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Use of Precision Time Protocol to Synchronise Sampled Value Process Buses

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***Abstract*—Transmission smart grids will use a digital platform for the automation of high voltage substations. The IEC 61850 series of standards, released in parts over the last ten years, provide a specification for substation communications networks and systems. These standards, along with IEEE Std 1588-2008 Precision Time Protocol version 2 (PTPv2) for precision timing, are recommended by the both IEC Smart Grid Strategy Group and the NIST Framework and Roadmap for Smart Grid Interoperability Standards for substation automation.**

IEC 61850, PTPv2 and Ethernet are three complementary protocol families that together define the future of sampled value digital process connections for smart substation automation.

A time synchronisation system is required for a sampled value process bus, however the details are not defined in IEC 61850-9-2. PTPv2 provides the greatest accuracy of network based time transfer systems, with timing errors of less than 100 ns achievable.

The suitability of PTPv2 to synchronise sampling in a digital process bus is evaluated, with preliminary results indicating that steady state performance of low cost clocks is an acceptable ±300 ns, but that corrections issued by grandmaster clocks can introduce significant transients. Extremely stable grandmaster oscillators are required to ensure any corrections are sufficiently small that time synchronising performance is not degraded.

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

ACRONYMS

GOOSE	Generic Object-Oriented Substation Event
IED	Intelligent Electronic Device
MU	Merging Unit
1PPS	One pulse per second
PTPv2	Precision Time Protocol version 2
SV	Sampled Values
TAI	International Atomic Time

I. INTRODUCTION

THE 'smart grid' has been defined as an umbrella term for technologies that are an alternative to the traditional practices in power systems, with the following benefits: reliability, flexibility, efficiency and environmentally friendly operation [1]. It is the novelty in the way that tasks are implemented that signifies the smart grid, and some suggest strongly that the smart grid should not be used to emulate existing systems, but should be used to promote new thinking, particularly with regard to protection schemes [2]. Sampled value (SV) process buses are a means of achieving this [3], and the benefits of a digital process bus have been well documented in the literature [4]–[6]. Full scale process bus based substations have been commissioned in China, and more are under construction [7].

The IEC Smart grid vision standardisation 'roadmap' identifies the IEC 61850 series of standards to be key components of substation protection, automation and control for the transmission smart grid [8]. The objective of substation automation standardisation with IEC 61850 is to provide inter-operable communication standards that meets existing needs, while supporting future developments as technology improves.

The primary plant in a substation is the high voltage equipment and includes bus bars, circuit breakers, isolators, power transformers, current transformers (CTs) and voltage transformers (VTs). The control equipment, the 'intelligence' in a substation, is termed the Substation Automation System (SAS), and includes protection, control and automation devices. The links between the primary plant and SAS are called 'process connections', and are generally copper multi-core cables with analogue voltages and currents (typically 110 V_{AC} and 1 A_{AC} respectively in Australia), or digital signals based on switching battery voltage (typically 125 V_{DC} in Australia). Fig. 1 shows this diagrammatically for a double-bus feeder bay in a 132 kV transmission substation.

The GOOSE (defined in IEC 61850-8-1) and SV (defined in IEC 61850-9-2) protocols are 'Specific Communication Service Mappings' and provide tangible interfaces to the abstract data model that underlies IEC 61850 based systems [9], [10]. GOOSE is primarily

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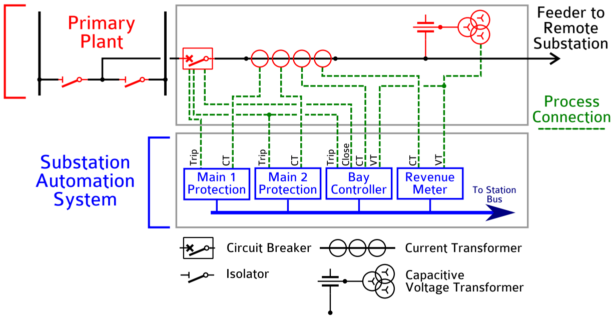

Fig. 1. Substation equipment definitions.

used to transmit binary data such as indications, alarms and tripping signals, but can also be used to transmit transduced analogue values. SV is currently used to send instantaneous current and voltage samples from CTs and VTs to the SAS, but may be used to send Boolean or transduced data in the future.

