Wireless Precision Time Synchronization Alternatives and Performance

Ganesh Basawapatna, Joshua White, and Phillip Van Hooser, *Riverside Research Institute*

BIOGRAPHIES

Phillip Van Hooser is a Research Engineer. He received the BSEE and MSEE degrees from The Ohio State University in 2020 and 2022. He has done Research work in very high-speed systems components at the Air Force Research Labs.

Joshua White is a Systems Engineer. He received the BSE in Computer Engineering, BS in Applied Mathematics, and MS in Computational & Applied Mathematics from Western Michigan University in 2018 and 2020 and is completing his MSE in Electrical Engineering degree at WMU. He has made contributions to the applications of Machine Learning and Artificial Intelligence techniques in circuits analysis and trust & assurance at Riverside Research.

Ganesh Basawapatna is a Principal Investigator. He received the B.Tech.(Hons) degree from Indian Institute of Technology, Kharagpur, India in 1963 and the MSEE degree from Illinois Institute of Technology in 1964. He was previously president at Encore International and Microsource, Inc., and prior to that in various capacities with Hewlett Packard and Raytheon.

ABSTRACT

Precision Time Synchronization techniques and approaches have assumed increasing importance in multi-body dynamic systems in Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) denied and degraded environments. In multi-body military systems based upon Alternative Position, Navigation and Timing (alt-PNT) and Assured Position, Navigation and Timing (APNT) scenarios many different approaches to time synchronization between bodies have been proposed and developed. Some of these have been extensions of CERN's White Rabbit (WR) system while others have been developed on the basis of the IEEE 1588 Precision Time Protocol and the Network Time Protocol. There have also been demonstrations of Satellite based two-way time transfer and Optical or Laser based time transfer.

In alt-PNT and APNT based military operations a mission might include a combination of Dismounted Soldiers, Land based vehicles, Drones, Fixed Wing and Rotary Wing aircraft, and Naval assets, all of which have different velocity and acceleration vectors associated with them at any instant. In such situations the requirements of a system that meets mission-based time precision between the various elements presents a higher order of complexity than two or multiple element static systems, two-way directional Over the Air (OTA) systems, and other GPS dependent systems. Often the time precision can be achieved by simple time transfer while at other times or in other parts of a mission phase coherence between many clocks in the system may be required. Since future military systems will be expected to adhere to the Modular Open Systems Approach (MOSA) and Sensor Open Systems Architecture (SOSA), the time synchronization considerations become significantly more complex because of added highly non-deterministic communication and signal transit times.

One of the important considerations in the type of missions envisaged, apart from MOSA / SOSA compatibility, is Size, Weight, Power Consumption and Cost (SWaP-C). We compare the different techniques for achieving the performance necessary, effects on SWaP-C reduction, and show the kind of performance that is possible in the type of missions under consideration.

This paper presents Riverside Research Institute's analysis and findings relating to the methods to achieve precision time synchronization under the above conditions. The authors present and compare the various techniques that have been developed in terms of applications compatibility, resource requirements, expected accuracy and ability to be used in future dynamic military missions. We will present the sensitivities of elements associated with the various approaches. We will also share results based upon our research to date.

1. Introduction

The aim of this work was to study Wireless Precision Time Synchronization (WPTS), first in a two-body wired system, extending it to a two-body fixed Over the Air (OTA) system and then to dynamic multi-body systems where the bodies are moving in different directions over a wide range of velocities and accelerations. An example of such a system might be a military mission where there are airborne elements such as fighter aircraft, helicopters and drones, ship-based elements, and ground-based elements including vehicles and dismounted soldiers. Such systems have a number of characteristics:

1. All the elements do not need the same level of precision in synchronization. The level of synchronization of each element could be mission Command and Control determined.
2. The motions of each of the elements are mission Command and Control specified. The velocity and acceleration vectors can be considered random.
3. Within the mission, the clocks should be synchronized. These clocks may not necessarily have to synchronize to any GPS reference clock for the purposes of the mission. They need to be aligned with the mission reference clock.
4. Assured Position, Navigation, and Timing (APNT) cannot be assumed unless all elements are equipped with appropriate M-Code receivers. Since Time Synchronization is critical, it is important for all elements to follow a Leader clock. The Leader clock may have a Chip Scale Atomic Clock (CSAC) or Rubidium built in reference, or it might be APNT or alternative PNT (alt-PNT) driven.
5. The communications including Position, Navigation and Timing (PNT) information between the elements will be encrypted. Each element may have single or multiple antennas to handle the Command-and-Control communications and PNT information, or they may all be bundled into one system that receives and distributes the information to different sensors or processors.

A seminal work has described the three basic ways in which clock synchronization can be achieved (Levine, 2008). Of these, one-way and two-way methods have been used in most applications. Three main protocols have been developed for time synchronization in different applications. Analytical and experimental techniques related to these have been described in the published literature. Prominent among these are WR, which was originally developed at CERN for the synchronization of multiple elements in the Large Hadron Collider, Network Time Protocol (NTP), which was developed initially for synchronization of computers and computer communications, and the IEEE 1588 Precision Time Protocol (PTP) which was developed for a variety of different precision timing applications. It should also be pointed out here that the term synchronization in this context might mean the synchronization of time stamps or time in each element itself to some accuracy, or the synchronization of clock frequency, called syntonization, or the synchronization of the clock phase, called phase synchronization.

In static wired systems with multiple levels of clocks, microsecond to nanosecond (ns) and sub-nanosecond level of synchronization precision has been demonstrated in WR (Wlostowski, 2011), PTP (IEEE, 2019), and NTP (Charbonneau et al., 2018). Synchronization with 10s of ns precision using WR in an OTA mode have been reported (Gilligan et al., 2020). In dynamic wireless communication systems using extensions of PTP, synchronization precision has been typically limited to microseconds (Aslam et al., 2022). One- and Two-Way Time Transfer via Satellite (OWSTT and TWSTT) have been proposed and demonstrated. TWSTT has demonstrated synchronization precision in the sub-ns range (Koppang & Wheeler, 1998). NIST and others have demonstrated optical two-way time transfer with sub-ps to femtosecond synchronization timing precision (Bergeron et al., 2017). While this is impressive it is based upon line-of-sight communication with high directionality, which is not possible in most missions under consideration in this work.

Our approach, as we describe in what follows, was to determine the applicability of the previously described methods, and to study the possibility of extending applicable methods to OTA fixed and dynamic systems. As we studied the various synchronization approaches, we focused our efforts on determining the factors that would lead to better synchronization in our systems and those that would make the task more difficult. This paper describes the considerations in extending WR for static and dynamic WPTS for our applications, describes our measurements, especially with a WR system, and our conclusions based upon our measurements. As an extension we describe the considerations associated with dynamic WPTS.

In what follows, we describe the motivation for our approach, describe the considerations in attempting to extend the general approach of WR / IEEE 1588 PTP, our experiments and conclusions with respect to WR PTP application to dynamic WPTS, and end with a short description of our future directions.

