Application Note

TCSPC Multi-Device Synchronization using MultiHarp and White Rabbit

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Introduction

The MultiHarp is a new family of TCSPC and time tagging devices that offer an exciting set of features and performance metrics. They support a timing resolution down to 5 ps, a timing precision of less than 45 ps rms, a dead-time of 650 ps. The MultiHarp 150 variant provides up to 16 channels plus sync[1]. Up to 64 channels plus sync are possible for MultiHarp 160 devices[2]. The MultiHarp is also the first TCSPC device to support White Rabbit, a technology that enables two key features: The first is that many MultiHarp devices can be operated synchronously in parallel, thereby drastically increasing the maximum number of channels. The other is that this can be implemented even across great distances of several kilometers.

White Rabbit is a collaborative Open Source project aimed at realizing an Ethernet-based network permitting simultaneous sub-nanosecond synchronization and Gigabit speed data transfer. To achieve this, it employs both modified Synchronous Ethernet (SyncE) and modified Precision Time Protocol (PTP v2.0)[3]. It is standardized as PTP IEEE-1588-2019 High Accuracy. Not all physical layers that are available for Ethernet are compatible with the rigorous timing requirements of White Rabbit. An example for a supported physical layer is 1000BX10, which uses optical fibers as its transmission medium. Using this physical layer, the optical fiber length between devices can be up to 120 km.

In a White Rabbit network, time is distributed in a tree topology from a grandmaster device down to other devices. On each link there exists a master-slave relationship between the two devices, with the master passing down its own time information to the slave. Through the use of optical fibers and the calibration of devices, the propagation delay of the White Rabbit messages can be measured very precisely. This way, the devices can be synchronized to a much better degree than through normal PTP.

A White Rabbit capable switch is a special device, that can receive timing information from another White Rabbit device on one port and distribute it to all others. This way, arbitrarily large networks can be constructed. One such device is the WRS-3-LJ/18 White Rabbit Switch low jitter[4], produced by Seven Solutions (Granada, Spain)[5], offering 18 ports.

In this application note, we investigate the impact of White Rabbit synchronization on the time accuracy of several MultiHarp devices connected through Seven Solutions switches in different topologies.

The experiment proves that - when using White Rabbit - the excellent timing performance of the MultiHarp can be maintained even across great distances. We show that for reasonably sized networks with 2 layers no precision degradation occurs. In those cases a timing jitter of around 40 ps rms can be expected. In larger networks a small increase in the jitter is observed. The maximum jitter measured across all experiments was 46 ps rms. Furthermore, we show that the impact of fiber length differences of up to 5 km or simultaneous Ethernet data transmission is negligible.

Table 1: This table lists all the devices used in the experiment as well as their key specifications.

Experiment Name	Product Name	Notes
MH1	PicoQuant MultiHarp 160 (MH160-M)	32 ps rms jitter between two local channels
MH2	PicoQuant MultiHarp 160 (MH160-M)	32 ps rms jitter between two local channels
MH3	PicoQuant MultiHarp 150 (MH150-16P)	40 ps rms jitter between two local channels
MH4	PicoQuant MultiHarp 150 (MH150-16P)	34 ps rms jitter between two local channels
MH5	PicoQuant MultiHarp 150 (MH150-8P)	32 ps rms jitter between two local channels
WRS1	Seven Solutions White Rabbit Switch (WRS-3-LJ/18)	/
WRS2	Seven Solutions White Rabbit Switch (WRS-3-LJ/18)	/
Blue transceiver	AXCEN AXGE-1254-0531	PHY standard: SFP-1000BX10-U4
Pink transceiver	AXCEN AXGE-3454-0531	PHY standard: SFP-1000BX10-D4
PC1	/	Windows PC for measuring data rate as an iperf3 server
PC2	/	Linux PC for measuring data rate as an iperf3 client
PDL800	PicoQuant PDL 800-D	Outputs NIM signal at 5 MHz with a 6 ns pulse width on its synchronization output

Experimental Set-up

In this experiment we measure the timing precision of several MultiHarp devices connected via White Rabbit and arranged in several set-ups. The goal is to find out how different network topologies impact the timing jitter. For the experiment several components are used. A detailed breakdown is provided in table 1.