A digital process bus carries information from the primary plant to the SAS (such as voltage and current samples, transformer temperature and circuit breaker status), and from the SAS to the primary plant (for example circuit breaker tripping and closing commands) over a digital network — it is not just the one-way flow of sampled CT and VT data. All likely protocols need to be considered (GOOSE, SV and PTPv2) in the design of a shared network process bus, especially the way in which they may interact. GOOSE and SV specify Ethernet as the transport protocol, and define structures and encoding schemes (ASN.1) that ensure that data can be exchanged between devices in an inter-operable fashion. GOOSE data typically updates tens of times per second and for intermittent events, while SV is more suited to thousands of updates per second. GOOSE and SV have been designed for the rapid publication of information to many subscribers. This is achieved through connectionless multicast (one to many) addressing of data packets to implement the publisher/subscriber transfer model.

A Merging Unit (MU) collects (from digital systems) or samples (from analogue systems) the output of three or four CTs and VTs (neutral measurements are often omitted) and transmits this information in a standardised form. MUs throughout a substation must accurately time stamp each sample if Intelligent Electronic Devices (IEDs), such as protection relays, use SV data from multiple MUs (through the use of time alignment of samples in buffer memory). This concept has been termed 'relative temporal consistency' by Decotignie [11]. An example of the digital process bus connections in a breaker-and-a-half 'diameter' is given in [12].

IEC 61850-9-2 details *how* SV data shall be transmitted over Ethernet, but does not explicitly define *what* information should be transmitted, nor at what rate. In an attempt to reduce the complexity and variability of implementing SV process buses complying with IEC 61850-9-2, an implementation guideline was developed in 2004 by the UCA International User Group (UCAIug) that is commonly referred to as '9-2 Light Edition' or '9-2LE' [13]. This guideline specifies the data sets that are transmitted, sampling rates, time synchronisation requirements and physical interfaces.

The physical interface for time synchronisation in 9-2LE is based upon the one pulse per second (1PPS) signals defined in IEC 60044-8 [14]. The ±1 µs accuracy requirement of 9-2LE is derived from the T4 timing class in IEC 61850-5 [15] (overall timing error within ±4 µs) when propagation delays and sampling errors are considered. The T4 class is intended for use with protection class P2 (transmission bays) and metering class M1 (class 0.5 and up to the 5th harmonic). A higher time performance class, T5, exists for protection class P3 (transmission bay with high performance synchronising) and metering classes M2 (class 0.2 and up to 13th harmonic) and M3 (up to the 40th harmonic). The overall accuracy requirement for T5 is ±1 µs, and this is the 'stretch target' for substation timing systems.

The same smart grid strategy that proposes IEC 61850 for substation automation and control recommends the use of IEEE Std 1588-2008, version 2 of the Precision Time Protocol (PTPv2) [16], for high accuracy time synchronisation in substations. Annex F of IEEE Std 1588-2008 defines a mapping for PTPv2 over Ethernet using multicast messages. The IEEE Std C37.238 'power system profile' specifies how PTPv2 will be used for power system applications, requires that Annex F be used with this profile [17]. The same data network infrastructure can therefore be used for SV, GOOSE and for time synchronisation. The combination of multicast GOOSE and SV messages for substation automation and multicast PTPv2 messages means that these protocols can affect one another, especially if the default settings for VLAN tagging are used (VID of 0).

Much of the research into the application of PTP and PTPv2 has been in the areas of industrial automation [18], telecommunications [19] and audio-video bridging [20]. It is only in recent years that power system applications have been investigated. Most of the power systems work to date has focused on phasor measurement [21], [22]. Some groups are investigating applications of PTPv2 for substation automation [23], [24], but only recently has the application of PTPv2 to SV process buses been discussed and reported upon [7], [25], [26].

The work in this paper extends that of De Dominicis *et al.* [23] by focusing on the SV process bus application, and by looking at the effect of outages in the timing system. The PTPv2 testbed for power system applications described by Amelot *et al.* did not examine grandmaster holdover and recovery from loss of GPS synchronisation [27], but is investigated by this paper, which is a technical extension of [12].

The paper is organised in the following manner. Section II describes the use of PTPv2 for SV time synchronisation. Section III presents the test methodology that was used, with the results shown in Section IV. Conclusions are discussed in Section V.

II. USE OF PTPv2 FOR SAMPLED VALUE TIME SYNCHRONISATION

It is expected that most master clocks in substations will be synchronised to International Atomic Time (TAI) via the GPS constellation, as GPS is an excellent tool for time transfer [28].

Outdoor transmission-level substations (typically 110 kV and above) cover a large area of land and cable lengths are significant. IRIG-B can be distributed over copper or fibre optic cables, but requires individual calibration of each MU [23]. 1PPS distributed over a dedicated fibre optic cable network is recommended in 9-2LE, but this does not contain the absolute time information that is required by the data security techniques specified in IEC TS 62351-6 to prevent 'replay' attacks of GOOSE and SV traffic [29].

