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Test and Evaluation System For Multi-Protocol Sampled Value Protection Schemes

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***Abstract*—Proposed transmission smart grids will use a digital platform for the automation of substations operating at voltage levels of 110 kV and above. 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 61850-8-1 and IEC 61850-9-2 provide an inter-operable solution to support multi-vendor digital process bus solutions, allowing for the removal of potentially lethal voltages and damaging currents from substation control rooms, a reduction in the amount of cabling required in substations, and facilitates the adoption of non-conventional instrument transformers (NCITs).

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.

This paper describes a specific test and evaluation system that uses real time simulation, protection relays, PTPv2 time clocks and artificial network impairment that is being used to investigate technical impediments to the adoption of SV process bus systems by transmission utilities.

Knowing the limits of a digital process bus, especially when sampled values and NCITs are included, will enable utilities to make informed decisions regarding the adoption of this technology.

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

ACRONYMS

GOOSE	Generic Object-Oriented Substation Event
IED	Intelligent Electronic Device
LN	Logical Node
MU	Merging Unit
1PPS	One pulse per second
NCIT	Non-Conventional Instrument Transformer
PTPv2	Precision Time Protocol version 2
RTDS	Real Time Digital Simulator
SV	Sampled Values
TAI	International Atomic Time
VLAN	Virtual Local Area Network

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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]. Much of the smart grid focus has been in the distribution arena where distributed automation provides many benefits, but there is also an opportunity to introduce smart technologies into transmission networks to improve observability and control of the power system, and to achieve greater interoperability. 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].

The IEC and NIST have developed smart grid vision documents that identify the IEC 61850 series of standards to be key components of substation automation and protection for the transmission smart grid [3], [4]. The objective of the IEC 61850 series of substation automation (SA) standards is to provide a communication standard that meets existing needs, while supporting future developments as technology improves. IEC 61850 communication profiles are based, where possible, on existing international standards. SA functions are decomposed into 'logical nodes' (LNs) that describe the functions and interfaces that are required, and are described in [5].

IEC 61850-9-2 details how high speed sampled values (SV) shall be transmitted over an Ethernet network [6]. IEC 61850-8-1 defines how transduced analogue values and digital statuses can be transmitted over an Ethernet network using Generic Object Oriented Substation Events (GOOSE) and Manufacturing Messaging Specification (MMS, ISO 9506) [7]. The most stringent of the various GOOSE timestamp accuracy requirements is 100 µs, and the most stringent requirement for SV is 1 µs [8]. Ethernet is a key component and provides a means for connecting intelligent electronic devices (IEDs) with primary plant and for interconnection between IEDs [9].

Alternatives to oil/paper insulation and porcelain for high voltage current transformers (CTs) have been available for some time. One option is to use polymer insulation and SF_6 gas [10], but these have only found favour at the higher voltages (typically 500 kV and above) and there is concern regarding the use of SF_6 as it is a very potent greenhouse gas, having a 100 year warming potential 22 800 times that of CO_2 [11]. A second option is to use 'non-conventional instrument transformers’ (NCITs) that do not rely on traditional iron cored inductive principles. These include air-cored transformers, such as Rogowski coils and fibre optic sensors, with the first fibre-optic CT (using Faraday rotation) for use in high voltage power systems demonstrated by Japanese researchers in 1966 [12]. NCITs provide significant safety and environmental benefits, greater dynamic range, wider frequency response and ease of installation [13].

This work presents a test and evaluation system that is being used to assess the performance of protection systems using Ethernet for a process bus and for sampling synchronisation. A test and evaluation system based on SV, GOOSE, MMS, PTPv2 and a real time digital simulator (RTDS) is used to assess SV protection schemes using ‘live’ equipment against the requirements of the National Electricity Rules (NER). This system will provide information on how the competing demands of these protocols can be met and is described in the rest of this paper. Previously published work has described a SV protection test system [14], but this work extends this by describing a specific test system and by incorporating PTPv2 for SV sample synchronisation.

II. Background

A. Transmission Substations

Fig. 1 shows a ‘breaker and a half’ transmission substation bay, typically used at 220 kV and above in Australia. The primary plant (transmission lines, circuit breakers, instrument transformers and power transformers) is connected to the secondary systems (control, protection and metering) through ‘process level’ connections. A digital process bus provides the process connections in a digital form rather than as scaled voltages and currents (typically 110 V and 1 A) or switched relay contacts. Merging units (MUs) digitise instantaneous analogue signals, typically the output of three or four voltage transformers (each using the ‘TVTR’ LN) and three or four current transformers (each using the ‘TCTR’ LN) and ‘publish’ (transmit) the results in multicast Ethernet frames. Protection IEDs ‘subscribe’ (receive) these frames and extract the instantaneous measurements of voltage and current. Multicasting allows more than one IED to use a single transmission. The publish/subscribe model is a one-to-many approach.

