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Evaluation of Precision Time Synchronisation Methods for Substation Applications

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***Abstract*—Many substation applications require accurate time-stamping. The performance of systems such as Network Time Protocol (NTP), IRIG-B and one pulse per second (1-PPS) have been sufficient to date. However, new applications, including IEC 61850-9-2 process bus and phasor measurement, require accuracy of one microsecond or better. Furthermore, process bus applications are taking time synchronisation out into high voltage switchyards where cable lengths may have an impact on timing accuracy. IEEE Std 1588, Precision Time Protocol (PTP), is the means preferred by the smart grid standardisation roadmaps (from both the IEC and US National Institute of Standards and Technology) of achieving this higher level of performance, and integrates well into Ethernet based substation automation systems. Significant benefits of PTP include automatic path length compensation, support for redundant time sources and the cabling efficiency of a shared network. This paper benchmarks the performance of established IRIG-B and 1-PPS synchronisation methods over a range of path lengths representative of a transmission substation. The performance of PTP using the same distribution system is then evaluated and compared to the existing methods to determine if the performance justifies the additional complexity. Experimental results show that a PTP timing system maintains the synchronising performance of 1-PPS and IRIG-B timing systems, when using the same fibre optic cables, and further meets the needs of process buses in large substations.**

***Index Terms*—Ethernet networks, IEC 61850, IEEE 1588, performance evaluation, power transmission, protective relaying, Precision Time Protocol, smart grids, time measurement**

I. INTRODUCTION

The ‘smart grid’ is defined as an umbrella term for technologies that are an alternative to traditional practices in power systems, offering improved reliability, flexibility, efficiency and reduced environmental impact [1]. Much of the smart grid focus has been in electricity distribution, however smart grid applications are now being proposed for the transmission sector. Improved disturbance recording and state estimation through phasor measurement is a goal of the transmission smart grid [2], and a networked process bus improves power network visibility by simplifying the connections required for advanced monitoring systems [3].

Time synchronisation is required in substations for consistent event time-stamping when investigating power system incidents and for some long distance protection schemes [4]. More accurate time-stamping, in the order of 1 µs, is now required for phasor monitoring and for digital process buses [5]. New time synchronisation systems, such as IEEE Std 1588 Precision Time Protocol (PTP) [6], are a means of achieving the high level of performance required by these new applications [7], [8].

Substation automation systems generally use IRIG-B [9] and Network Time Protocol (NTP) [10] for distribution of absolute time [11]. One pulse per second (1-PPS) provides an accurate synchronisation reference, but does not include time of day information. IRIG-B and 1-PPS are unidirectional and do not compensate for propagation delay [12]. NTP and PTP are bidirectional network based systems that compensate for network delays. PTP provides master clock traceability and support for redundant master clocks.

The International Electrotechnical Commission (IEC) Smart Grid Vision and US National Institute of Standards and Technology (NIST) standardisation ‘roadmaps’ both recommend the use of PTP for high accuracy time synchronisation in substations [13], [14]. PTP also provides flexibility in its implementation. The IEEE Std C37.238 ‘power system profile’ [15] specifies how PTP will be used for power system applications by restricting options and mandating additional data to be transmitted, and is recommended by the NIST roadmap. The same Ethernet network infrastructure can therefore be used for substation protection, monitoring and control, and for time synchronisation. This is of particular benefit when the timing system is installed in a large switchyard.

There is a need to consider the performance of established substation timing techniques to see whether these meet the requirements for synchrophasors and process buses, and then to see what additional benefits a PTP system will provide, and at what cost. This paper describes a series of experiments to measure performance of 1-PPS,

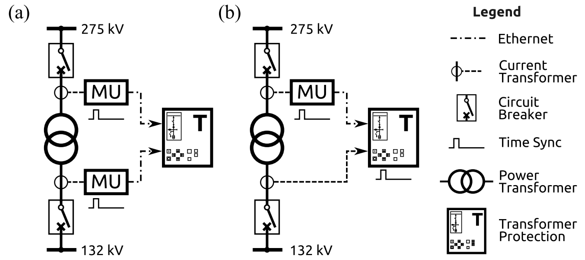

Figure 1. Transformer differential protection with (a) two merging units and (b) one merging unit and one conventional input.