The optical fiber lengths were varied for each experiment from 0.6 m to 1 km and 5 km. During the tests PC1 and PC2 were connected to ports of WRS1 and WRS2 used to measure the network data rate between them using the iperf3 application. They were connected through the 1000Baset-T physical layer using copper cables.

MultiHarp devices can make use of the Ethernet network between them in order to negotiate a simultaneous start of measurement. This functionality was used for this experiment. A 5 MHz NIM signal was generated by a PDL 800 laser driver on its synchronization output. This signal was fed through an impedance matched 5-way passive fan-out and into one input of each of the MultiHarp devices. For each set-up $5{\times}10^6$ timing events were collected per MultiHarp device.

Using the MHLib programming library for the MultiHarp systems, a C program was developed to gather the T2 data generated by the MultiHarp devices. As the devices observe the same signal and their clocks as well as starting points are synchronized, the generated data from each MultiHarp can be trivially compared to each other. This way, the timing jitter can be computed.

Several network topologies were tested. They are listed in figure 1. For set-up 1 only a single switch connects all MultiHarp devices into one network, which is two layers deep. Set-up 2 increases the depth by one layer by operating the switch in boundary clock mode and making it the slave of MH1. Set-up 3 is also three layers deep, but the masters are both switches. The MultiHarp devices are spread between two layers in this set-up. Finally, set-up 4 adds another layer by making MH1 the master of WRS2. Set-up 4 is the deepest network that can be constructed using the devices that were available for this experiment.

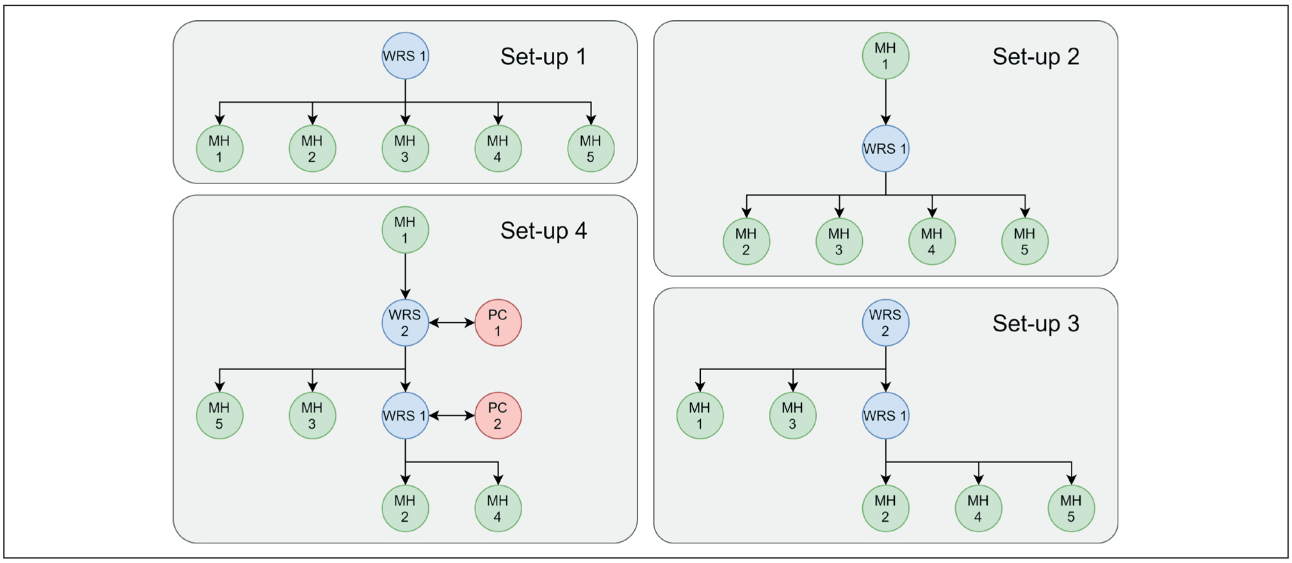

Figure 1: This figure shows schemes of the four network topologies that were used in this experiment. In each set-up, the green bubbles stand for a MultiHarp 150 or MultiHarp 160 device. The blue bubbles represent the White Rabbit switches. The arrows indicate the direction of the White Rabbit master-slave relationship on each physical link. The arrows are pointing from master to slave. Also shown in red are the two PCs communicating over TCP/IP.