1PPS systems do not automatically compensate for propagation delay as transmissions are unidirectional. A typical 'general arrangement' diagram of an urban transmission substation is shown in [12]. The longest cable distance from the control building to an instrument transformer at this site is approximately 420 m, and this would result in propagation delays in excess of 2 µs for fibre optic cable (velocity factor of 0.62). Cable runs of 300–400 m are not uncommon in transmission substations. PTPv2 provides a means of distributing time across a substation that compensates for propagation delay and provides absolute time.

A. *Generation of 1PPS Signal by a* PTPv2 *Time Slave*

PTPv2 slave clocks that can generate a 1PPS signal are available from many suppliers. MUs can use this 1PPS signal as if it was generated from a GPS or IRIG-B receiver, but will not experience the propagation delays associated with distant time sources. 9-2LE requires MUs to compensate for propagation delay if this exceeds 2 µs and this is supported by several manufacturers, but this is not an issue for locally generated 1PPS signals.

B. *Native Support for* PTPv2 *in Merging Units*

Native support of PTPv2 is desirable as most of the extra data available with PTPv2 is lost with 1PPS, including accuracy information, absolute time and date (which could be incorporated into SV or synchrophasor messages) and details of the clock source.

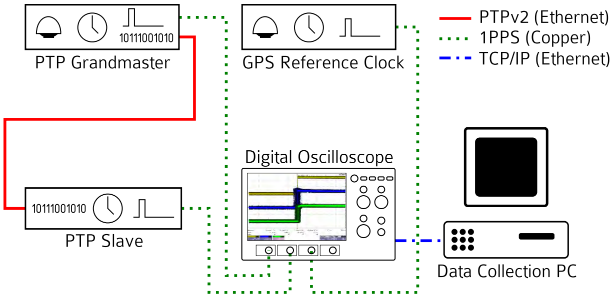

Fig. 2. Experimental arrangement to assess performance of PTPv2 with directly connected grandmaster and slave.

MUs are now available in the marketplace that have native support for PTPv2 and this avoids the need for an external slave clock [7], [30]. A disadvantage with in-built PTPv2 slaves is that there is no longer an external timing signal that can be used to analyse the response of the slave, and so all work in this paper uses standalone slave clocks with 1PPS outputs. Packet capture based analysis can look at network performance, but it does not reveal the internal synchronisation performance of slave clocks.

Integrating the slave clock function into the MU should lead to increased reliability as there are fewer components. The complexity and number of devices required in a digital Process Bus and its effect on reliability has been widely studied [31], [32].

III. TEST METHOD

Jitter is defined in ITU-T G.810 as "the short-term variations of the significant instants of a timing signal from their ideal positions in time", and wander is defined in the same standard as "the long-term variations of the significant instants of a digital signal from their ideal position in time" [33].

Tests were performed with commercially available PTPv2 clocks to determine whether PTPv2 is a viable source of 1PPS timing signals for MUs. These tests examined the steady-state and dynamic performance of slave clocks, with particular emphasis on recovery from contingencies. Fig. 2 illustrates the equipment used to measure the jitter and wander of 1PPS outputs from a slave clock directly connected to a grandmaster, representing the best case scenario. The GPS reference clock provided a 1PPS signal synchronised to TAI at all times and allowed the wander of the grandmaster to be measured when its GPS antenna was disconnected. This technique is similar to that described in [34].

Automatic pulse delay measurements were made with an oscilloscope (LeCroy WaveSurfer 424) sampling the

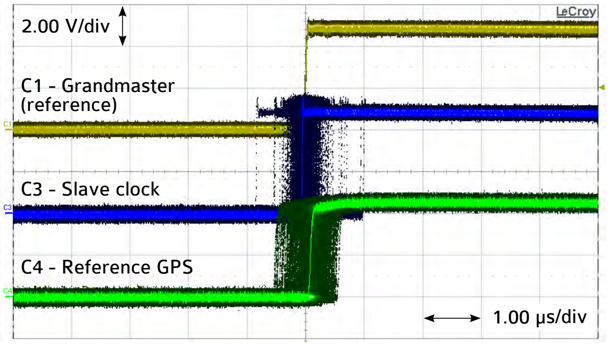

Fig. 3. Sample captures from oscilloscope based pulse delay measurement.

1PPS outputs of the grandmaster clock and slave clocks, which is an established technique [35], [36]. The sampling rate was 10^9 sample/s, with a timebase accuracy of 10 ppm. The record depth was 200 000 samples per channel, giving a pulse delay measuring range of ±100 µs with 1 ns precision. The oscilloscope was computer controlled, with a standard configuration sent to the oscilloscope at the start of each test. Fig. 3 is a sample of the 1PPS waveforms captured by the oscilloscope, with infinite persistence to visualise the jitter on screen during the test. Pulse delay measurements were transferred to the PC after each 1PPS pulse for detailed statistical analysis.