IRIG-B and PTP using the same communications media, and using the same substation clock devices.

II. BACKGROUND

A. Substation Application

The high voltage equipment in a substation (for example bus bars, circuit breakers, isolators, earth switches, power transformers, current transformers and voltage transformers) is referred to as the ‘primary plant’. The control equipment in a substation is termed the substation automation system (SAS), and includes protection, control, automation and monitoring devices. A ‘process bus’ carries sampled value measurements and status information from the primary plant to the SAS, and conveys commands from the SAS to the high voltage circuit equipment (e.g. circuit breakers and transformer tap change controllers), over a digital network. Merging units (MUs) sample the output of conventional current transformers and voltage transformers and transmit this information over the process bus. Secondary converters (SCs) convert the proprietary output of Non-Conventional Instrument Transformers (such as optical or electronic transducers) into a standard form that then connects to the SAS. IEC 61850-9-2 defines an interoperable format for the sampled value output of MUs and SCs using a process bus [16].

Some protection schemes, in particular transformer protection, require inputs from either two or more MUs/SCs, or from process bus and conventional analogue inputs. Intelligent electronic devices (IEDs) require that the current/voltage samples are synchronised. Any synchronising error (regardless of method used) will manifest as phase error, and this in turn gives ‘spill current’ in differential protection schemes, increasing the chance of false tripping. Fig. 1 shows two example configurations where this is required.

IEC 61850-9-2 specifies the requirements for an interoperable process bus. This standard provides significant flexibility in its implementation. The UCAIug Implementation Guideline, commonly referred to as ‘9-2 Light Edition’ (9-2LE), was developed to provide a reduced set of options to simplify implementation and to improve multi-vendor interoperability [17].

Table I

SAMPLED VALUE TIME ACCURACY CLASSES FROM IEC 61850-5.

Protection Class	Required Accuracy	Edition 1 Timing Class	Edition 2 Timing Class
P1	±25 μs	T3	TS3
P2	±4 μs	T4	TS4
P3	±1 μs	T5	TS5

B. Synchronisation Requirements

Process buses based on IEC 61850-9-2 must meet sampling accuracy requirements specified by IEC 61850-5 [18]. Table I lists the timing classes from IEC 61850-5 ed.1 that are relevant to process bus networks, along with the proposed classes in a draft of IEC 61850-5 ed.2. Protection class P2 is intended for transmission substation bays and class P3 for transmission substation bays with high accuracy requirements. Class P1 is for distribution substations.

9-2LE specifies that one pulse per second (1-PPS) timing pulses with an accuracy not exceeding ±1 μs be used to synchronise MUs and SCs. Up to 2 μs of propagation delay in the synchronising signal is permitted without the need for compensation, giving an overall synchronising error range of –1 μs to +3 μs. This meets the requirements of the T4/TS4 class and allows for some sampling error within the MU or SC. If the propagation delay exceeds 2 μs then location specific compensation is required at the MU or SC, and some manufacturers support this in product available on the market today.

A widely adopted standard for phasor measurement, IEEE Std C37.118, specifies a maximum Total Vector Error of 1%, taking into account phase and magnitude [19]. If there is no magnitude error this equates to ±26 μs for a 60 Hz power system and ±31 μs for a 50 Hz power system [5]. Magnitude errors, especially those from instrument transformers, must be allowed for, and so it has been generally agreed that the synchronising accuracy will be no worse than ±1 μs.

Outdoor transmission-level substations (typically 110 kV and above) cover a large area, and cable lengths can be significant [8]. IRIG-B can be distributed over copper or fibre optic cables, however the amplitude modulated code used with coaxial cable does not have the accuracy required for process bus synchronisation.

Cable runs of 300–500 m are not uncommon in transmission substations, particularly those operating at 275 kV and above [20]. Signal propagation speeds are generally specified in two ways: metallic cables with a velocity factor (VF) specified as a percentage of the speed of light in a vacuum, while for glass fibre, propagation speed is specified in terms of the refractive index of the glass. A Cat 5 twisted pair Ethernet cable has a VF $\approx 66\%$ and multimode silica glass fibre optic cable has $n \approx 1.5$ [21].