2. Motivation

As described below, the primary aim of our work is to create a method to achieve the highest possible time synchronization between elements of certain military mission scenarios. WR and IEEE 1588 PTP represent the best results to date of precision time synchronization between large numbers of bodies. However, WR has until now been applied only to systems where all the members are static. There has been only one published work (Gilligan et al., 2020) that uses the WR structure to create time synchronization between two elements connected by an Over-the-Air (OTA) RF Link, which also was essentially static. Prior to attempting WR-based designs for the systems under consideration, we needed to understand WR usability under system operating and environmental conditions. The motivation of the present work is to begin to answer these questions and to understand whether and to what extent WR and, in particular, some of its key components could be used in such systems.

2.1 Typical Mission Requirements

Many military missions can be expected to include elements separated by both short (sub-km) and long (100s of km) distances moving at different rates with respect to each other, and yet needing to be time coordinated with each other (Government Accountability Office, [GAO], 2022). In the absence of reliable GPS and without the assurance that all elements are equipped with APNT capability, it would make sense to have the clocks in all elements which we herein call Follower clocks follow a selected Leader clock.

Some of the key considerations in such systems are:

1. The Leader and all the Followers are in relative motion. Therefore, the antennas need to be omnidirectional. This makes optical or line-of-sight-based time synchronization not easily usable.
2. The environment might include dense urban canyon areas, which would make satellite communications not always possible and hence eliminates OWSTT and TWSTT approaches.
3. For the same reasons, Doppler and Multipath corrections as well as Forward Error Correction (FEC) will be needed in most elements.
4. Time transfer messages may need to share the RF propagation and signal processing path and encryption/decryption with Command-and-Control functions in many elements.
5. Many elements of the system, such as drones and dismounted soldiers could have significant SWaP-C constraints.
6. Most future system elements will need to be Modular Open systems Approach (MOSA) and Sensor Open Systems Architecture [SOSA] compliant. These allow much better system upgrading, but typically add signal processing overhead and associated nondeterminism in processing times.
7. All elements in the system may not need the same level of time synchronization. The solutions may not have to be one size fits all.

We come to the following conclusions. First, it would be limiting to design a system that depended on directional antennas needed for satellite communications, or on satellite communications themselves, including Low Earth Orbit (LEO)-based PNT. Second, the need for Doppler and Multipath and other corrections implies that there will be a significant component of nondeterminism in the transit time between the Leader and the Follower timing and clock signals.

2.2 Two-Way Time Transfer

Two-way time transfer has been studied and employed in most NTP, PTP and WR applications, and such applications have been reported in significant detail in the past. We will not go into the details of these in this paper, except to point out that another way of looking at this is to say that if the forward and reverse paths are equal, then the effects of the distance between the two elements can be common-moded out. Although in dynamic systems the forward and reverse paths may not be equal, the availability of Inertial Navigation Unit (INU) data from most of the high-speed elements in the systems under consideration implies that this particular issue can be overcome.

Satellite Time Transfer provides advantages in time synchronization, if the elements involved have a direct view of the satellite being used, and if the elements have antennas that can track the satellite being used. The biggest advantage is that the distance to the satellite and back is so much larger than the distance between the elements that the forward and reverse signal path lengths can be considered almost equal, which allows for very accurate Two-Way time transfer. Said differently, the satellite path makes the common-moding of forward and reverse timing signal transit times possible in dynamic situations where direct communications would not allow it. While this is indeed very attractive, the inability to guarantee satellite visibility and the cost of satellite transceivers in our applications makes the use of TWSTT difficult (Celano et al., 2007).

WR offered many advantages. If the issue related to forward and reverse path length in a dynamic system could be overcome mathematically, then we could perhaps take advantage of all the open-source development work already done. Our approach was to extend WR to OTA and then to dynamic OTA. Previous work by Gilligan et al. (2020) has demonstrated that static OTA was possible. Our question was to determine whether it would be possible to extend WR performance in deployable systems with Size Weight Power and Cost (SWaP-C) limitations and the ability to perform in systems within the MOSA and SOSA framework.

2.3 Nondeterminism

Nondeterminism in the context of time synchronization is the uncertainty in the amount of time it takes for a signal, in particular a Time Marker Pulse (TMP) to move from some point A in one element of a system to some other point B in another element of the system. Ideally, if there was no transit time nondeterminism, an a priori measurement of all the transmit elements in the leader and all the receive element in the follower, plus the knowledge of the INU parameters of the Leader and the follower would be sufficient to correct the Follower's clock based upon information such as clock waveform and TMP from the Leader's clock.

Figure 1 shows an example of how the MOSA/SOSA approach addresses communications between two elements. The Timing signals can typically be expected to be embedded in Command-and-Control communications between the Leader and the Follower. The Timing Sensor receives the Leader's TMP pulse embedded in a reference clock and an associated time stamp after processing in the Leader, transiting between the Leader and the Follower antennas, and being processed by the Follower. To achieve Two-way time transfer, this process has to be performed in reverse.

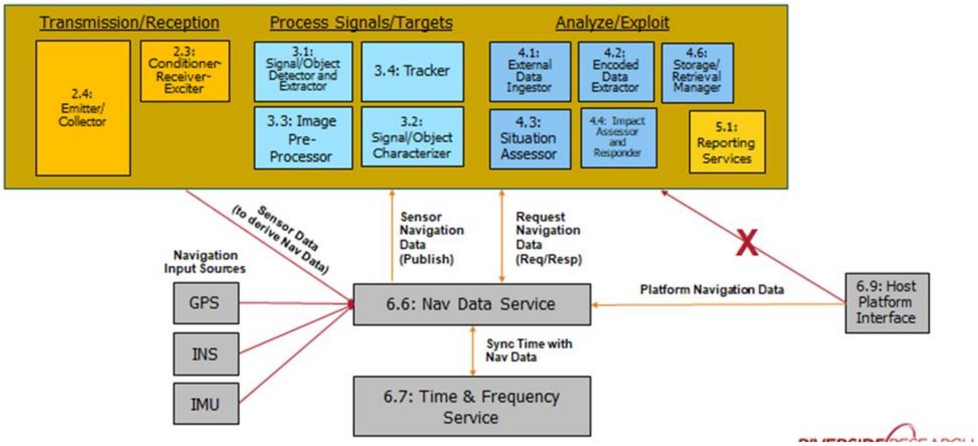


Figure 1
The Time and Frequency Service (Sensor), Element 6.7 in a typical SOSA structure (The Open Group, 2022b).

The entire signal chain between the Leader's TMP and the Follower's time stamp has a large number of elements with varying levels of nondeterminism. These include the processing time in the Leader up to and including the encryption, modulation, up-conversion and antenna feed, and similarly in reverse in the Follower, where, in addition there needs to be Doppler and Multipath correction and Forward Error Correction especially if there is fading. In MOSA/SOSA based systems there could be additional time delays associated with the parsing of incoming data streams to the Command and Control and various sensor elements.