Results

The measurement results are shown in figure 2. As the absolute arrival time for each event is recorded by each MultiHarp, we can compute the rms jitter for each pair of devices according to following formulae:

$$\sigma = \sqrt{\sum_{0}^{N} \frac{(\chi_N - \gamma_N - \mu)^2}{N-1}} \qquad \mu = \frac{\sum_{0}^{N} \chi_N - \gamma_N}{N}$$

where σ denotes the rms jitter between two MultiHarp devices. The variables χ and γ denote the time values measured by the respective MultiHarp devices. N was chosen as 5×10^6 for this experiment.

For set-up 1, we see that the jitter is between 38.2 ps rms in the best case and 40.5 ps rms in the worst case. Comparing this with the specifications of the MultiHarp 150 and the MultiHarp 160, which for both list a datasheet precision of 45 ps rms, this is an excellent result. The average jitter across each device pair is 39.44 ps.

In set-up 2, even though there is one additional network layer - with one of the MultiHarp devices being a master - timing does not degrade substantially. The minimum increases from 38.2 ps to 38.5 ps rms and the maximum decreases to 40.2 ps rms. The average increases by only 0.02 ps rms, which may be a measurement inaccuracy.

A more significant timing difference can be observed for set-up 3. The average timing jitter increases by 2 ps to 41.37 ps rms. Looking at the 2D plot in figure 2, it can be seen that the timing between MH3 and all other devices is noticeably worse. The jitter between MH3 and MH2 is the largest with 46.3 ps rms and MH3 and MH4 with 44.9 ps rms.

In set-up 4 the average jitter between all devices is 41.95 ps rms. Comparing it to set-up 3, we can see that the timing of MH1 compared to any other MultiHarp worsened slightly. It can also be seen that, again, the highest jitter can be found in combination with MH3. This time MH4 and MH3 have the highest jitter at 44.9 ps rms.

Figure 3 shows distribution of timing differences between two MultiHarp devices in a histogram for

Set-up 1	MH1	MH2	MH3	MH4	MH5
MH1		38.7ps	39.0ps	38.7ps	38.2ps
MH2	38.7ps		39.9ps	39.7ps	40.0ps
MH3	39.0ps	39.9ps		39.7ps	40.5ps
MH4	38.7ps	39.7ps	39.7ps		39.9ps
MH5	38.2ps	40.0ps	40.5ps	39.9ps	

Set-up 2	MH1	MH2	MH3	MH4	MH5
MH1		38.8ps	39.3ps	39.2ps	39.0ps
MH2	38.8ps		38.5ps	40.2ps	40.0ps
MH3	39.3ps	38.5ps		39.8ps	40.1ps
MH4	39.2ps	40.2ps	39.8ps		40.0ps
MH5	39.0ps	40.0ps	40.1ps	40.0ps	

Set-up 3	MH1	MH2	MH3	MH4	MH5
MH1		39.5ps	41.5ps	39.4ps	38.3ps
MH2	39.5ps		46.3ps	40.5ps	39.9ps
MH3	41.5ps	46.3ps		44.9ps	43.9ps
MH4	39.4ps	40.5ps	44.9ps		39.5ps
MH5	38.3ps	39.9ps	43.9ps	39.5ps	

Set-up 4	MH1	MH2	MH3	MH4	MH5
MH1		41.0ps	40.1ps	41.5ps	38.0ps
MH2	41.0ps		40.7ps	39.4ps	40.5ps
MH3	40.1ps	40.7ps		44.9ps	43.5ps
MH4	41.5ps	39.4ps	44.9ps		39.5ps
MH5	38.0ps	40.5ps	43.5ps	39.5ps	

Figure 2: This figure shows the results from the timing measurements for each set-up in an N:N matrix. The value shown in picoseconds in each cell is the timing jitter between two corresponding devices.

