Enhanced Synchronization Accuracy in IEEE1588

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***Abstract*— Various applications require or can benefit from high accuracy of synchronization between networked elements. The White Rabbit (WR) project includes enhancements to the now widespread IEEE1588 Precision Time Protocol (PTP) to support supplying synchronization in the sub-nanosecond level.**

The WR solutions for achieving enhanced accuracy of synchronization are being studied and analyzed within the work of the High Accuracy sub-committee (SC) of the P1588 Working Group (WG). The work of the High Accuracy SC aims at adding optional protocol features for supporting WR enhancements, and their possible generalizations.

The sub-ns accuracy of synchronization achieved in WR can be attributed to mechanisms and methodologies that enhance PTP in two aspects: (1) identification of various contributors of asymmetries in the PTP two-way time transfer, and definition of measurements and calibrations to compensate for their effects, and (2) achieving higher precision in the timestamping of PTP event messages which results in precise roundtrip measurement and precise determination of the offset between master and slave clocks.

We first outline the contributions of the above-mentioned aspects to achieving a high accuracy PTP network. We then analyze and formulate in detail the utilization of the Layer-1 (L1) signals for the second aspect. These L1 signals, that are available within the PTP link, are used to enhance synchronization accuracy in general and in particular the timestamping precision. We specify the conditions under which enhanced accuracy is achieved in WR and suggest various possible generalizations.

Keywords—synchronization, accuracy, precision, White Rabbit, phase detection, syntonization, IEEE1588, SyncE

I. INTRODUCTION

The P1588 Working Group (WG) [1] is working on a new revision of IEEE1588. The High Accuracy subcommittee (SC) within P1588 is studying the White Rabbit (WR) [2] extension to PTP [3], as a valuable reference demonstrating the ability to achieve sub-nanosecond accuracy of synchronization [4].

This article first presents what have been distinguished as high accuracy dependencies, based on the different aspects of the original White Rabbit protocol. Then, terms used throughout the article, and discussed within the work of the High Accuracy SC, are defined to facilitate further explanations. The article concentrates on aspects facilitated by the utilization of L1 signals. It is discussed how the usage of L1 signals contributes to both enabling precise event message timestamping, and supporting stable and accurate syntonization between PTP nodes.

II. HIGH ACCURACY DEPENDENCIES

Clock synchronization in a PTP network is achieved by minimizing the measured offset between slave clocks and their master (offsetFromMaster). The offset is measured by a two-way message transfer. For example, when using the delay request-response mechanism[1], both the egress of the Sync message from master and ingress to slave are timestamped; similarly the Delay_Req message is timestamped both on egress from slave and ingress to master. These four timestamps enable solving for the mean path delay, and the offset from the master as observed by the slave.

Achieving a network-wide high accuracy of synchronization is strongly dependent on the ability to achieve high accuracy in a single PTP link. It is important to remember that in a typically hierarchical PTP network the inaccuracy introduced on a PTP link may accumulate over the network from the grandmaster to the leaf slaves.

The level of accuracy on a PTP link depends on addressing the following aspects depicted in Fig. 11:

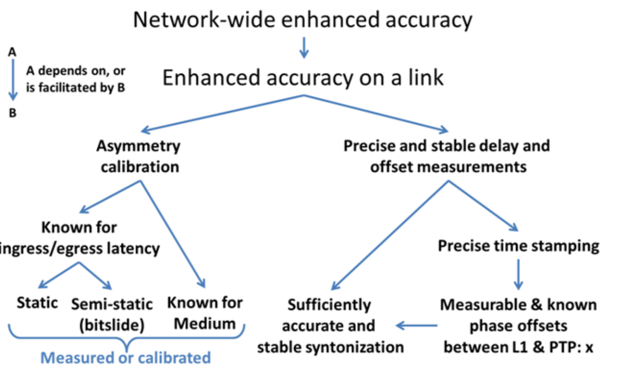

Fig. 1. High accuracy dependencies.

[1] For simplicity the paper refers only to the delay request-response mechanism. Generalization to address the peer delay mechanism is feasible.

A. Precise and stable delay and offset measurement

Maintaining a high level of synchronization between a slave and a master clock requires the ability to precisely know that the offset between them (offsetFromMaster) remains at a sufficiently low level at all times. In order to precisely know the offsetFromMaster it is required to precisely measure the observed delays of the PTP messages during the PTP message exchange. It also requires the ability to know the level of change of the offset, during and between PTP message exchanges.