2.4 White Rabbit Modification Approach

We approached our WR work in a two-pronged fashion. We needed to develop a system that met the SWaP-C requirements of the mission, would have the necessary interface capabilities for a SOSA type timing sensor element, and be able to be continuously upgraded as more advanced components became available. For this, we needed to recreate the critical elements of the WR internal structure. At the same time, we needed to understand the capabilities and limitations of the WR OTA block diagram. This work is described below.

3.0 White Rabbit Elements

WR was designed to use Gigabit Ethernet over a Single Mode Fiber (SMF) network and to use Synchronous Ethernet based communication to transfer clock information. WR, like PTP, uses a hierarchy of Master Clocks, Transparent Clocks and Boundary clocks in a tree like structure to distribute timing signals to the end elements, called Slaves. In order to most accurately transfer the clock waveform and time information, WR uses Serializer/Deserializers, Clock and Data Recovery circuits, and a Digital Dual Mixer Time Difference (DDMTD) version of the classic Dual Mixer Time Difference circuit to create a low jitter

Phase Frequency Detector for the Phase Locked Loops. Our systems will not necessarily use Gigabit Ethernet and will not be SMF based. Many of the elements are also available in COTS form, sometimes at lower cost and with higher performance. Our efforts to obtain the best performance at the lowest SWAP-C is continuing.

3.1 White Rabbit Internal Structure

The WR developers at CERN have made available all source code and software that they used to realize a Field Programmable Gate Array (FPGA)-based WR slave, found at the WRPC Open Hardware Repository (CERN, 2022a). This FPGA-based WR slave is referred to as the WR Precision Timing Protocol (WRPTP) core. A block diagram of the WRPTP core is shown in ***Figure 2***.

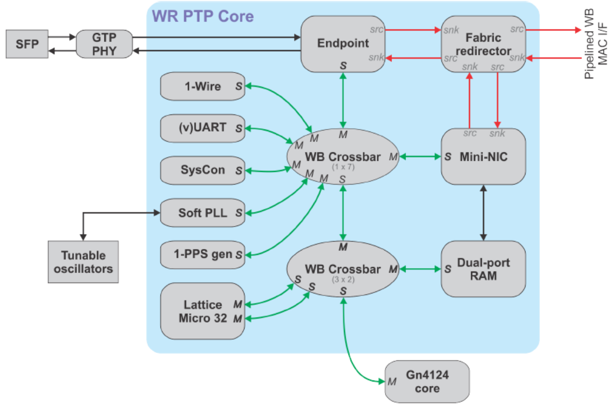


Figure 2
WR PTP Core (Daniluk, 2012)

Both timing and non-timing related data enters/exits the WRPTP core through the PHY (e.g., a Xilinx GTP transceiver) and is processed by the WR Endpoint. The WR Endpoint decodes/encodes the data and generates timestamps while interfacing with the Wishbone (WB) Crossbar to route clock signals to/from the Soft PLL for clock recovery. The Soft PLL and Tunable Oscillators are described in later figures. The Fabric Redirector separates timing data from regular data. Timing data is routed to the Mini-NIC while non-timing related data is sent to a pipelined WB interface to exit the core. The Lattice Micro 32 (LM32) is a processor implemented in the FPGA's programmable logic (PL) fabric which is used for lock detection and various system control functions, instructions for which are stored in and fetched from the Dual-port RAM (DPRAM). The 1-PPS generator generates the 1-PPS signal that should be precisely aligned with that of its master, thus reflecting the degree of synchronization. The 1-Wire, UART, SysCon, and Gn4124 modules are not directly relevant to WR functionality and therefore will not be elaborated upon further.

The vast majority of WR functionality is implemented in the FPGA's programmable logic, however complete functionality requires external components and hardware. In ***Figure 2***, it is shown that the Soft Phase Locked Loop (PLL) module interfaces with tunable oscillators external to the WR PTP Core. These external oscillators form a feedback loop with the Soft PLL module, shown in ***Figure 3***.

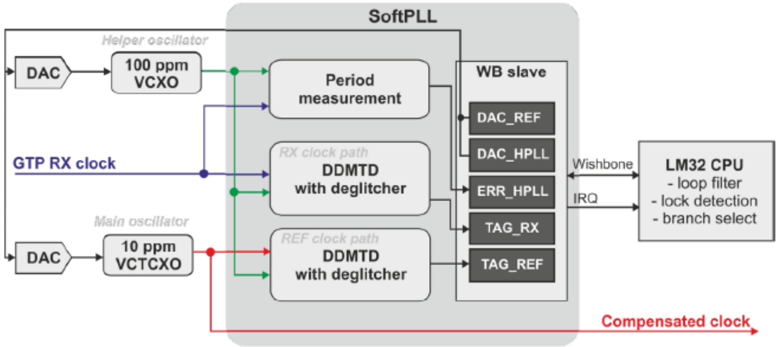


Figure 3
Soft PLL with External Feedback Loop (Daniluk., 2012)

A traditional PLL uses feedback to phase lock an oscillator to a stable reference signal. This is typically implemented using phase-frequency detectors (PFDs), loop filters, and voltage (or numerically) controlled oscillators (VCO/NCO) with the loop dynamics set by the designer. Both analog and digital PLL topologies are common. The WR Soft PLL utilizes a more sophisticated feedback mechanism to generate both the DDMTD clock and the Compensated clock. Loop control is handled in the LM32 processor, with instructions being sent to DACs that tune the Helper and Main oscillator to recover and produce required clocks. WR systems require very precise calibration, phase measurements, and compensation. Therefore, having a PLL that can be easily reconfigured via a firmware update eases hardware complexity and debugging.

The Helper oscillator, Main oscillator, and two DACs shown in ***Figure 3*** are external to the FPGA. Control logic in the LM32 soft core first calculates the necessary DDMTD frequency and tunes the Helper oscillator via a Serial Peripheral Interface (SPI)-controlled DAC. More detailed descriptions of these modules as well as the WR system are found in Daniluk (2012).

Dual-Mixer Time Difference (DMTD) has been a method of measuring picosecond time differences for decades, described in Allan & Daams (1975). Measuring the phase difference between two syntonized reference oscillators is a common DMTD application. DMTD utilizes a local oscillator slightly offset in frequency (e.g. 10 kHz offset from reference oscillators) fed to a downconverting mixer pair. The output is a beat frequency that still maintains the relative phase difference of the two reference oscillators. This permits PFD functionality to occur at much lower frequencies, being less expensive to measure and reducing the consequences of jitter. DDMTD is a clever digital realization of DMTD, able to be implemented entirely inside the FPGA fabric. Once proper DDMTD operation is established, miniscule phase differences can be more easily measured, and the Main oscillator is tuned to be phase synchronized to the recovered Ethernet Physical Interface (PHY) clock to form the Compensated clock.