B. Automation Standards

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 [6]. Generic Object Oriented Substation Events (GOOSE) and Manufacturing Messaging Specification (MMS, ISO 9506) are used to transmit transduced analogue values or digital status from high voltage plant [7]. A digital process bus may use proprietary systems, but those based upon IEC 61850 (GOOSE, MMS and SV) are the subject of this research.

In an attempt to reduce the complexity and variability of implementing SV complying with [6], an implementation guideline was developed in 2004 by the UCA Internation User Group (UCAIug) that is commonly referred to as ‘9-2 Light Edition’ or ‘9-2LE’ [15]. This guideline specifies the data

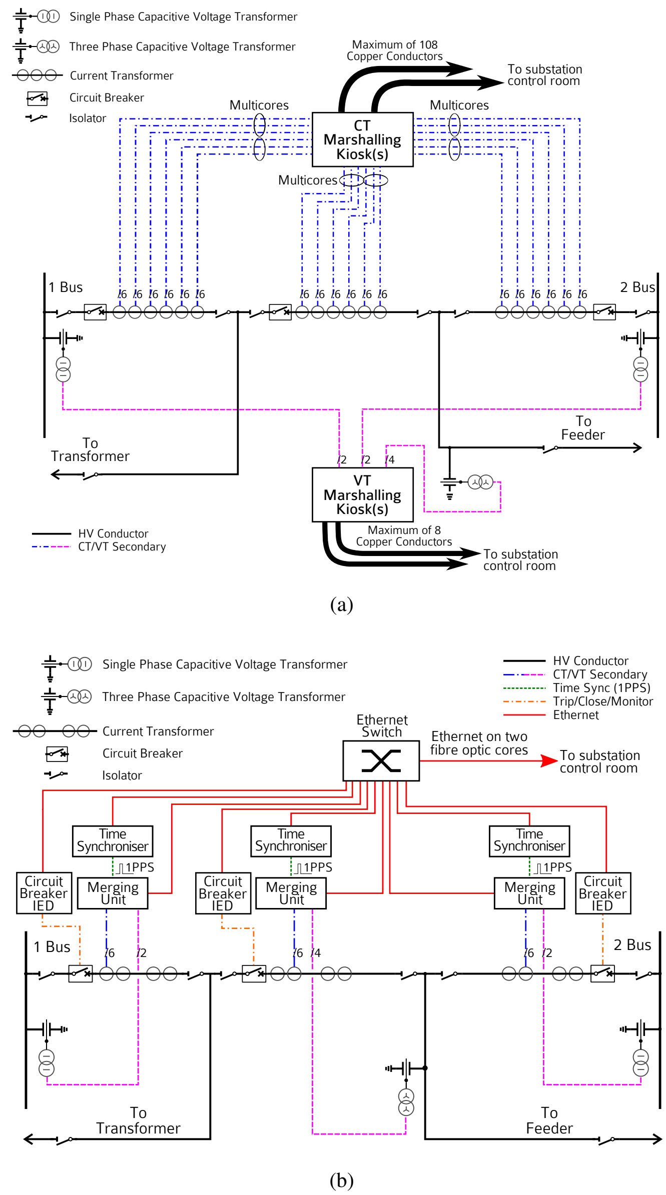

Figure 1. Schematic of a breaker-and-a-half (1½ CB) transmission substation bay using (a) conventional CT and VT wiring, and (b) digital process connections.

sets that are transmitted, sampling rates, time synchronisation requirements and physical interfaces, but does not specify the transient response of devices. The transient response of NCITs differs from conventional magnetic CTs and VTs, and this has ramifications for differential protection [13]. The IEC 61869 series of standards are being developed by IEC Technical Committee 38 (TC38) to include this and are based in part on 9-2LE, which has roots in IEC 60044-8 [16].

Several vendors of non-conventional instrument transformers (NCITs) are using 9-2LE to interface their equipment to IEDs from other manufacturers, and this inter-operability is a definite benefit of an Ethernet SV process bus.

MUs throughout a substation must accurately time stamp each sample to allow protection IEDs to use SV data from several MUs (through the use of time alignment of samples in buffer memory). This concept has been termed ‘relative temporal consistency' by Decotignie [17]. 9-2LE specifies an optical 1 pulse per second (1PPS) timing signal with ±1 µs accuracy for this purpose. It should be noted that other automation systems exist that are based upon IEC 61850-9-2, however most, if not all, are not based on 9-2LE and use point to point connections and are therefore outside the scope of the test system presented here.