It is the intent of a SV process bus to use a common Ethernet network for SV data and for PTPv2 synchronisation, and therefore Ethernet switches will be needed to connect MUs and slave clocks in the field, and to connect IEDs and grandmaster clocks at the control room. This was achieved through the use of peer-peer transparent clocks, as mandated in the C37.238 power system profile.

The Ethernet network topology was varied to assess the effect of transparent clocks on synchronising performance. Initial tests were performed without the use of any transparent clocks so as to avoid the effect of any other network traffic. Fig. 4 shows the network topology for (A) direct connection, (B) one transparent clock and (C) three transparent clocks.

The accuracy and timeliness of PTP announce messages were assessed by capturing all PTPv2 messages with Wireshark [37] while the wander tests were performed. A script was written for Wireshark to extract the *grandmasterClockQuality.clockClass* and *grandmasterClockQuality.clockAccuracy* fields from each announce message, and then save these to a file for further analysis. Detailed satellite visibility information was logged directly from the grandmaster clock's GPS receiver through a dedicated RS232 connection.

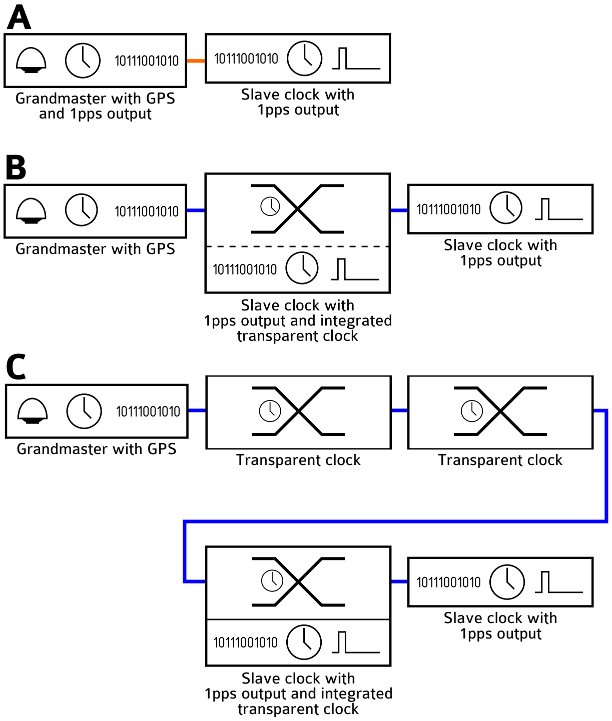

Fig. 4. Network topologies for PTP jitter evaluation.

IV. RESULTS

Jitter and wander were the two performance indicators considered, with jitter being of most interest with the system intact, while wander was of more importance during contingency events.

A. Steady State Performance

PTPv2 provides flexibility in how the synchronisation system will operate and a key parameter is synchronisation message rate (although this can be restricted by a PTPv2 profile). The results presented here show that less frequent synchronising messages resulted in less jitter. Fig. 5 shows the tails of 1PPS jitter probability density observed over one hour intervals with sync message rates ranging from once every two seconds through to sixteen times per second. In each case, the grandmaster and slave were directly connected to each other with a cross-over Ethernet cable to remove any influence from other network traffic. Peer-peer delay requests and grandmaster announcements were set to 2 s intervals and one-step operation was used. Table I shows that the mean jitter is very close to zero for this combination of grandmaster and slave and that the standard deviation of jitter is between 60 ns and 70 ns for most sync message rates. The variation between rates is most apparent in the extremities of observed jitter. The final PTPv2 power profile has since explicitly restricted

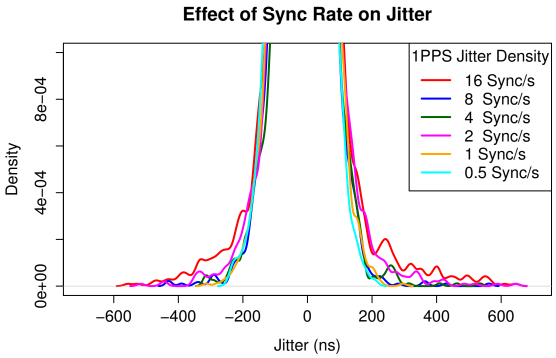

Fig. 5. Jitter observed between 1PPS outputs of a grandmaster and slave, using peer-peer path delay and one-step operation.