3.2 Challenge and Solution

WR hardware developers implemented the feedback configuration with Commercial off the Shelf (COTS) PLLs, DACs, and Voltage Controlled Crystal Oscillator (VCXO)/Voltage Controlled and Temperature Controlled Crystal Oscillators (VCTCXOs) on custom Printed Circuit Boards (PCBs). WR’s large, complex, and custom PCBs, such as the SPEC Board (Seven Solutions, 2022b) or the FASEC Board (CERN, 2022b), are SWaP-C inefficient and therefore inconvenient to integrate into a wireless dynamic system. A WR implementation that utilizes commercial hardware (e.g., an FPGA development board) is beneficial for speed and ease of rapid prototyping a precision timing system. This idea falls short due to common FPGA development boards not being able to accommodate these DAC-Oscillator feedback configurations that WR relies on. However, there is a way to fully utilize an FPGA development board while minimizing the amount of custom hardware needed to achieve a functional WR solution. The way to do this is to design an FPGA Mezzanine Card (FMC) with the external COTS clocking components needed to close the control loop. The FMC with necessary components has been designed and can aid in future development of a SWaP-C efficient WR system.

3.3 Future Opportunities

We came to the conclusion that WR as implemented in CERN is not applicable as a focus for development of a WPTS system. However, individual components of WR that are common to most time synchronization systems could potentially be useful in future WPTS projects. WR core elements are FPGA-based and therefore very portable. Effort has shifted to using various blocks from the WR core such as the timestamping module, DDMTD, Serial/Deserializer (SERDES) calibration, etc. and exploring how they can enhance the functionality of COTS timing chips in an Over the Air (OTA) dynamic system. For example, the timestamping module could capture timestamps at various spots in a signal path and be useful for reducing the overall nondeterministic delays and latencies of a signal chain. The DDMTD module can be useful for measuring very fine phase differences, with the advantage of being contained entirely in an FPGA as opposed to expensive custom hardware. The SERDES module uses a custom wrapper for certain transceivers that are deemed suitable for WR operation. The suitability of a transceiver for WR operation is contingent upon various delays and latencies remaining constant once a link is established so they can be measured and calibrated out. Transceiver chips with varying delays and latencies (once the link is established) are not suitable for WR operation (CERN, 2019). These custom transceiver primitives could potentially be useful for calibrating out PHY delays and latencies, although modifications would likely be necessary.

4.0 White Rabbit Experiments

There are many manufacturers of WR equipment and devices that incorporate WR into their designs. Of the ones that we examined, a system available from Seven Solutions in Granada, Spain (now a division of Orolia) had the most complete set of elements from which we could fashion experiments to determine the applicability of a WR-like structure to our scenarios.

4.1 Seven Solutions-based White Rabbit Experimental Setup

The Seven Solution WR system (***Figure 4***) that we tested consisted of the following devices.

1. Seven Solutions Disciplined Oscillator White Rabbit (DOWR) GPS-disciplined oscillator as a time base
2. Seven Solutions WR-Switch – an 18-port White Rabbit switch configured as a grandmaster
3. Two slave nodes:
    a. Seven Solutions WR-ZEN time provider
    b. Seven Solutions WR-ZEN TP-FL time provider

In what follows, any reference to a WR element implies the corresponding Seven Solutions hardware.

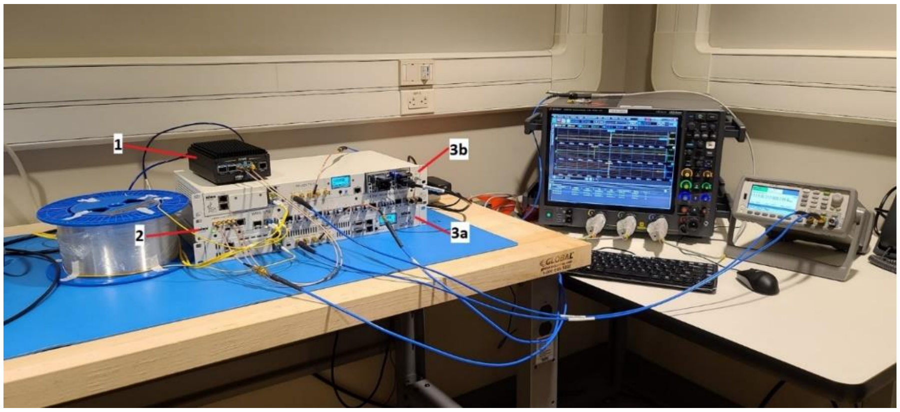


Figure 4
White Rabbit measurement setup (1: DOWR, 2: WR-Switch, 3a: WR-ZEN, 3b: WR-ZEN TP-FL)

The DOWR is a high-performance GPS grandmaster clock and network time server capable of distributing GPS time or UTC using WR, with sub-nanosecond accuracy over long-distance fiber links. According to the manufacturer, the DOWR is built as a white box solution, including timing integrity monitoring of the GPS navigation data. It provides raw GPS data for the calculation of a precise antenna position and for legal traceability to UTC(k) laboratories (Seven Solutions, 2022a). According to the manufacturer, the 18 port WR switch is capable of distributing time and frequency within a sub-nanosecond accuracy to thousands of nodes through standard optical fiber over Metro Area network distances and also to work as a 1 Gbps data switch (Seven Solutions, 2022c). The WR-ZEN time provider is a flexible stand-alone node that offers WR features for different applications with redundant connections for reliable performance in timing applications. According to the manufacturer, it combines ultra-stable clocks with low jitter and temperature compensated clock resources to enhance its synchronization (Seven Solutions, 2022d). The WR-ZEN TP-FL is, similarly to the WR-ZEN, a fundamental standalone node that provides WR time synchronization to a wide range of applications making use of its redundant connections. It distributes time and frequency to other equipment by implementing widely available timing protocols including PTP, NTP, 10MHz/PPS (Seven Solutions, 2022e).

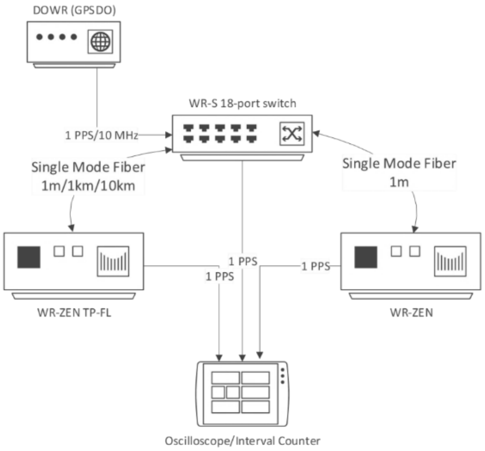


Figure 5
White Rabbit experimental setup.

The WR-ZEN and the WR-ZEN TP-FL were both configured as slave nodes and the WR-Switch was configured as grandmaster with 10 MHz and 1 PPS timing signals provided by the DOWR used as a timing reference. The two slave nodes allow for direct comparisons between different experimental setups, such as different SMF lengths or between an SMF connection and a SMF-OTA - SMF connection. Both a Keysight UXR-0134 oscilloscope and a Keysight 53230A time interval counter were used (***Figure 5***) to measure synchronization precision.