The precision of delay measurements depends on the resolution and precision of timestamps which usually introduce several nanoseconds of jitter (imprecision) in the synchronization process. The delays relevant to PTP calculations are those observed "on the wire" (observed L1 propagation delays). Therefore, precise timestamping requires knowledge about any possible phase offset between the L1 signals used for transmission and reception of messages in the medium and the PTP clocks. WR achieves picoseconds level of timestamping precision through appropriate utilization of the Digital Dual Mixer Time Difference (DDMTD) phase detection [5] between relevant clock signals.

Since the PTP mechanism enables the measurement of delays and observed offsets only during message exchanges, knowledge about the offset dynamics is required in order to know their size in between measurements. A high level of physical syntonization between the clocks facilitates maintaining a high level of synchronization at all times, specifically in between PTP-based offset measurements. The syntonization performance may also affect the precision of the delay measurements, as the changes in the values during the message exchange may hamper the accuracy of the delay measurements.

B. Asymmetry calibrations

Precise and accurate knowledge of the asymmetries introduced within various parts of a PTP link is required to correctly determine the offsetFromMaster from mean path and one-way delay measurements. In many cases these asymmetries can be either considered constant, or at least changing slowly enough to be considered constant within the PTP measurement intervals. The asymmetries are both device-dependent and medium-dependent, giving two groups of asymmetry contributors. Achieving high accuracy requires knowledge of both of them:

- **Ingress and egress latency asymmetry** is introduced by the difference of delays in the different hardware components within the transmission and reception paths. White Rabbit accounts for this asymmetry through the online measurement of bitslide [6] and a system-wide calibration procedure [7].
- **Medium asymmetry** is introduced by the difference of propagation delays within the two directions in the medium. White Rabbit provides a method to estimate this asymmetry for a single-mode single fiber used as a bidirectional medium [8].

III. TERMS USED IN THIS ARTICLE

Discussing accurate synchronization requires a precise language. This section provides basic terms that will be used throughout this article (always in *italic*).

A **PTP node** is used to mean a PTP-capable network element that acts as a Boundary, Ordinary or Transparent Clock. A *PTP node* can have several **PTP ports.**

A **Clock signal** provides frequency and phase. It is represented by a physical signal that has periodic events (e.g. an oscillator output). The events mark the significant instants at which a time counter is incremented.

A **Time counter** maintains a digital time representation, increased at each event of the *clock signal* by period of the *clock signal*.

A **Clock** provides time at desired instances of the timescale it maintains. It is either:

- **Physical**: this type of *clock* is modeled as a *clock signal* and a *time counter* that is driven by the *clock signal*;
- **Mathematical**: this type of *clock* is generated by a model that describes the relation of this *clock* to another *clock* (e.g. to a *physical clock* in a different timescale). The model enables the calculation of the time of the *clock* from the time of the other *clock*.

The time maintained by a *clock* can be adjusted by alterations to the period of the *clock signal* driving it (**frequency steering**), or by direct updates of the digital value of the *time counter* (**phase jumping**).

A **clock in coherent operation** is used to refer to a *clock* of which the timescale is currently maintained only by frequency steering and without phase jumping. Utilization of phase jumping causes discontinuities in the observed delays and offsets between clocks. A phase jump applied in the master node may instantaneously increase the offsetFromMaster as observed in the slave. Unless noted otherwise, this paper considers only clocks during coherent operation[2].

A **Local PTP clock signal** drives the *time counter* used within a *PTP node* for the generation of the PTP time observations[3].

A **Local PTP clock** provides the PTP time. It is the *clock* of a *PTP node* that provides the local estimate of the time of its grandmaster, i.e. it is synchronized to the time of the grandmaster.

A **L1 clock signal** provides the L1 frequency and phase. It is the *clock signal* that is used by the physical elements (e.g. PHYs) in the transmission or reception of data over the medium. **L1 tx clock signal** is used in the transmission of data; **L1 rx clock signal** is recovered from the reception of data[4].

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[2] Non-coherent operation may be required during non-steady state synchronization operation (e.g. for decreasing the observed offsetFromMaster during initial stages of adjusting the slave clock).

