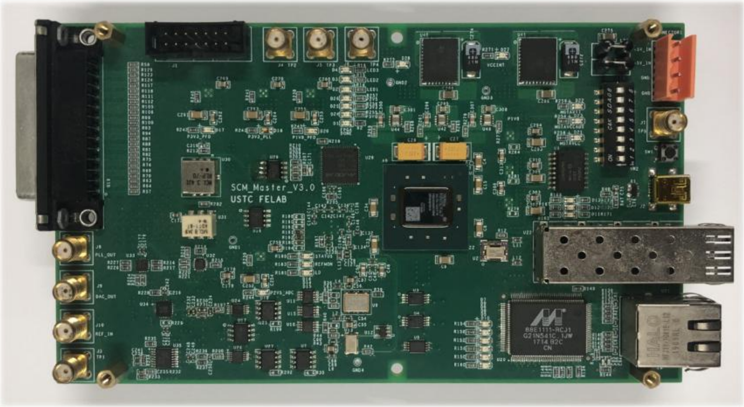
- The DDS (Direct Digital Synthesis) and D flip-flops (DFFs) are adopted for RF signal transfer and pulse configuration
- Off-chip delay for beam-synchronous trigger and on-chip delay for random-event trigger



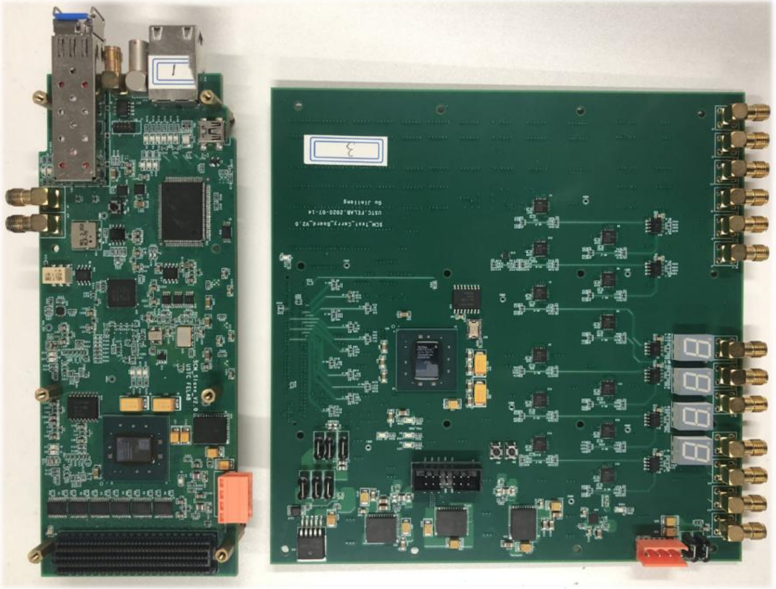
SHINE

Prototype II (Pulse Signals Distribution)

- Clock (125/62.5MHz) distribution and synchronization based on standard White Rabbit network
- The DDS (Direct Digital Synthesis) and D flip-flops (DFFs) are adopted for RF signal transfer and pulse configuration
- Off-chip delay for beam-synchronous trigger and on-chip delay for random-event trigger