In each case the unit delay is very close to 5 ns/m. A cable run 500 m long would result in propagation delays in excess of 2.5 µs, requiring the connected MUs or SCs to be compensated. The compensation of each MU/SC will differ, and require detailed knowledge of cable lengths or measurement with an Optical Time Domain Reflectometer (OTDR).

C. *Absolute Time Transfer*

The 9-2LE guideline only requires synchronisation (relative time) of MUs or SCs, and not the time of day (absolute time). This is adequate for simple process bus networks where IEDs are installed in substation control rooms, and are provided with absolute time via IRIG-B or NTP. Absolute time is required in the switchyard for several new applications.

The first of these is the adoption of information security standards such as IEC TS 62351-6 that are intended to prevent tampering and replay-attacks of sampled value messages [22]. This level of security will likely be required when process bus connections are used for revenue metering and will take the place of security seals on conventional connections. Absolute time, using the IEC 61850 *UTCtime* type, ensures each sampled value message has a limited lifetime. The 9-2LE guideline does not include absolute time, but this is an optional attribute in IEC 61850-9-2 (*RefrTm*, attribute 4).

Utilities are starting to install IEDs in the switchyard using suitable protective enclosures. This reduces the size of control rooms and the field cabling required. Synchrophasors require absolute time to enable comparison of measurement between substation, and PTP is the only Ethernet based system that achieves the required accuracy.

III. METHOD

This section describes the experiments that determined the 'benchmark' performance of 1-PPS and IRIG-B, as well as PTP performance. Three lengths of fibre optic cable were used to evaluate the effect of propagation delay on synchronising performance. Actual fibre lengths were determined by the printed length markers on the cable sheath.

The test method used is an established means of assessing synchronising accuracy of clocks, and is based on 1-PPS electrical outputs of master and slave clocks. A digital oscilloscope (Tektronix DPO2014) sampling at 10^9 samples/s calculated the time difference (which is referred to as 'Master-Slave Offset' in these results) between the reference (master) and slave over a 30 minute period. A computer recorded each measurement (1800 in total for each test) for statistical analysis which is presented in Section IV. Fig. 2 shows this general arrangement, with the 'cloud' representing the various synchronising methods under test, and Fig. 3 shows accumulated 1-PPS waveforms for one test where PTP was used for synchronisation.

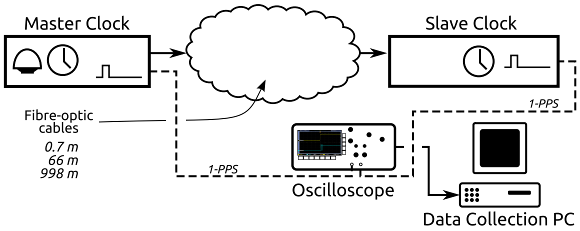

Figure 2. Test equipment used for accuracy testing, using a digital oscilloscope to measure pulse delays. Three lengths of fibre optic cable were used (0.7 m, 66 m and 998 m).

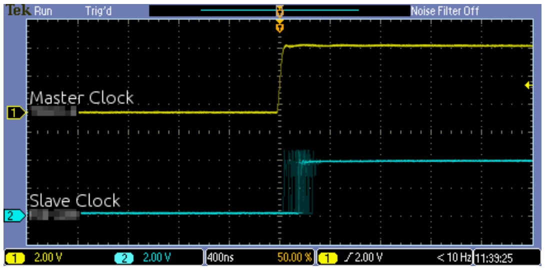

Figure 3. Screen capture of 1-PPS waveforms on the oscilloscope used for measurement.

A range of fibre optic cable lengths were used to simulate the variation in distance that occurs in a transmission substation. A short jumper cable (0.7 m long) was used to assess delays in clock outputs and provided the baseline time for comparing changes in propagation delay. The 66 m cable represents connections within a substation control room or an indoor substation, and the 998 m cable represents a large outdoor substation. Matched length coaxial cables were used to connect the 1-PPS output of the clocks to the oscilloscope.

A. *One Pulse Per Second*

The Master A clock transmitted an identical 1-PPS signal on its electrical output and its optical output. A fibre optic receiver was used to regenerate an electrical signal from the received light pulse after it had travelled through the three lengths of fibre optic cable. The short jumper cable enabled any delays introduced by the optical receiver to be measured.