[3] The observations can be seen as time snapshots; two events spaced in time within the same period of the *clock signal* will observe the same PTP time. The observations can be either direct snapshots of the *local PTP time* or indirect estimations of *local PTP time* generated via the mathematical model from direct observations of a non-synchronized *clock* (based on a local oscillator).

[4] In this paper it is assumed that the nominal frequency of the *L1 clock signal* is equal to the *local PTP clock signal* within the *PTP nodes*. Generalizations to when this is not the case may be made.

If the short term rate of phase accumulation attributed to *clock signals* or *clocks* is equal within a period (up to an inaccuracy whose effect on performance can be neglected as specified in context of the desired applications), these *clock signals* or *clocks* are considered **syntonized** in that period.

Port transmit coherency exists if the *L1 tx clock signal* at a port of a node and the *local PTP clock* of the node are syntonized.

Port receive coherency exists if the *local PTP clock* of a node and *L1 rx clock signal* at a port of the node are syntonized. For example, in WR *port receive coherency* is achieved by deriving the *local PTP clock signal* from the *L1 rx clock signal* recovered on a slave port; this slave port is synchronized to a port on which *port transmit coherency* exists.

Node-to-node coherency exists among nodes if the *local PTP clocks* of the nodes are *syntonized*. For example, this can be achieved by deriving the *local PTP clock* of a node from the *L1 rx clock signal* transmitted by another node that is *port transmit coherent*.

Port congruency exists if the timing flow of L1 syntonization (details in the following sections) and PTP synchronization is the same at a port, i.e.

- Slave port congruency: the *local clock* is syntonized by the *L1 rx clock signal* of the port, the recommended port state is PTP slave, and and *local PTP clock* is or will be synchronized via this port;
- Master port congruency: the *L1 tx clock signal* of the port is syntonized by the *local clock*, the recommended port state is PTP Master, and the *local PTP clock* is or will be distributed via this port;

Bitslide is the delay resulting from any bit-level misalignment between the *L1 rx clock signal* recovered from the serial bit stream and the serial word border. While the parallel word (upon which the timestamp is generated) is aligned with the *L1 rx clock signal*, the actual timestamping point is aligned with the serial word border, resulting in a *bitslide*. As an example, for Gigabit Ethernet, it is the phase offset between the ”edge” of the 8b/10b symbol and the edge of the *L1 clock signal* (with which the 8 bit parallel word is aligned) as depicted in Fig. 2.

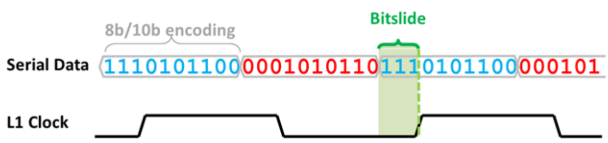

Fig. 2 Bitslide.

IV. PTP CLOCK SYNTONIZATION

The ability of a *PTP clock* to consistently and accurately know the current PTP time depends on the way syntonization between the PTP slave and its master is maintained, and the resulting syntonization performance.

Maintaining syntonization in a network of connected clock elements is an application that was addressed in telecommunication networks a long time ago in order to support time division multiplexing data transfer. Syntonization in these networks uses the data transmission signals. An example can be International Telecommunication Union (ITU) recommendations (e.g. ITU G. 781 [9]) that provide descriptions and specifications on syntonization in Synchronous Digital Hierarchy (SDH) networks. The ITU G.8264 [10] expands this concept to support syntonization within packet data networks by utilization of the L1 signals within L2 Ethernet links (this is termed Synchronous Ethernet or SyncE).

When PTP is used for time transfer in a packet network where elements are syntonized using L1 signals, the syntonization of the *PTP clock signals* can take advantage of the available L1 syntonization. This technique is used in the ITU recommendation G.8275 [11] that assumes in the timing architecture that all intermediate PTP nodes have a physical layer frequency support.

Another approach to syntonization utilizes the rate of change of the observed offsetFromMaster to estimate the frequency offset between master and slave clocks. By minimizing the observed frequency offset, the PTP slave syntonizes to its master. A similar mechanism is used in the ITU recommendation 8265.1 [12] that defines a PTP profile for supporting frequency transfer (i.e. syntonization) in PTP networks. It should be noted that for the purpose of syntonization only a one way PTP message transfer is required.