4.2 Measurements and Results with Various Fiber Lengths

We first verified that the WR system as configured in Figure 4 met the manufacturer's specifications for time synchronization. We then compared performance of the system using the manufacturer recommended single-strand Single Mode Fiber (SMF) 1310/1490 nm SFP transceivers and dual-strand SMF 1310 nm SFP transceivers. For this, we connected the WR-ZEN to the WR-Switch using the single-strand SMF 1310/1490 nm SFP transceivers and a 1 m SMF cable and the WR-ZEN TP-FL to the WR-Switch using the dual-strand SMF 1310 nm SFP transceivers and a 2 m SMF cable and compared the synchronization of the three devices (***Figure 6***). We found that regardless the SFP type used, the system was able to synchronize to within the manufacturer's specifications. The data (***Figure 7***) shows an advance of approximately 318 (±73) ps from the master for the node connected with the 2 m dual-strand SMF cable, compared to an advance of 73 (±57) ps from the master for the node connected with the 1 m single-strand SMF cable.

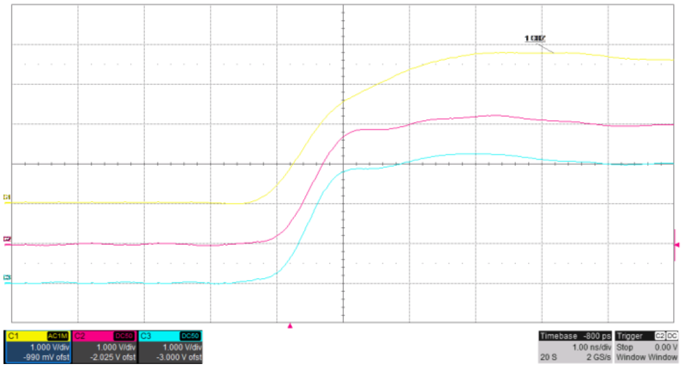
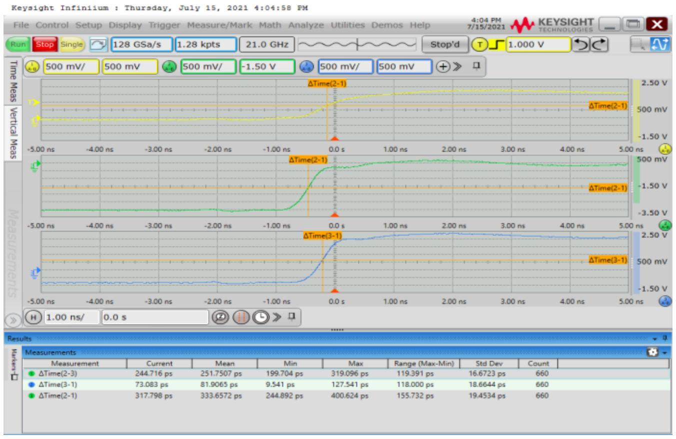


Figure 6

Comparison of performance of single-fiber SFP to dual-fiber SFP: WR-Switch [master] (yellow trace), WR-ZEN [single-strand] (magenta trace), WR-ZEN TP-FL [dual-strand] (cyan trace), 1 ns/div horizontal

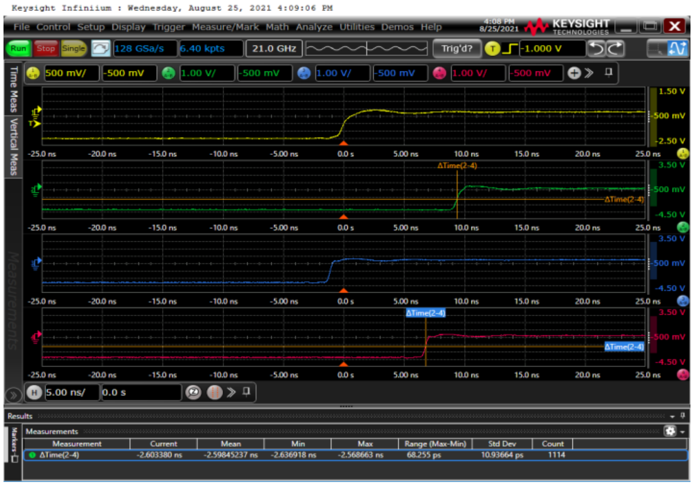


Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
ΔTime(2-3)	244.716 ps	251.7507 ps	199.704 ps	319.096 ps	119.391 ps	16.6723 ps	660
ΔTime(3-1)	73.083 ps	81.9065 ps	9.541 ps	127.541 ps	118.000 ps	18.6644 ps	660
ΔTime(2-1)	317.798 ps	333.6572 ps	244.892 ps	400.624 ps	155.732 ps	19.4534 ps	660

Figure 7

Comparison of performance of single-fiber SFP to dual-fiber SFP: WR-Switch [master] (yellow trace), WR-ZEN TP-FL [dual-strand] (green trace), WR-ZEN [single-strand] (blue trace), 1 ns/div horizontal

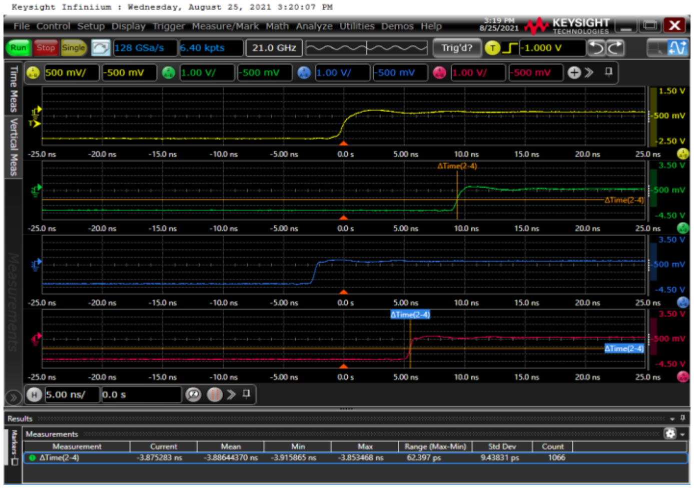
We then tested the system with SMF cables of 1 km and 10 km lengths comparing the synchronization to that of the 1 m SMF cable length. We observed that the offset in the 1 PPS and 10 MHz clock outputs of the slave nodes was linearly proportional to the length of the connecting fiber. When connected with a 1 m SMF cable, the WR-ZEN shows an offset of 2.6 ns (±34 ps) advanced from the master clock (***Figure 8***). At 1 km, this advance increases to 3.9 ns (± 31 ps) [+1.3 ns from 1 m] (***Figure 9***). At 10 km, the advance is 16.3 ns (± 29 ps) [+13.7 ns from 1 m] (***Figure 10***)). Using the (E-A)/E definition of error, this amounts to a 6% deviation from linear. This behavior is observed regardless of which device is connected to the longer cable and regardless the instrument being used to measure the time difference. It is unclear what is causing this behavior.