B. *IRIG-B*

Two master clocks were used to transmit IRIG-B messages using the 'B002' code. The optical output of Master A was used directly to drive the fibre. The other clock (Master B) required a fibre optic transmitter to inject the IRIG-B signal into the fibre optic cables. The same fibre optic receiver used for 1-PPS testing was used to convert the optical IRIG-B signal to an electrical form that was suitable for decoding by the slave clock.

C. *Precision Time Protocol*

The settings required by IEEE Std C37.238 were used by all PTP devices, even though they did not explicitly

Table II
PTP SETTINGS USED FOR EVALUATION TESTS.

Parameter	**Setting**
Sync Message Rate	1 s
Announce Message Rate	1 s
Path Delay Mechanism	Peer to Peer
Path Delay Rate	1 s
Line Rate	100 Mb/s
Message Type	Layer 2 Multicast

support this profile, and are given in Table II. A PTP transparent clock (TC) was required by one of the master clocks as it had a copper 100BASE-TX Ethernet connection. The TC was used with the other master to ensure consistency. The PTP slave clock had a 100BASE-FX optical interface and was connected directly to the fibre optic cable.

The Master A and Master B clocks used for IRIG-B timing were PTP capable, and were used as the grandmasters (GMs) for these experiments. The IRIG-B slave clock also supported PTP and was used to generate a 1-PPS output based on the incoming PTP timing messages.

IV. RESULTS

Table III summarises the synchronising performance of the three methods tested. Delays are normalised to those of the 0.7 m cable to highlight the effect of path length, and are shown as the mean $\left(\Delta\overline{t_d}\right)$ and standard deviation (s_{t_d}). The 1-PPS and IRIG-B results are very close to the predicted delay, with some variation expected as the refractive index of the fibre optic cable was an estimate.

Table III
SYNCHRONISING PERFORMANCE RESULTS FOR THE THREE METHODS UNDER TEST.

Method	**66 m Fibre**	**998 m Fibre**
Predicted Delay	$t_d = 330\,ns$	$t_d = 4493\,ns$
1-PPS	$\Delta\overline{t_d} = 351\,ns$ $s_{t_d} = 0.561\,ns$	$\Delta\overline{t_d} = 5048\,ns$ $s_{t_d} = 1.23\,ns$
IRIG-B Master A	$\Delta\overline{t_d} = 361\,ns$ $s_{t_d} = 52.3\,ns$	$\Delta\overline{t_d} = 5054\,ns$ $s_{t_d} = 52.0\,ns$
IRIG-B Master B	$\Delta\overline{t_d} = 352\,ns$ $s_{t_d} = 24.6\,ns$	$\Delta\overline{t_d} = 5015\,ns$ $s_{t_d} = 25.6\,ns$
PTP Master A	$\Delta\overline{t_d} = 0.904\,ns$ $s_{t_d} = 73.6\,ns$	$\Delta\overline{t_d} = -1.62\,ns$ $s_{t_d} = 52.1\,ns$
PTP Master B	$\Delta\overline{t_d} = 21.2\,ns$ $s_{t_d} = 26.8\,ns$	$\Delta\overline{t_d} = 34.1\,ns$ $s_{t_d} = 30.0\,ns$

A. *One Pulse Per Second*

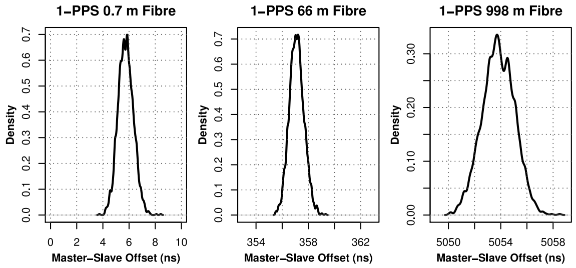

Figure 4. One pulse per second (1PPS) synchronising performance with three lengths of fibre optic cable.