The syntonization of PTP clocks via PTP can be facilitated by protocol transfer of supporting information. For example the 802.1AS standard [13] defines the rateRatio which is transferred between neighboring *PTP nodes* along the synchronization path. It is used in determining the frequency offset of the local *physical clock* from the desired *local PTP clock* which is usually a *mathematical clock*.

It is important to note that the nominal frequencies used within the L1 transmission and reception signals are generally several orders of magnitude higher than the message exchange rates used in PTP time transfer. Therefore, syntonization mechanisms utilizing L1 information have a much higher rate of phase offset information available for syntonization. Consequently, high performance of syntonization can be achieved while using reference frequencies generated by simple and cheap oscillators. On the other hand, the performance of the PTP-based syntonization on a PTP link, in-between the PTP message exchanges, is highly dependent on the characteristics of the *local PTP clock signals* in the two *PTP nodes*. If stable oscillators are used in both nodes, the frequency offset between them varies slowly and enables achieving relatively high syntonization performance; however a low stability reference may cause a frequency offset between the two nodes which may accumulate to a significant time difference between PTP offsetFromMaster measurements.

In WR, a high level of syntonization accuracy is achieved by basing the *local PTP clock* on the *L1 clock signal* (in a manner ensuring *node-to-node coherency*); with the L1 syntonization tree being congruent to the PTP time distribution tree [4]. This enables maintaining accurate syntonization without utilization of high stability local oscillators in the *PTP nodes*.

V. PRECISE DELAY AND OFFSET MEASUREMENTS

Enhancing the precision of the PTP delay and offset measurements is being addressed in the work of the P1588 High Accuracy SC on the optional feature which is currently termed *Layer-1 based synchronization performance enhancement* (L1SynOp). An appropriate implementation that supports sufficient resolution and precision of timestamps is a key requirement to the enhanced precision measurements. However, it was recognized that protocol support may facilitate this process. The protocol may support the ability of interconnected *PTP ports* to agree on configuration and ensure a proper state that enables the enhancement. The protocol may be used to transfer additional information between the nodes to facilitate the enhancement mechanisms.

In this section we introduce the idea of enhancing timestamp precision. We present a reference model that describes the signals involved in the precision enhancement of delay and offset measurements on a single link, and define the conditions under which enhancement is achieved in WR. We follow by suggesting several different cases where enhancements under more generalized conditions may be useful, and we outline optional protocol information that may facilitate such enhancements.

A. Enhancing timestamp precision

PTP timestamps should be observations of the times when ingress and egress event messages cross the reference plane made with the *local PTP clock*. Usually, timestamp generation is implemented by taking a snapshot of the *time counter* driven by the *local PTP clock signal*. However, the message frames are received/transmitted using the *L1 clock signal* that, in general, is different from the *local PTP clock signal*. This may result in a timestamping imprecision that amounts up to the L1 signal period. For example, if the frequency of the *PTP and L1 clock signals* is 125MHz, the *time counter* has a resolution of 8ns. Misalignment between the *clock signals* may cause a comparable size of imprecision in the individual PTP timestamps. It is possible to enhance the timestamping precision if the phase offset between the *local PTP* and *L1 clock signals* can be measured with a sufficiently increased resolution. In general, the performance level of such phase measurements is expected to depend on the dynamics of the phase offset (i.e. its variation in time). In the simplest case, the phase offset is effectively constant which enables to use a long observation window for the measurement. A constant phase offset means that the *local PTP and L1 clock signals* are *syntonized*. This is the condition under which the DDMTD is utilized in WR. It is expected that a slowly changing phase offset may decrease the precision of the DDMTD-based offset measurement but will still enable to get meaningful and useful value. Note that sufficiently fast variation of the phase offset can be also used to enhance timestamping precision via averaging of multiple measurements; this is a substantially different technique with different types of performance benefits; it is not addressed in this paper.

B. Reference Model

The idea of enhancing PTP timestamping precision is modeled for a two-way message transfer over a PTP link. Fig. 3 depicts such a link between two *PTP nodes*. In each node, three clock signals are distinguished: *local PTP clock signal* (clk_{PTP_A}, clk_{PTP_B}), *L1 Tx clock signal* ($clk_{L1\_Tx\_A}$, $clk_{L1\_Tx\_B}$), and *L1 Rx clock signal* ($clk_{L1\_Rx\_A}$, $clk_{L1\_Rx\_B}$).