TABLE I
ANALYSIS OF DIRECTLY CONNECTED PTPV2 CLOCK JITTER.

Message Rate	$\overline{x}$	σ	Range
0.5 Sync/s	-21 ns	63 ns	-246 to 212 ns
1 Sync/s	-14 ns	65 ns	-313 to 296 ns
2 Sync/s	-5 ns	82 ns	-516 to 646 ns
4 Sync/s	-9 ns	67 ns	-317 to 534 ns
8 Sync/s	-13 ns	68 ns	-431 to 562 ns
16 Sync/s	-5 ns	102 ns	-556 to 645 ns

sync, announce and peer-delay messages to once per second, and the results here support this decision.

Scheiterer *et al.* suggested that less frequent updates allow a slave clock to better estimate its rate correction factor (RCF) used for local oscillator compensation, and this would improve performance when clock aging was not an issue [18]. The best performance was found to be with a synchronising message sent every one or two seconds, which is contrary to results presented by Amelot *et al.* [27]. Amelot used slave clocks with high performance TXCO local oscillators, whereas the slave clocks in this study used low cost crystal oscillators (XO) without compensation. An XO oscillator may naturally deviate further from its nominal frequency, and so improved RCF estimation through less frequent updates may outweigh the noise reduction a faster update rate would provide.

Best case jitter was approximately ±300 ns, and for much of the time was less than ±200 ns. This meets the requirements of 9-2LE, and future work will determine whether this is achievable with a larger timing network and in the presence of SV network traffic (up to 5.4 Mbit/s per MU).

The steady state performance of two makes of slave clock were examined to look for performance variation between vendors. The probability density plot in Fig. 6 shows a noticeable difference, with Vendor B's clock having less jitter, albeit with an offset in its 1PPS output.

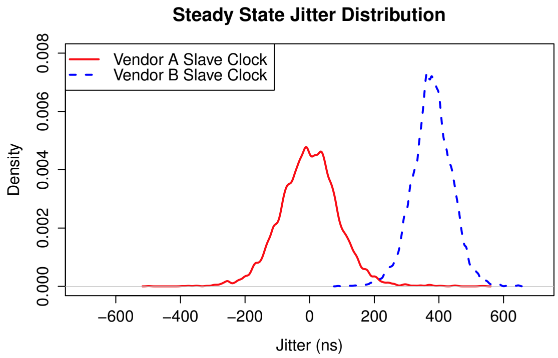

Fig. 6. Steady state comparison of two slave clocks as a time series and probability density.

B. Effect of Transparent Clocks

The effect of adding peer-peer transparent clocks to the timing network was material, with the average synchronising error increasing by more than 500 ns for some slaves. The spread of jitter also increased, but not significantly. Ethernet cables were less than 2 m long, limiting propagation delay to no more than 10 ns, and so the pulse output offset is largely the effect of transparent clocks. Fig. 7 shows that the 1PPS offset between the grandmaster and both makes of slave clock increases as the number of transparent clocks used increases. The mean jitter remains constant over the 30 minute observation period, and does not show the convergence modelled by Fontanelli and Macii [38]. Variation in bridge delay may limit the ability of the PTP system to completely compensate for delays introduced by transparent clocks. The follow-up message correction field contains estimates of the bridge and link delays between the grandmaster and that point, therefore, if the bridge delays vary, the correction field may not be accurate. Adoption of one-step operation where the sync message is modified as it passes along the bridges would ensure the delay estimate is as current as possible. The effect of transparent clocks on time error is likely to be more of an issue when the transparent clocks are passing SV messages, as this effects bridge delay. Further investigation of these interactions would be required.

This is a concern as PTPV2 based timing networks for substations as these may incorporate several levels of transparent clock, ranging from the bay level up to the station level. The combination of three transparent clocks and an offset in 1PPS output from Vendor B is pushing the upper limits of jitter close to the ±1 µs limit specified by 9-2LE. The presence of SV network traffic

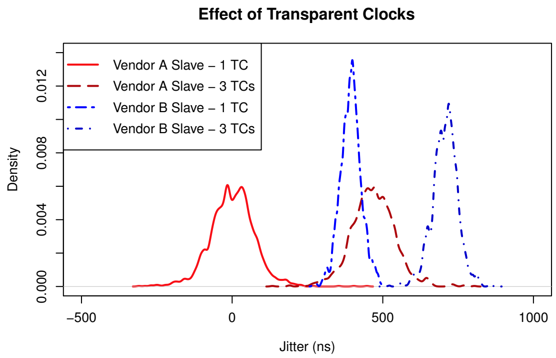

Fig. 7. Effect of transparent clocks on jitter offset.

is expected to increase jitter and will be the subject of further research.