Fig. 4 shows the statistical distribution of time difference between the 1-PPS receiver (slave) and transmitter (master) for the three lengths of fibre. Density on the *y*-axis of the graphs represents the probability distribution of the offset, and is effectively a continuous histogram. The reference delay is 5.8 ns, and this shows that the fibre optic receiver does not introduce a significant delay to the timing pulse. The increase in jitter of approximately two times with the 998 m fibre is of interest. This is most likely due to modal dispersion, as the pulse is monochromatic (wavelength of 850 nm) and multimode fibre was used [21].

The 1-PPS synchronising method yields timing pulses with little jitter, with a standard deviation of less than 2 ns for 1000 m of fibre optic cable. The need for compensation is apparent in Fig. 4, with average delays exceeding 5 µs when a 998 m fibre optic cable is used.

B. *IRIG-B*

Fig. 5 shows the IRIG-B synchronising performance with two master clocks. As with 1-PPS, the mean delay varies linearly with cable length. There is more jitter, and the standard deviation with IRIG-B is approximately 120 times that of 1-PPS. A second IRIG-B master clock was used with the original slave to look for device dependent performance variation. Master B has less jitter in the observed delay than Master A, however the distribution is bimodal.

The bimodal nature of IRIG-B synchronisation with Master B was confirmed with a time series plot, as the same distribution may have been created by a step change in the delay. The two minute time series extract in Fig. 6 shows that the 1-PPS delay between the slave and master periodically increases by 50–100 ns. The mechanism for this bimodality is unknown, as the design of the IRIG-B master device is not published by the manufacturer. A possibility is a periodic correction of a phase locked loop.

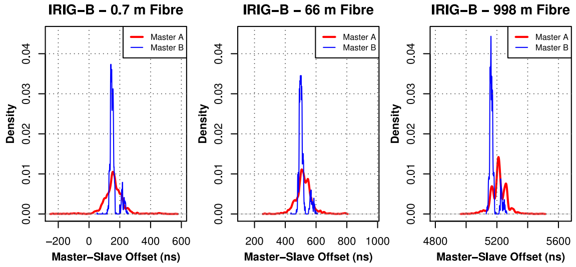

Figure 5. IRIG-B synchronising performance with three lengths of fibre optic cable and two master clocks. The same slave clock was used for all tests.

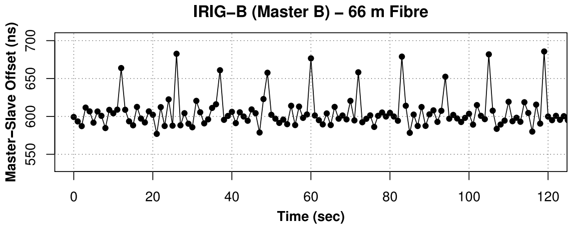

Figure 6. Time series of IRIG-B synchronising performance for Master B with 66 m of fibre optic cable.

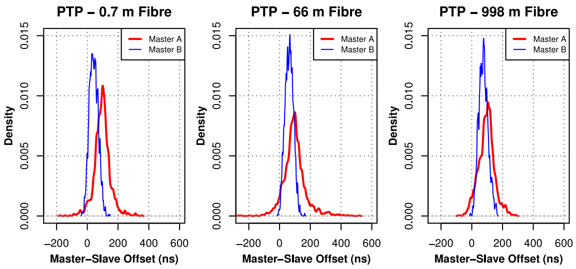

Figure 7. PTP synchronising performance with two grandmaster clocks, each with three lengths of fibre optic cable. The same slave clock was used for all tests.

De Dominicis *et al.* found the majority of IRIG-B pulses in their system were in a 50 ns range [23], whereas the best results presented here (Master B) have an approximate range of 150 ns. The clocks used in this experiment were specifically designed for substation applications and used low cost crystal oscillators (XOs) and temperature compensated crystal oscillators (TCXOs).

C. Precision Time Protocol

Two series of tests were conducted using PTP for synchronisation; one each with the two GM clocks. Fig. 7 shows the synchronising performance with Master A and Master B. As was the case with IRIG-B, Master B (TCXO local oscillator) gave much better performance than Master A (XO local oscillator), with reduced jitter. The results shown in Table III and Fig. 7 demonstrate that path delay compensation was effective with PTP, but there were device dependent fixed offsets in observed delays.