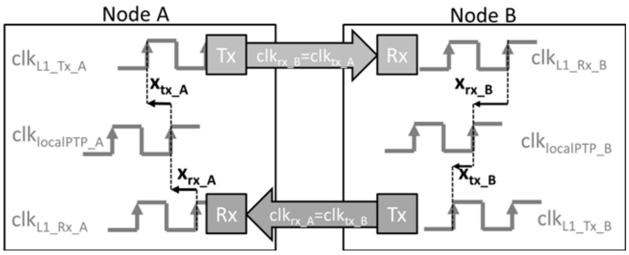

Fig. 3. Precise delay measurement reference model.

The transmission circuit (Tx) of *Node A* is connected to the reception circuit (Rx) of *Node B*, and vice versa. Consequently, thanks to the clock and data recovery (CDR) circuit in each receiver, the frequency of the *L1 rx clock signal* in *Node B* is effectively equal to the frequency of the *L1 tx clock signal* in *Node A* ($clk_{L1\_Rx\_A}$ *and* $clk_{L1\_Tx\_B}$ respectively), and vice versa (i.e. they are *syntonized*). The phase offset between the rising edge of the *local PTP clock signal* and the transmission *L1 tx clock signal* is marked as $x_{Tx\ A}$ and $x_{Tx\ B}$ for *Node A* and *Node B* respectively. The phase offset between the rising edge of the reception *L1 rx clock signal* and the *local PTP clock signal* is marked as $x_{Rx\,A}$ and $x_{Rx\,B}$ for *Node A* and *Node B* respectively.

The fine part (sub-period of the *clock signal*) of the observed delays can be calculated when the values of all the phase offsets, i.e. x_{Tx_A}, x_{Tx_B}, x_{Rx_A}, and x_{Rx_B}, are known for the appropriate instances (i.e. the transmission and reception times of the relevant event messages). Therefore, both nodes participating in the communication path need to "know" their phase offsets. The slave must be informed about the phase offsets of the master. "Knowing" can take different forms. For example, if the *L1 rx clock signal* is used directly for the PTP timekeeping ($clk_{PTP} = clk_{L1\ Rx}$), their phase offset can be assumed to be zero (i.e. $x_{Rx} = 0$)[5]. Similarly, if the *local PTP clock signal* is used directly to encode the transmitted data (i.e.$clk_{PTP} = clk_{L1\_Tx}$), the phase offset between the *PTP and L1 clock signals* is known to be zero (i.e. $x_{Tx} = 0$). If not known by design, the phase offset must be measured or derived through utilization of other available information.

The reference model enables the enhancement of PTP precision under the following conditions:

- The two *PTP Nodes* on the link are directly L1 connected.
- The implementation is capable of knowing the phase offset between *PTP and L1 clock signals* with a sufficient precision in the expected working conditions.
- The *PTP slave node* is provided with the values of phase offsets by the *PTP master node*. These values can be directly used by the master node to update the PTP timestamps.

It is the intended task of the protocol mechanisms currently being developed within L1SynOp to facilitate meeting these conditions within the PTP link.

[5] The value of x_{Rx} and other respective values are assumed zero for simplicity. They may actually be non-zero constant values due to internal propagation delays. These constants are accounted for by the appropriate calibrations.

C. *High accuracy application examples*

The following sections discuss various conditions and/or application that can benefit from enhancing the precision of synchronization. First a White Rabbit link is examined, then achieving high accuracy under more generalized conditions is considered.

1) *White Rabbit*

This section applies the *reference model* to White Rabbit (in parentheses conditions previously defined):

- Both nodes use the *local PTP clock signal* for the data transmission (clk_{PTP} = $clk_{L1\ Tx}$), therefore the transmission phase offsets are known to be zero (x_{Tx} = 0). (**Port transmit coherency)**
- The *PTP slave node* uses its recovered *L1 clock signal* for driving the *local PTP clock signal* (clk_{PTP_B}) (**Port receive coherency, Port congruency)** but phase shifts it to achieve phase alignment with the desired phase of the *local PTP clock*. The reception phase offset on the *PTP slave node* is known (according to the applied phase shift): x_{Rx} = *set_point*.
- The *PTP master node* measures (using the DDMTD phase detector [5]) its reception phase offset: x_{Rx} = *DDMTD_measurement*.
- The *PTP slave node* is assured that all the phase offsets are known after successfully accomplishing the *WR link setup procedure* [8].
- The *PTP master node* utilizes its reception phase offset (x_{Rx}) to correct the t4 timestamp, including the fractional nanosecond part in the correction field.