C. Timing

IEEE Std 1588-2008, version 2 of the Precision Time Protocol (PTPv2) [18], significantly improves time synchronising performance [19], making this a viable option for synchronising MUs. The same IEC and NIST smart grid strategies that propose IEC 61850 for substation automation and control also recommend the use of IEEE Std 1588-2008 for high accuracy time synchronisation [3], [4]. The same data network infrastructure can then be used for SV, GOOSE and for time synchronisation.

This is of great benefit when MUs are located throughout a substation, adjacent to the primary plant they are connected to. Synchronising with 1PPS signals over fibre optic cable is straightforward when MUs are located in substation control rooms (as done by many suppliers of non conventional instrument transformers), but distributed MUs would require a separate fibre optic network throughout the substation just for 1PPS, and this is avoided with PTPv2. Recently published work has described the first of many process bus substations in China using PTPv2 for time synchronisation of an IEC 61850-9-2 process bus [20].

III. The Test System

A test bed to evaluate the performance of protection systems using SV has been constructed. This test bed comprises the following components: RTDS, PTPv2 clocks, Ethernet emulator, traffic generator and a precision Ethernet capture card. These are shown in schematic form in Fig. 2.

The test system can be separated into two areas: the 'field' and the 'control room'. The 'field' comprises the instrument transformers, MUs and time synchronisation devices, and is represented by the RTDS and equipment shown in Fig. 3. The 'control room' contains Ethernet switches, grandmaster clocks and protection IEDs and is shown in Fig. 4.

This work complements proposals for control system simulation [21] by focussing on protection applications, and differs from the analysis of SV systems by event-based simulation [22] by implementing a scale model using production or late stage prototype devices.

A. Real Time Digital Simulator

The Real Time Digital Simulator (RTDS) is a multi-processor simulation system that is running electromagnetic transient program (EMTP) simulations of power systems in real time [23]. Power system models are created using a graphical interface, compiled and then executed on the RTDS hardware. The real-time execution speed allows the EMTP model to respond to external stimuli and for hardware (such

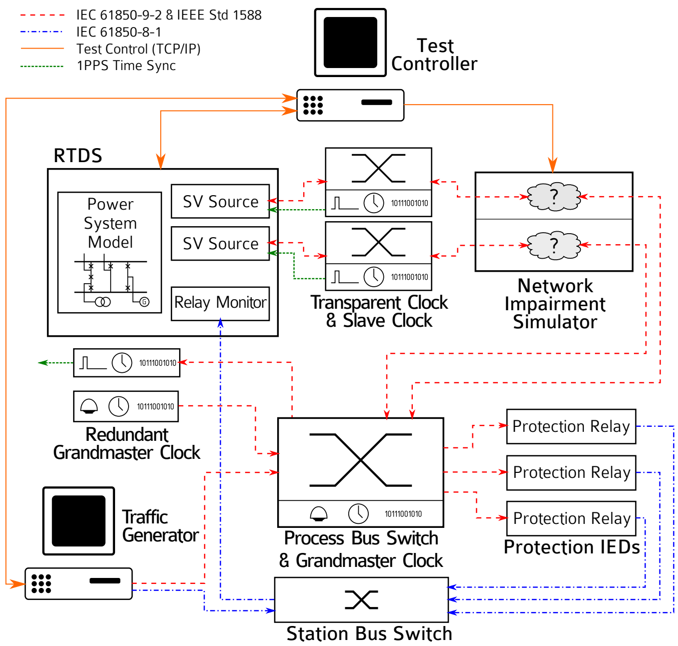

Figure 2. Schematic of the test and evaluation system.