Keysight Infiniium : Wednesday, August 25, 2021 4:09:06 PM

Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
ΔTime(2-4)	-2.603380 ns	-2.59845237 ns	-2.636918 ns	-2.568663 ns	68.255 ps	10.93664 ps	1114

Figure 8

Clock alignment between master (WR-Switch) and slave (WR-ZEN TP-FL) [1 m]: yellow trace – master PPS, green trace – master 10 MHz, blue trace – slave PPS, magenta trace – slave 10 MHz

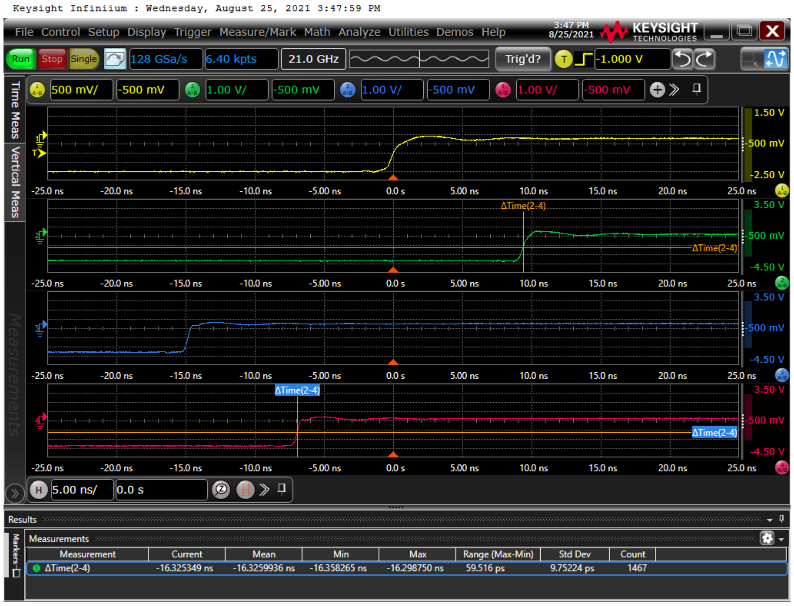

Keysight Infiniium : Wednesday, August 25, 2021 3:20:07 PM

Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
ΔTime(2-4)	-3.875283 ns	-3.88644370 ns	-3.915865 ns	-3.853468 ns	62.397 ps	9.43831 ps	1066

Figure 9

Clock alignment between master (WR-Switch) and slave (WR-ZEN TP-FL) [1 km]: yellow trace – master PPS, green trace – master 10 MHz, blue trace – slave PPS, magenta trace – slave 10 MHz

It is clear that the WR can indeed performs sub-ns time synchronization at 10 km. Recent announcements from the manufacturer indicate that performance at lengths of >1,000 km have been demonstrated. From the perspective of our application, this implies that if there is a static system need that can be satisfied with SMF, then sub-ns results can indeed be obtained with a WR setup.



Keysight Infiniium : Wednesday, August 25, 2021 3:47:59 PM

Measurements

Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
ΔTime(2-4)	-16.325349 ns	-16.3259936 ns	-16.358265 ns	-16.298750 ns	59.516 ps	9.75224 ps	1467

Figure 10

Clock alignment between master (WR-Switch) and slave (WR-ZEN TP-FL) [10 km]: yellow trace – master PPS, green trace – master 10 MHz, blue trace – slave PPS, magenta trace – slave 10 MHz

4.3 OTA WR Experiments and Results

OTA Experimental Setup. Gilligan et al. (2020) have shown that OTA synchronization using White Rabbit is feasible. Our goal was to build an OTA system, (***Figure 11***), to study possible extensions to our applications of interest. We identified a Gigalink E-band transceiver from Renaissance Electronics HXI division that operates at 72 GHz and has SERDES and Clock and Data recovery functions and performs up and down-conversion but does not modulate the Gigabit Ethernet waveform. Though susceptible to temperature and atmospheric effects, the E band was chosen due to it being in an FCC unlicensed band. The relatively short (approx. 100 m) link distance allows later experiments to be performed to (a) determine the feasibility of an RF connection to the antennas for applicability to our missions, (b) build locally manageable systems with omni-directional antennas, as opposed to the very directional HXI transceiver, also with a view towards our applications, and (c) determine the system design changes needed for operation at frequency ranges presently of interest. This OTA test was a first step.

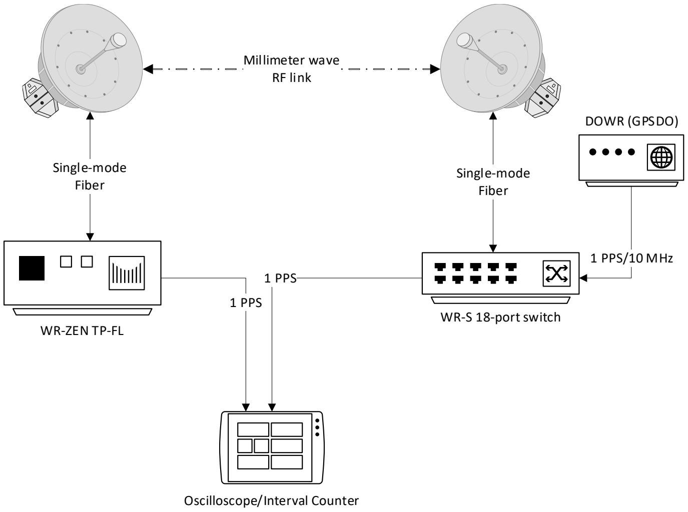


Figure 11

White Rabbit OTA experimental setup

The optical data input received by the transceiver is converted into an amplitude modulated electrical waveform and amplified. The resulting waveform is the digital baseband data waveform and has a data rate of 1.25 Gb/s. The waveform then goes through a signal-conditioning block, after which it is up-converted to 72 GHz before being passed to the power amplifier and sent to the antenna. When the RF mm-wave signal reaches the receiver, it is routed through a low-noise amplifier and mixed down to baseband. The resulting waveform is passed through an anti-aliasing low pass filter and amplified before being converted to an optical signal for transport over fiber. The SMF cables from the two transceivers are approximately 100 m in length each.

Experimental Results. Our initial results exceeded expectations, with short-term (~10-minute averaging period) synchronization stability (***Figure 12***) having an absolute range of 74 ps (-48 ps to 25 ps phase difference from master), with a standard deviation of 14 ps. For the purposes of this test, the absolute mean difference between master and slave is less important than the stability (i.e., variance in successive measurements), and while this test had an excellent mean difference of about 6.65 ps between the master and the slave clocks, this value is somewhat arbitrary as an offset calibration can bring the two clocks into close agreement. The results were similar when we swapped the slave device connected with the RF link (***Figure 13***); the absolute range of the phase difference from the master was 75 ps with a standard deviation of 14.3 ps. Both of these results were achieved with fair weather and an atmospheric temperature of about 10°C. Looking at long term stability of synchronization, we compared the phase offset of a slave clock from the master clock over a 12-hour period with the OTA RF link compared to the phase offset of a slave clock from the master clock with an optical fiber connection over the same time period. The weather was fair with a stable temperature of 14°C-17°C over the whole time period. As can be seen (***Figure 14***), the synchronization over RF link was relatively stable, with a downward drift of about 10 ps on average over the course of the test, compared to no appreciable drift in the slave connected with optical fiber.