A conventional two-port switching media converter was used in place of the TC to assess the requirement for sophisticated networking equipment. 1-PPS synchronising errors in excess of 14 µs were observed. Media converters are often two-port switches, and should not be overlooked in a PTP network. This confirms that all active Ethernet devices in a peer-delay PTP network need to support the peer-delay mechanism required by IEEE Std C37.238.

V. DISCUSSION

Table III shows that the mean offset increases linearly. While compensation is possible with some MUs and SCs, this requires access to accurate cable length records or an OTDR to measure distance. This process is time consuming and subject to human error, particularly in large substations. The upper cable length limit, without remote end compensation, is 400 m. It should be noted that any reconfiguration or changes to cabling would require the timing system to be checked for compliance.

A. Small Substations

All three synchronisation methods examined meet the requirements of 9-2LE (and hence IEC 61850-5) for physically small substations where propagation delay does not exceed the 2 µs guideline. 1-PPS and IRIG-B will still require a separate distribution network. Distribution of these signals with active devices (to reduce the amount of cabling used) is not trivial, as the additional delays created by these devices cannot be measured with an OTDR. If active distribution (for example in tree or cascade topologies) is not used, each MU/SC will require a separate fibre optic cable and a master clock capable of driving all of these cables. When MUs and SCs are mounted in the control room, rather than in the switchyard, this is not an insurmountable problem [24].

B. Large Substations

The key finding of Table III is that a PTP timing system provides very similar jitter performance to IRIG-B, albeit with significantly reduced offset, using the same clock hardware. PTP also offers the following benefits of an Ethernet-based distribution system:

- Reduced cabling. No additional field cabling is required as the Ethernet network used to convey sampled value measurements from the switchyard to the control room is used to carry timing messages from the control room to the switchyard.
- Improved redundancy. The Best Master Clock algorithm defined in IEEE Std 1588 allows multiple GM clocks to be placed on a network, with automatic fail-over when either the quality of a GM reduces (e.g. antenna failure) or if the primary GM stops transmission (e.g. network failure). Process bus networks are critically dependent on time synchronisation for normal steady-state monitoring and control, and therefore redundancy is highly desirable.
- Path compensation. Large transmission substations may have in excess of 50 MUs, with cable lengths ranging from 10 m to 700 m. Automatic path compensation using the peer to peer delay mechanism reduces time required for commissioning, and handles changes to network topology during operation. The automatic measurement of delay reduces the chance of human error and provides real-time detail of network delays.
- Source clock information, such as that required by IEC 61850-9-2 ed.2, is included in PTP messages. This provides traceability of the synchronising source.

Cascaded transparent clocks will be required in a substation to build the "tree" connection, and may include bay, diameter (for breaker-and-a-half or double-bus configurations) and voltage level switches. IEEE Std C37.238 requires that the overall error does not exceed 1 µs with sixteen hops, and 800 ns is allocated to the transparent clocks. Testing of transparent clocks for substation applications is the subject of research yet to be published, however other researchers have looked at the performance of transparent clocks in general [25].

A fully corrected PTP system should not have any offset between the grandmaster and slave clocks, however network asymmetry can result in an offset. The Cat 5 network cables used in these experiments were less than 2 m long, and the fibre-optic cable was a two-core design. As a result network based asymmetry would be minimal. Previous testing has shown that the slave clock does exhibit an offset in its 1-PPS output, while its PTP system reports no offset.

VI. CONCLUSIONS

This paper has assessed the accuracy of two established substation time synchronisation methods (1-PPS and IRIG-B) to provide a benchmark for PTP. 1-PPS provides the least jitter of any method, but does not convey absolute time information required for cyber-security or field based phasor measurement, and does not compensate for path delay. IRIG-B conveys absolute time, but is not capable of passing source clock information that will be required by IEC 61850, does not compensate for path delay, and requires a separate distribution network.

PTP overcomes the short-comings of 1-PPS and IRIG-B through a bidirectional protocol. This allows for a comprehensive set of information to be transmitted from the GM to slave clocks.

Significant benefits of PTP include automatic path length compensation, support for redundant time sources and the efficiency of a shared network. The results presented in this paper show that these benefits are not at the expense of synchronising performance, and that PTP is suitable for precision synchronisation in substation applications.

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