Master Node



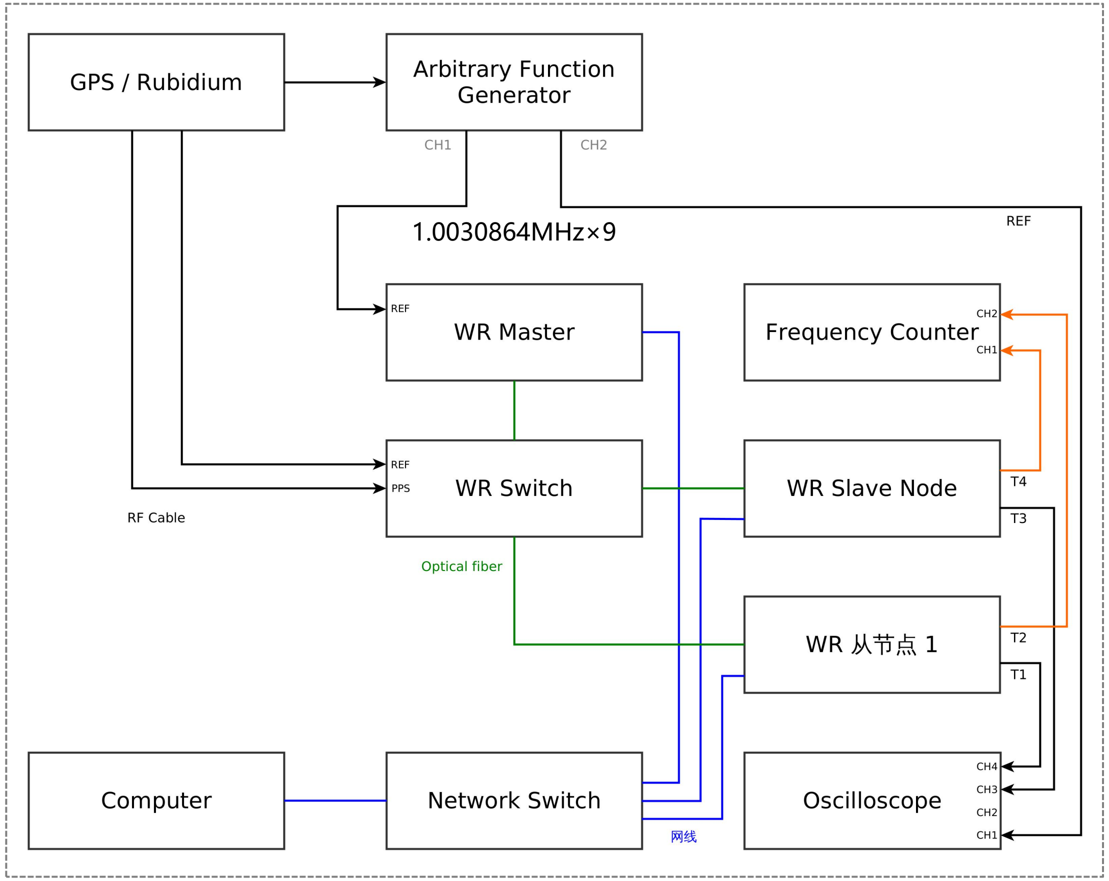
Slave Node

SHINE

Prototype II (Pulse Signals Distribution)

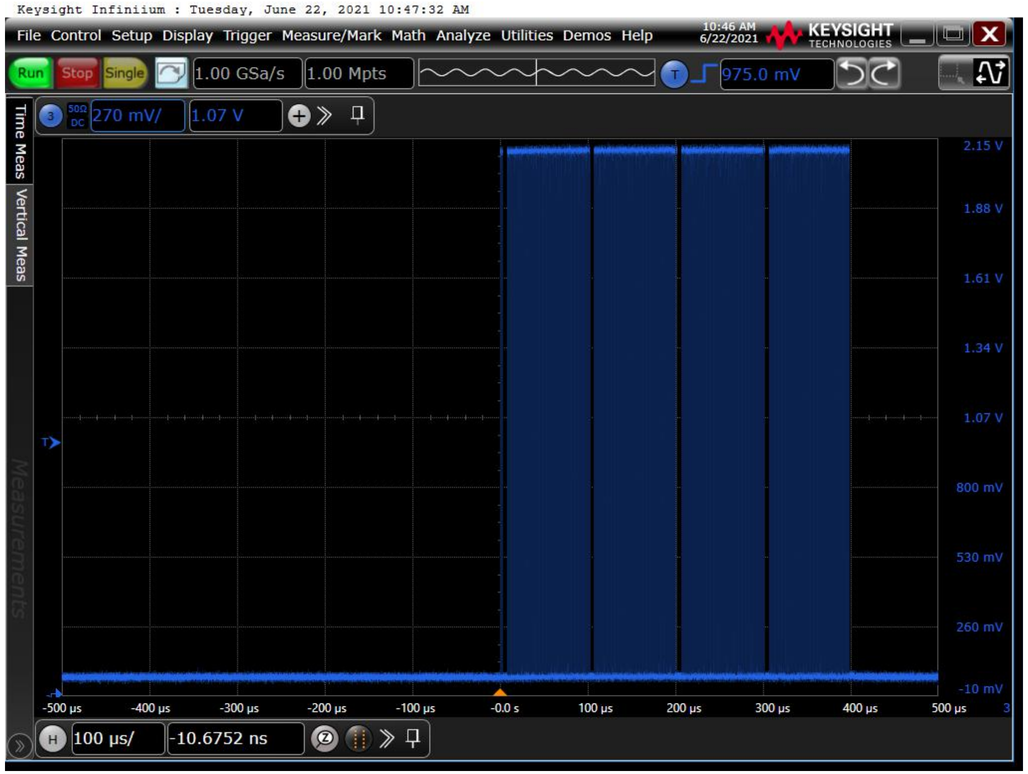
- Beam-synchronous trigger signal distribution
  - Jitter between the slave node output and reference signal <20ps
  - Jitter between slave nodes outputs <10ps

- Random-event trigger signal distribution
  - Jitter between the slave node output and input trigger <35ps



SHINE

Prototype II (Pulse Signals Distribution)



A=10Hz, B=<u>11110000</u> ···, C=<u>10100011</u> <u>10100011</u> ···

SHINE

Summary

- The SHINE timing system is currently under construction.
- Three functions are designed, beam-synchronous trigger signal distribution, random-event trigger signal distribution and data exchange between multiple nodes.
- Two prototype systems were developed.
- The non-standard clock transmission was proposed and verified.

Acknowledgment

- We would like to thank CERN colleagues of the Hardware and Timing Section, Beam Controls Group (BE-CO) for the discussions and suggestions.

Team

- P.X.Yu, G.H. Chen, Q.W. Xiao (SARI, CAS)
- G.H. Gong, Y.M. Ye (Tsinghua University)
- J.L. Gu, L. Zhao, Z.Y. Jiang (USTC)

Thank you for your attention.