Measurements

Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
ΔTime(1-2)	264.989 ps	239.51306 ps	199.741 ps	280.189 ps	80.448 ps	15.52548 ps	2016
ΔTime(1-3)	3.926 ps	6.65428 ps	-28.959 ps	45.318 ps	74.276 ps	14.77872 ps	2016
ΔTime(2-3)	-261.063 ps	-232.85878 ps	-272.996 ps	-187.579 ps	85.418 ps	17.05131 ps	2016

Figure 12

Comparison of WR performance with optical and RF links (yellow trace: master, green trace: optical fiber, blue trace: mm wave RF)

Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
ΔTime(1-2)	-22.339 ps	-29.51961 ps	-65.856 ps	9.271 ps	75.127 ps	14.30692 ps	1540
ΔTime(1-3)	306.755 ps	320.00382 ps	275.060 ps	351.099 ps	76.040 ps	14.65024 ps	1540
ΔTime(2-3)	329.094 ps	349.52344 ps	306.310 ps	380.549 ps	74.238 ps	15.70132 ps	1540

Figure 13

Comparison of WR performance with optical and RF links swapped (yellow trace: master, green trace: mm wave RF, blue trace: optical fiber)

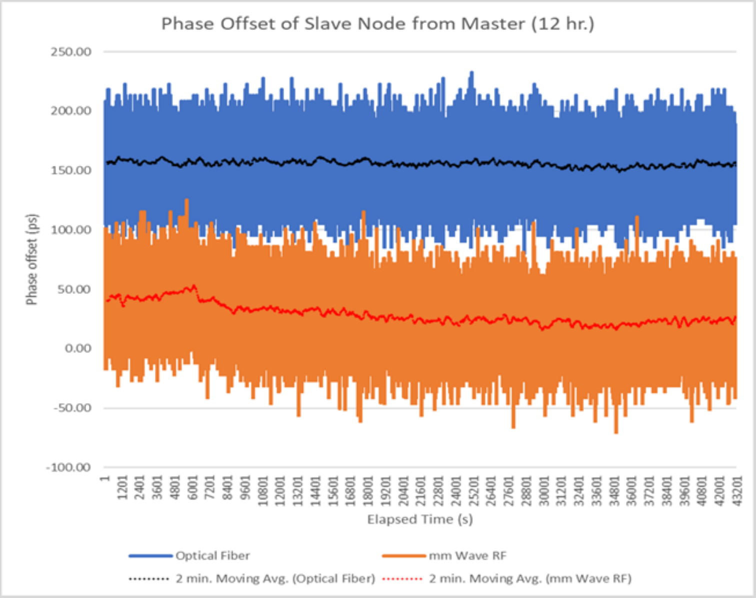


Figure 14

Long-term Stability of WR synchronization over RF link compared to optical fiber

Follow-on measurements showed more variation. As can be seen (***Figure 15***), the synchronization over RF link was relatively stable, with an upward drift of about 10 ps on average to about the 48-hour mark, when it increases sharply, by about 50 ps for about 24 hours, before returning to its previous level. This compares to no appreciable drift in the slave connected with optical fiber. This was verified by analyzing the long-term Allan deviation of the synchronization of the two datasets (OTA and optical fiber), where the drift in the OTA results can be seen in the result and the convex shape of the time deviation curve, while the results from the optical fiber connection show the expected linear relationship and a value of ~3e-10/τ (***Figure 16***). Even with the observed drift, the synchronization error stays under 350 ps over the whole 72-hour test. We conclude that in a static environment using a direct Ethernet connection over RF (as opposed to Wi-Fi), WR can achieve its advertised sub-ns synchronization.

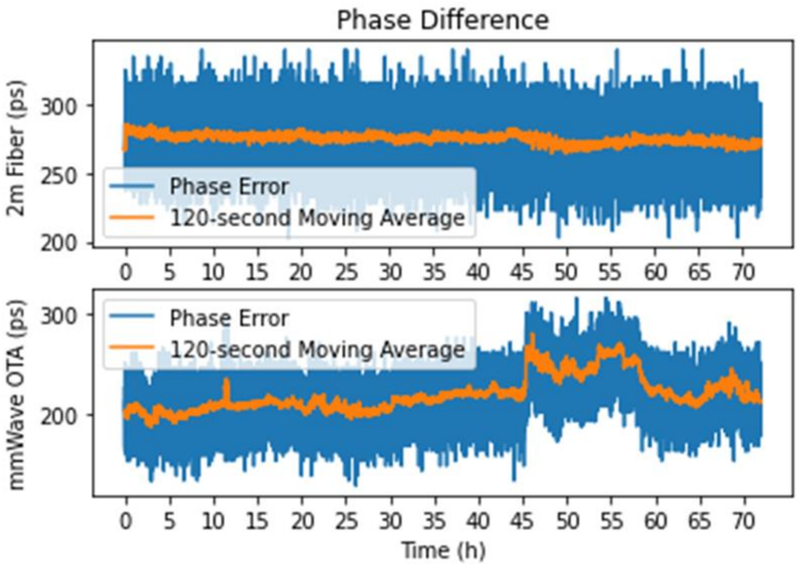


Figure 15

Long-term Stability of WR synchronization over RF link compared to optical fiber

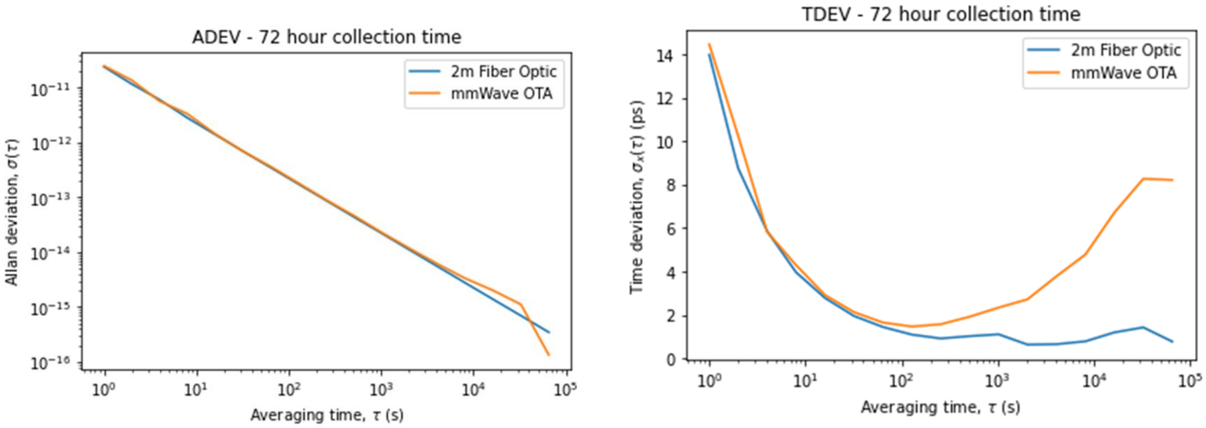


Figure 16

Allan and Time deviation of WR synchronization over RF link compared to optical fiber

4.5 Environmental effects

We originally hypothesized that the drift seen in the OTA synchronization data might be due to atmospheric and weather effects on the RF link connecting the WR master and slave node. However, a detailed statistical analysis performed using all 4083 possible combinations of the 12 weather factors available was unable to find any statistical significance in the correlation between weather and synchronization, with even the best model showing an extremely weak significance of $r_{adj}^2 = 0.33$ and $C_p = 211.6$. Further analysis showed that any appearance of periodicity or significant autocorrelation in the synchronization data disappears when examining the discrete derivative of the data using the forward difference operator. We thus theorize that the drift seen in the synchronization data is due to random effects in the RF transceivers.