2) *Indirect L1 syntonization*

Fig. 4 shows a grandmaster *PTP node* A connected to two *PTP nodes*, B and C, that are synchronized and syntonized to the grandmaster. There is a direct link between nodes B and C that is currently redundant within the synchronization and syntonization spanning trees. The *local PTP clock signal* of node B is not physically syntonized to the *L1 rx clock signal* recovered on its West interface. Neither is the *local PTP clock signal* of node C on its East interface. However, the *local PTP clock signals* of both nodes are syntonized through their parallel direct syntonization to the grandmaster. We say that nodes B and C are indirectly syntonized. Therefore a precise round-trip measurement is possible on such an indirectly syntonized link provided the reference model requirements from section V.B are fulfilled.

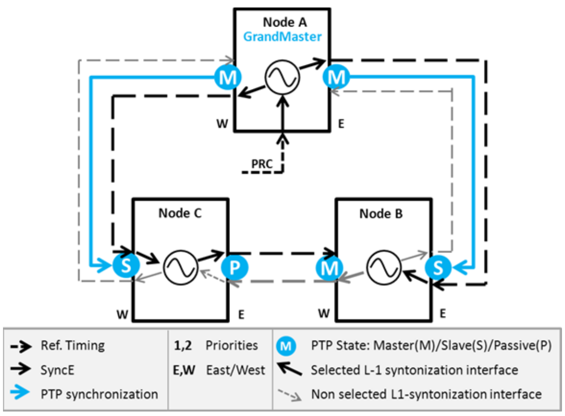

Fig. 4. Indirect syntonization on a redundant and "passive" link.

3) *(Non-) congruency & (Non-) coherency between L1 syntonization and PTP synchronization*

Non-congruency between the L1 syntonization spanning tree and the PTP synchronization spanning tree can be useful in a number of cases. One example scenario is described below. An existing ITU-T SyncE network is partially upgraded to support High Accuracy PTP, as depicted in Fig. 5. Two nodes in the network are replaced with PTP HA-capable devices (blue). The HA installation provides synchronization between a Primary Reference Time Clock (PRTC) at the Experiment headquarters and the experimental installation base station at another site. It is not desired that the addition of the PTP time transfer causes changes in the network syntonization spanning tree (red) of the operational SyncE network. Therefore, it is required to provide synchronization for the HA installation via the non-congruent HA links, e.g. the link between the HA grandmaster at the Experiment installation headquarters and the HA node in the SyncE network. The grandmaster uses the SyncE L1 clock signal (red) to distribute its PTP time (blue), i.e. the local PTP clock of the HA grandmaster. It measures the relation between the blue and red clock signals. This information is then distributed to the other HA nodes to facilitate recreating the blue PTP time along the HA synchronization path (dashed blue and red line). Finally, the experimental base station is synchronized to the blue PTP time of the HA grandmaster.

It is worth noting that the frequency distributed over a standard SyncE network is usually traceable to a Primary Reference Clock (PRC). PRC specifications only ensure that the long term frequency offset from the PTP timescale is up to 1 part in 10^{-11}. Therefore, the *L1 clock signals* may not be fully coherent to a *local PTP clock signal* of a *physical PTP clock* maintaining time in the PTP HA nodes.

It should be noted that enhancing performance in an ITU SyncE network may be hampered by L1 signal dynamics due to possible L1 syntonization tree rearrangements. The possible effect of these rearrangements on the ability to enhance accuracy needs to be determined and is not addressed in this article.

In general, enhancement of accuracy requires the rate of change of the phase offset between the PTP (blue) and L1 (red)

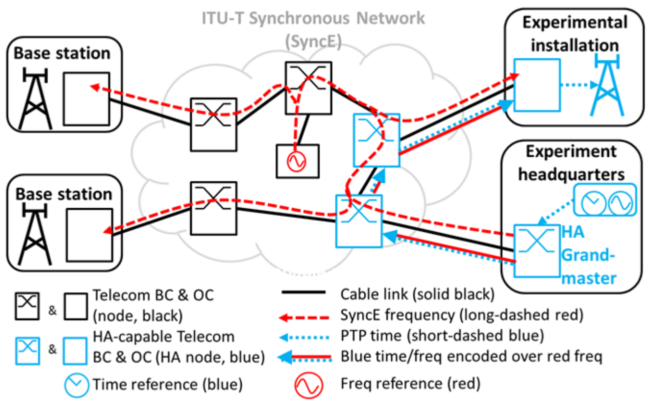

Fig. 5. Telecom synchronous network partially upgraded to high accuracy

clock signals to be small enough to enable meaningful phase detection.