Peer-peer transparent clocks are specified instead of standard Ethernet switches for their ability to compensate for switching and network delays, but this cannot be at the expense of increased timing error for 1PPS outputs.

C. Power On Performance

Slave clocks vary significantly in their ability to synchronise to a grandmaster when first powered on. Slave clocks from two vendors were connected to the same grandmaster with a transparent clock, and were powered up at the same time. Fig. 8 shows the 1PPS output from each slave, relative to the grandmaster. The slave clock from Vendor A required 35 s to synchronise and its 1PPS output was within the 9-2LE specification (±1 µs) as soon as it was activated. Vendor B's slave clock required 10 minutes to stabilise, although it was within the ±1 µs specification at 5 minutes and exhibited less jitter overall (albeit with an offset). This has ramifications for substation operation after maintenance, especially since Vendor B's slave clock enabled its 1PPS output when the offset exceeded 20 µs. MU samples would be skewed if these slaves were providing the sampling reference, and may result in deterioration of protection performance (especially for differential protection).

D. Loss of Network between Grandmaster and Slave

The effect on time synchronisation when a slave clock loses its connection to the grandmaster was investigated. This may occur due to network cabling faults or a failure of the grandmaster. The Best Master Clock (BMC) algorithm is intended to deal with loss or degradation of a grandmaster, but does not deal with a network failure at a slave [16].

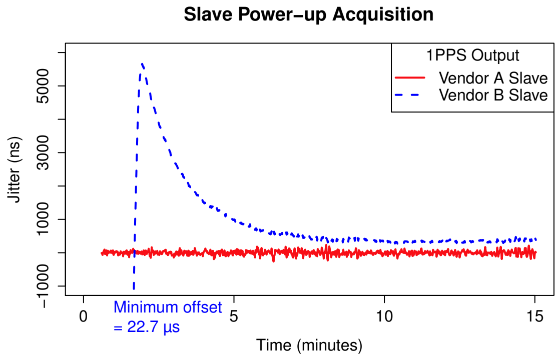

Fig. 8. Power up performance for slave clock from two vendors.

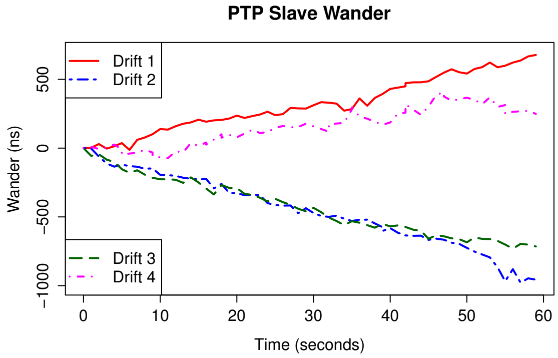

Fig. 9. Wander between PTPv2 grandmaster and slave when the network connection was broken.

The slave and grandmaster were synchronised with one PTP message per second and then the network cable between the two was disconnected. The slave was configured to keep generating its 1PPS output using its internal oscillator by using a long holdover time. Fig. 9 shows wander can vary in sign and magnitude. The slope varied between 10 ns/s and 20 ns/s, giving approximately 35 s of operation before the ±1 µs limit of 9-2LE was reached (based on an initial worst case jitter of 300 ns). This is useful information when setting appropriate holdover times. The transient responses of slave clocks recovering from a local network outage are presented in [12].

The internal oscillators in the grandmaster and slave clocks used for this experiment are low-cost crystal oscillators. Use of temperature controlled oscillators (TXCO) or oven controlled oscillators (OCXO) would improve performance, but at increased expense. Amelot *et al.* found that the worst case wander for slaves with TXCO local oscillators was 10 ns/s [27], however Scheiterer *et al.* concluded that a costly master has a much larger benefit compared to spreading the same expense across the slave clocks (which would be numerous in a transmission substation) [18].

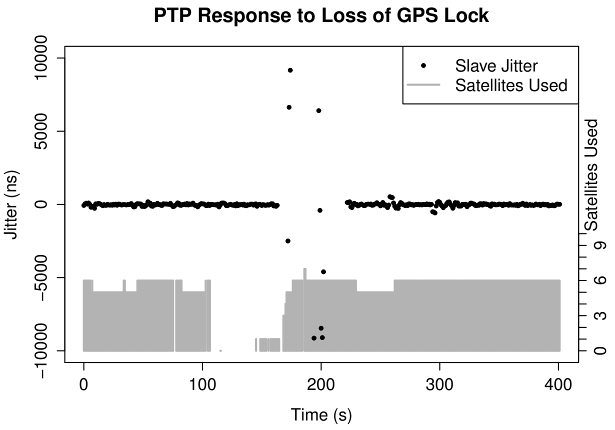

Fig. 10. Slave clock jitter when grandmaster reacquires GPS lock after an outage.