5.0 APPLICABILITY OF WR IN OTA AND DYNAMIC WPTS

Our primary goal was to determine if and how the WR architecture could be extended to first static and then to dynamic WPTS, and to identify the elements within WR that could be used in such an extension. It is clear from our data that WR under certain circumstances could indeed be extended to static OTA applications to provide sub-ns precision time synchronization. We list some of our key conclusions on the applicability based on our experiments.

1. The Seven Solutions equipment we used, as previously described, was based on 1 Gbps ethernet over fiber. There has been work reported on 10 Gbps solutions , but there was no complete solution when this work was done.
2. Our measurements indicate that whether connected via SMF or a combination of SMF and OTA, the synchronization was within Seven Solutions specification. It is clear that the correction itself could effectively have a Follower leading a Leader by several or tens of ns.
3. The E-band frequencies used in the OTA testing was used primarily because it was a frequency range that needed no spectral licensing. This required very directional antennas, which minimized multipath. When used in military missions with omnidirectional antennas at other frequencies, Doppler, Multipath, and other effects will need to be considered.
4. In addition to the factors above, in operating systems with MOSA/SOSA based elements, if the time synchronization signal path is also shared by the mission communication functions, there will be significant non-determinism added. The methods to mitigate this and achieve WR comparable or better performance are being studied.

6.0 CONCLUSIONS

As a result of our WR core replication efforts and experimental measurements we have been able to draw the following conclusions.

1. For WPTS in general and dynamic WPTS in particular, WR cannot easily be modified. However, many components used in WR are indeed candidates for dynamic WPTS.
2. In complex operations where APNT cannot be taken for granted a more general Leader –Follower approach is needed. This is a focus of our present work.
3. It will be necessary to focus more on COTS based designs to achieve SWaP-C reduction. Already COTS PLLs have shown femtosecond type total jitter compared to nanosecond type jitter.
4. It will be critical to devise methods to minimize the effects of non-determinism to achieve ps and sub-ps accuracy. This too is the focus of our present work.

REFERENCES

Allan, D.W. & Daams, H. (1975). Picosecond Time Difference Measurement System, *29th Annual Symposium on Frequency Control*, pp. 404-411, doi: 10.1109/FREQ.1975.200112.

Aslam, M., Liu, W., Jiao, X., Haxhibeqiri, J., Miranda, G., Hoebeke, J., Marquez-Barja, J., & Moerman, I. (2022). Hardware efficient clock synchronization across Wi-Fi and ethernet-based network using PTP. *IEEE Transactions on Industrial Informatics*, *18*(6), 3808–3819. https://doi.org/10.1109/tii.2021.3120005

Bergeron, H., Deschenes, J.-D., Sinclair, L. C., Swann, W. C., Khader, I., Baumann, E., & Newbury, N. R. (2017). Doppler-tolerant synchronization of clocks over free space at the femtosecond level. *2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*. https://doi.org/10.1109/fcs.2017.8088823

Celano, T., Warriner, J., Francis, S., Gifford, A., Howe, P., & Beckman, R. (2007). *Two-way time transfer to airborne platforms using commercial satellite modems* [White Paper]. Symmetricom, Inc. https://www.microsemi.com/document-portal/doc_download/133191-two-way-time-transfer-to-airborne-platforms-using-commercial-satellite-modems

CERN. (2019, February 12). *White rabbit specification (latest version) · Wiki · Projects / White Rabbit Standardization*. Open Hardware Repository. https://ohwr.org/project/wr-std/wikis/Documents/White-Rabbit-Specification-(latest-version)

CERN. (2022a, April 11). *Wrpc core · Wiki · Projects / White Rabbit core collection*. Open Hardware Repository. https://ohwr.org/projects/wr-cores/wiki/wrpc-core

CERN. (2022b, November 9). *Home · Wiki · Projects / FPGA and ARM SoC FMC Carrier FASEC*. Open Hardware Repository. https://ohwr.org/project/fasec/wikis/home

Charbonneau, A., Douglas, R., & Gertsvolf, M. (2018). Traceable time dissemination with NTP. *Proceedings of the 49th Annual Precise Time and Time Interval Systems and Applications Meeting*. https://doi.org/10.33012/2018.15621

Daniluk, G. (2012). *White Rabbit PTP core: the sub-nanosecond time synchronization over Ethernet* [Unpublished master's thesis], Warsaw University of Technology.

Gilligan, J. E., Konitzer, E. M., Siman-Tov, E., Zobel, J. W., & Adles, E. J. (2020). White Rabbit time and frequency transfer over wireless millimeter-wave carriers. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, *67*(9), 1946–1952. https://doi.org/10.1109/tuffc.2020.2989667

Government Accountability Office. (2022). *GPS alternatives: DOD is developing navigation systems but is not measuring overall progress*. (GAO Publication No. 22-106010). Washington, D.C.: U.S. Government Printing Office.

IEEE. (2019). *IEEE standard for a precision clock synchronization protocol for networked measurement and control systems* (IEEE Std 1588-2019). https://doi.org/10.1109/IEEESTD.2020.9120376

Koppang, P., & Wheeler, P. (1998). Working application of TWSTT for high precision remote synchronization. *Proceedings of the 1998 IEEE International Frequency Control Symposium (Cat. No.98CH36165)*. https://doi.org/10.1109/freq.1998.717916

Levine, J. (2008). A review of time and frequency transfer methods. *Metrologia*, *45*(6). https://doi.org/10.1088/0026-1394/45/6/s22

The Open Group. (2022a). *SOSA (Sensor Open Systems Architecture) business guide edition 1.0*. https://publications.opengroup.org/

The Open Group. (2022b) *SOSA reference implementation guide*. https://publications.opengroup.org/

Seven Solutions. (2022a). *DOWR*. https://sevensols.com/dowr/

Seven Solutions. (2022b). *SPEC Board*. https://sevensols.com/spec/

Seven Solutions. (2022c). *WR Switch*. http://sevensols.com/wr-switch/

Seven Solutions. (2022d). *WR-ZEN TP*. https://sevensols.com/wr-zen-tp/

Seven Solutions. (2022e). *WR-ZEN TP-FL*. https://sevensols.com/wr-zen-tp-fl/

Wlostowski,,T. (2011). *Precise time and frequency transfer in a White Rabbit network* [Unpublished master's thesis], Warsaw University of Technology.