4) High Accuracy in a multi-domain PTP network

The example given in the previous section is a specific case where two different synchronization networks may be deployed over the same packet data network (the SyncE syntonization network and experimental HA PTP network). The design of the PTP protocol enables several independent PTP synchronization networks to be deployed over a shared physical network, each in a separate domain. The timescale in each domain is maintained by its grandmaster.

The *local PTP clocks* of different grandmasters show current times that are different to some level, even if the grandmasters are attempting to maintain the same timescale. For example, two grandmasters synchronized using separate GPS receivers are expected to be off by tens of nanoseconds. Similarly, some level of a frequency offset is expected to exist between the *local PTP clocks* of these grandmasters.

As discussed before, L1 syntonization can supply a high level of syntonization between *PTP nodes*. However, only a single physical frequency can be transferred through a network and used to directly syntonize only a single PTP *domain*. However, the knowledge about the phase offset between the *PTP clock signal and the L1 clock signal* may be used to facilitate enhancing timestamping precision in several different PTP domains. Maximum flexibility to support this application and others can be made possible by enabling enhanced accuracy links in both non-congruent and non-coherent conditions. Such flexibility and multi-domain HA synchronization may be facilitated by exchanging phase and frequency offset parameters, as described in the next section.

D. Phase and frequency offset parameters

Enhanced precision and other applications (diagnostics, Research & Development, etc.) may be facilitated by utilization of the L1 signals shared between the *PTP node* connected in a link. It may be further useful for such applications to enable the nodes to share their knowledge about the relations between their *local PTP clock* and *L1 tx clock signal*. The following two parameters convey this information:

1. **Phase offset (x_{tx})** – a value that indicates the phase-difference between the desired timestamping time at the reference plane, and a sampling time aligned to the local PTP clock (Fig. 3). In general, it is time varying and the time for each known value should be supplied.
2. **Frequency offset (ΔF_{tx}) –** a value indicating the known rate of change of the Phase offset that can be expressed e.g. in nanoseconds per second. In general, it is time varying and the time for each known value should be supplied.

A node receiving the values x_{tx}, ΔF_{tx} for a time $t(x_{tx})$ may use the Frequency and Phase offset parameters to approximately correct a timestamp taken at another time t(1) as if it was taken at the reference plane, even if the transmitting node does not perform such a correction itself. The level of approximation will depend on the accuracy of such an extrapolation in the specific system. A node receiving the values of ΔF_{tx} for a time t(ΔF_{tx}) may use the Frequency offset value and the received *L1 rx clock signal* to generate a *local PTP clock* approximately syntonized to the *local PTP clock* of the transmitting node. The level of approximation will depend on the stability of ΔF_{tx} within the specific system.

VI. CONCLUSIONS & FUTURE

This paper analyzed and attempted to generalize the various aspects involved in enabling the White Rabbit solution to achieve sub-ns accuracy of synchronization. A reference model that is useful in analyzing and understanding the L1 contribution to enhancement of synchronization accuracy was defined. Various applications of accuracy enhancements under more generalized conditions were suggested.

Future work on high accuracy enhancements can address an in-depth study of relative and absolute calibrations of asymmetries. Precise knowledge of asymmetries is needed to leverage enhanced precision into enhanced accuracy. Further research, case-studies and implementations of the generalized accuracy enhancements are desired.

The P1588 High Accuracy Subcommittee, which is a collaboration of specialists from different backgrounds, is working on defining extensions to PTP that may be useful in a variety of generic applications. The intended protocol tools are aimed at supporting different implementations to enhance the accuracy of synchronization, and enabling interoperable implementations. It is still to be decided which of these tools and generalizations are deemed applicable for standardization. Finding a trade-off between complexity, generality, and sufficiently widespread applicability in real-world conditions is one of the interesting challenges in the work of the P1588 WG.

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