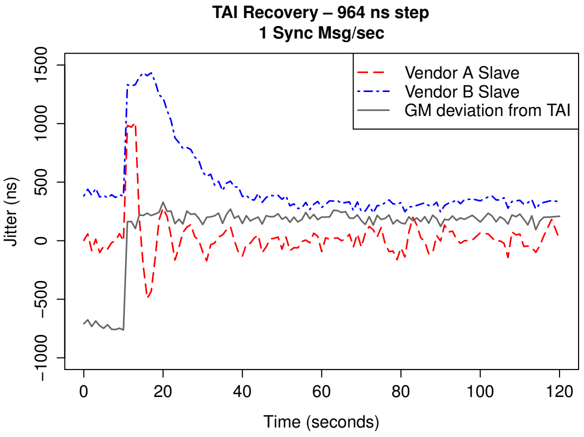

Fig. 11. Simultaneous measurement of slave clock jitter after 1 µs TAI recovery with two different clocks.

E. Loss of Grandmaster GPS Synchronisation

A clear view of the sky is required for optimum GPS reception as the satellites move in low earth orbit. There are times where building shading that reduces the viewable area of the sky may result in a GPS receiver losing synchronisation to TAI. The internal oscillator will wander from TAI, with the wander rate dependent upon the oscillator's stability [18]. The alternate-master election system using the BMC algorithm is intended to deal with degraded accuracy of a grandmaster, but there is still a disturbance in slave clock 1PPS outputs as sync is achieved with the alternate master [25]. Substation protection redundancy normally precludes interconnection of redundant devices, preferring instead to duplicate systems and operate these independently.

Loss of lock between the grandmaster and the GPS system was identified as a problem during this investigation when the 1PPS output of the slave clock exhibited large excursions for no obvious reason. Data logging from the GPS receiver showed that the jumps occurred when the GPS receiver reacquired lock, as illustrated in Fig. 10 at the time point 170 s.

This effect was recreated by disconnecting the GPS antenna on the grandmaster and observing the wander between its 1PPS output and that of a reference GPS. The wander was allowed to reach 1 µs and 4 µs before the antenna was reconnected.

Fig. 11 shows the behaviour slave clocks when the grandmaster recovers synchronisation with TAI after a wander of 1 µs with two makes of slave clock. Two separate recoveries from approximately 4 µs of grandmaster time error, with different vendors, are shown in Fig. 12. The PTP sync message was sent once per second in all tests. The step and oscillation in synchronism are not acceptable for a SV based protection system and must be addressed, and the difference in response between vendors is a major concern. The under-damped behaviour of Vendor A's slave clock and the over-damped behaviour of Vendor B's clock mean that there will be times where the sign of the jitter will be opposite, increasing the sampling error between the MUs synchronised by the slave clocks.

One solution to this problem is to use a highly stable internal oscillator in the grandmaster, such as an OCXO or temperature compensated rubidium (Rb) cell, to reduce the wander from TAI when synchronisation with the GPS system is lost. These typically have four (OCXO) or six (Rb) orders of magnitude better stability than uncompensated crystal oscillators [39]. There are typically one or two master clocks in a substation, and so the use of a PTPv2 grandmaster with an extremely stable oscillator can be justified both economically and technically, as this allows low-cost slave clocks with uncompensated oscillators to be used in field devices. This supports Scheiterer's conclusions regarding investment in the master clock rather than the slaves.

F. PTP Accuracy Reporting

PTPv2 grandmaster clocks report their estimated accuracy in announce messages. This experiment measured the absolute error between a grandmaster clock and a synchronised GPS while the grandmaster's GPS antenna was removed and then reconnected. Fig. 13 shows that the grandmaster conservatively reports its accuracy while it is in holdover mode, and that synchronisation to the GPS system is reported in the next announce message (fixed at one second intervals with the PTPv2 power system profile). A time correlated record of the number of GPS satellites used in the timing system shows that the PTP subsystem is updated immediately. Measure-