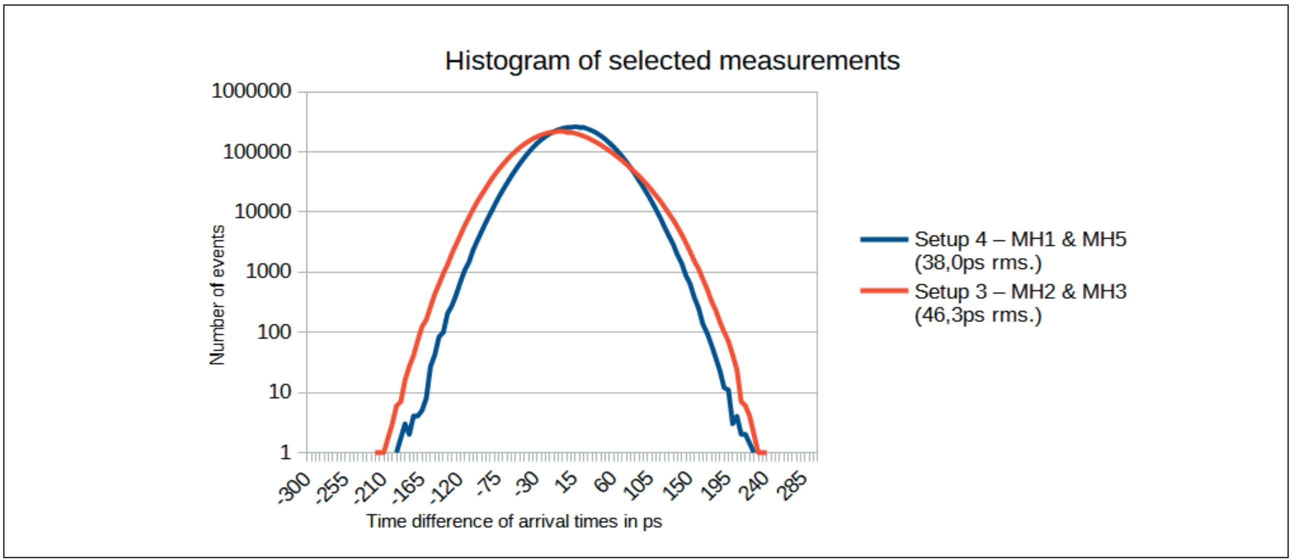

Figure 3: This figure shows histograms of the time difference between the arrival times across two synchronized devices, shifted by their average values for clarity. The measurements with the lowest jitter (blue) and the highest jitter (orange) are shown as examples.

the two setups with the smallest and the largest jitter. Repeating those measurements with different fiber lengths did not influence the results in a measurable way. The details of those measurements are therefore omitted for the sake of clarity here.

The data rate measurements between PC1 and PC2 were consistently around 920 MBit/s. As the iperf3 benchmark was run in TCP/IP mode over a 1 Gbit/s Ethernet connection using IPv4, this is close to the theoretical maximum of around 945 MBit/s. No degradation of the timing jitter could be observed while benchmarking the data rate.

Conclusion

In this experiment we tested the applicability of White Rabbit synchronization for MultiHarp devices and the flawless interoperability with the WRS-3-LJ/18 by the leading White Rabbit component manufacturer Seven Solutions. We show with set-up one and set-up two, that for networks consisting of only two layers and at most one switch no noticeable degradation of jitter can be observed between the MultiHarp devices. This means that, using the WRS-3-LJ/18 switch and the MultiHarp 160, up to 18 MultiHarp devices can be operated synchronously, thereby enabling up to 1170 channels across those 18 devices. Using MultiHarp 160 devices with 64+1 channels each this means that up to 1170 channels are possible.

Other use cases such as physically distant but precisely synchronized measurement points were tested with set-ups three and four. Here we see that, somewhat expectedly, as the depth of the network increases, the jitter increases. However, there are outliers in these jitter measurements when MH3 was used. Looking at the individual device characteristics outlined in table 1, it can be seen that MH3 has the largest jitter of all the tested MultiHarp devices, independently of White Rabbit. This is possible as small differences in the timing precision can arise through production differences of the devices.

Nevertheless it can be seen that the timing precision is still suitable for many applications. The Ethernet performance of the Seven Solutions switches is close to the theoretical maximum and Ethernet transmission did not influence timing precision.

White Rabbit is a powerful tool that, combined with devices from the MultiHarp device family, can enable researchers to conduct experiments on a scale previously unthinkable in terms of number of channels or the distance between them.

References

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