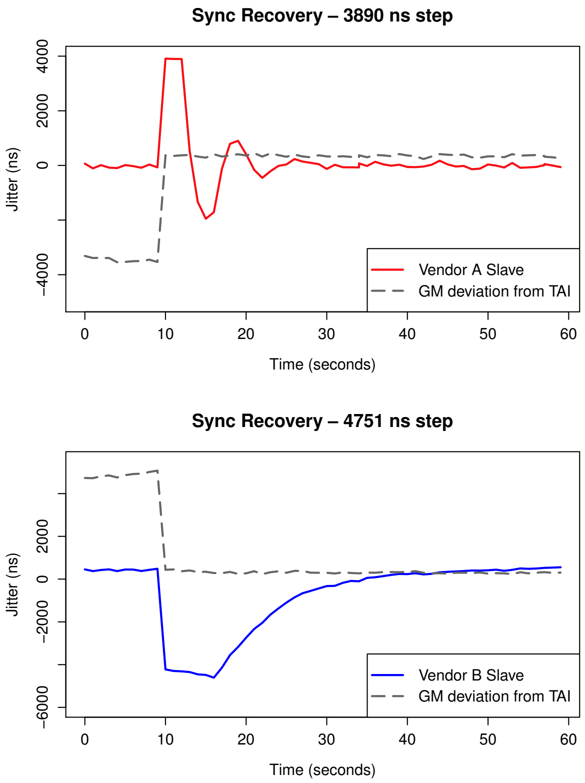

Fig. 12. Slave clock jitter after recovery from approximately 4 µs error from TAI (separate observations).

ment error from the reference GPS contributes to the discrepancy between the observed drift and estimated accuracy below 1 µs.

V. CONCLUSIONS

The results presented demonstrate that PTPv2 is a viable method of providing time synchronisation for a sampled value process bus using IEC 61850-9-2, in particular 9-2LE. The best case timing jitter with directly connected low-cost PTPv2 clocks is shown to be ±300 ns. It has been discovered that the use of transparent clocks does impact the PTPv2 timing system, with sampling errors increasing as transparent clocks are added to the system. Further research is required to identify the source of this fixed offset and to eliminate it, which in turn may allow the synchronising pulse specification of 9-2LE to be relaxed to ±2 µs. This would reduce the cost and complexity of implementing PTPv2.

This work has investigated the transient response of slave clocks to corrections transmitted by grandmasters when recovering from a time error. The magnitude of the slave response is almost identical in magnitude and sign as the correction experienced by the grandmaster, but the transient response varies significantly between makes of slave clock. Stabilisation after a correction event takes tens of seconds, during which time the synchronising signals for MU will be outside the specified limits. The wander from TAI experienced by a grandmaster when GPS synchronisation is lost is a significant concern, and while such wander cannot be eliminated, minimisation through the use of grandmasters with extremely stable internal oscillators is recommended.

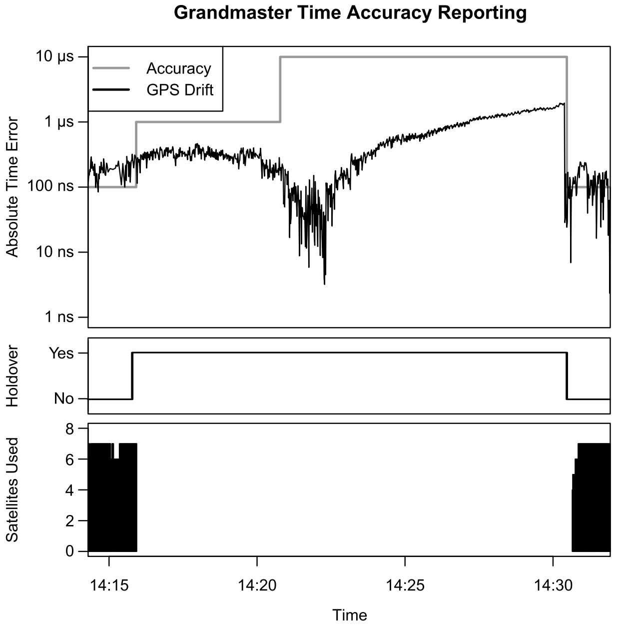

Fig. 13. Grandmaster announce message accuracy reports with loss and recovery of GPS signal.

The design of slave clocks plays an important part in the performance of a PTP system. The servo-loop in the clock recovery function is a compromise between low jitter levels during steady state operation and having a fast transient response to deal with time corrections from grandmasters. Variations in the implementation of slave clocks may preclude a standardised servo response, but a description of slave clock characteristics by vendors would assist in the selection of the most appropriate product. These variations become largely irrelevant when the root cause of step changes in time, grandmaster wander, is reduced to an acceptably small level through the use of highly stable internal oscillators.

A digital process bus is an important building block for the transmission smart grid as it enables interoperable use of digitised primary voltages and currents, transduced signals and digital I/O. IEEE Std 1588-2008 and IEEE Std C37.238 will facilitate the adoption of this technology, but more work is required to understand, and then standardise, its behaviour before it can be widely and routinely implemented in transmission substations.

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