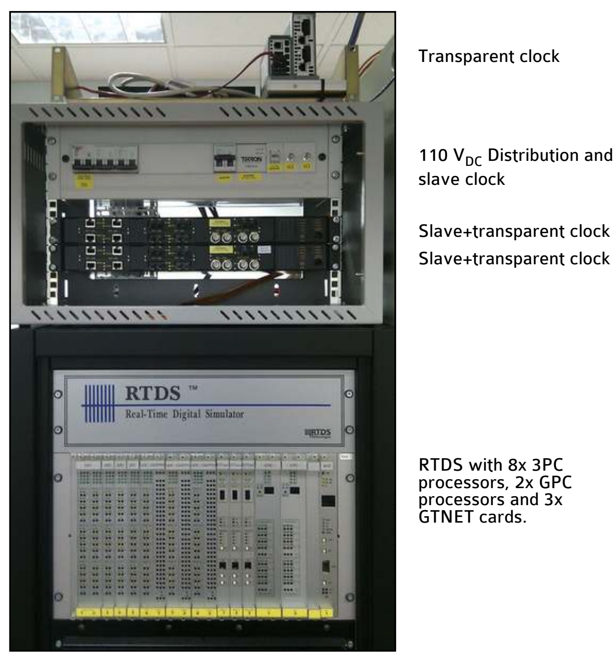

Figure 3. Photograph of the 'field' equipment, with the RTDS acting as the SV source and PTP slave clocks providing time synchronisation.

as protection IEDs) to interact with the simulation. This is a significant improvement over playback of pre-calculated faults, as the response of the IEDs changes the outcome of the simulation. GTNET cards enable the RTDS to send and receive GOOSE messages (to take the place of digital IO) and to send SV messages (which act as analogue outputs) over Ethernet [24]. The RTDS used in this test bed has a total of 28 processors and three GTNET cards.

Scripting in the RTDS power system model varies the location and impedance of faults. It is expected that different

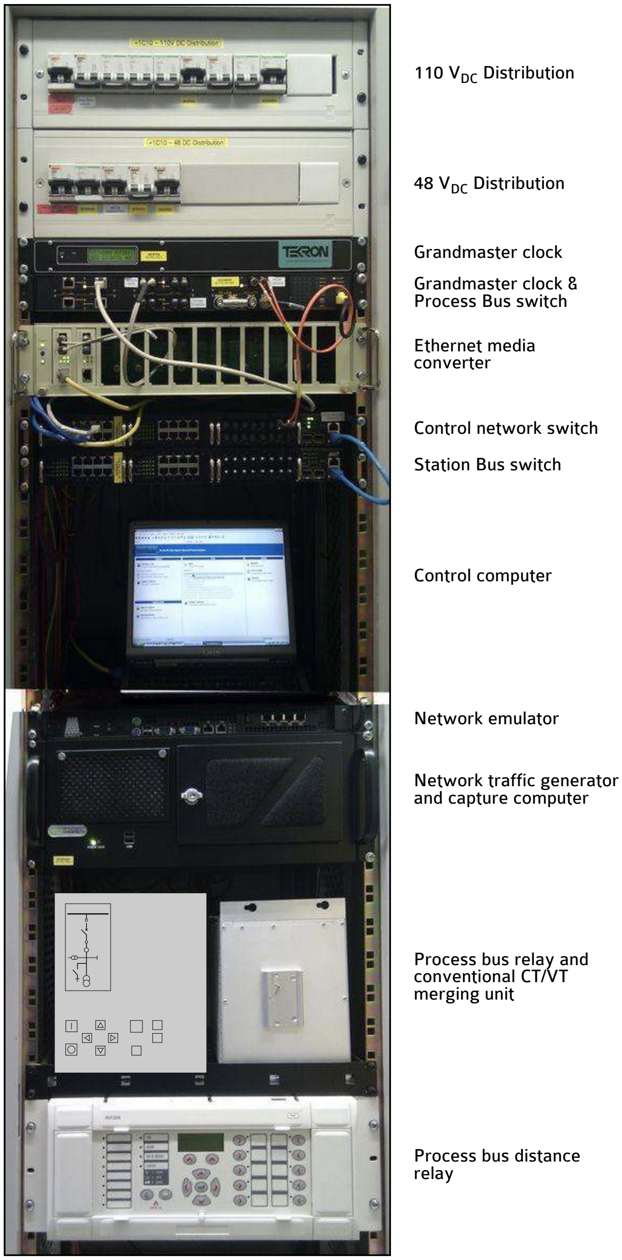

Figure 4. Photograph of the 'control room' components, including Ethernet switches, Ethernet simulator and grandmaster clocks.

protection schemes will respond differently to network latencies, and using the RTDS will permit these schemes to be exhaustively tested under a variety of communication network conditions and fault locations. Conventional protection testing using secondary injection verifies that the protection settings have been correctly entered into the IED, but testing with the RTDS demonstrates that the protection settings are themselves correct.

GTNET cards will act as MUs by generating SV streams, rather than using analogue connections and power amplifiers. Protection IED operation will be evaluated by having the RTDS subscribe to GOOSE trip and close messages generated by the IEDs. These GOOSE messages will be transmitted over a separate Ethernet network representing a station bus, or over the process bus when the RTDS takes the role of a circuit breaker interface IED.

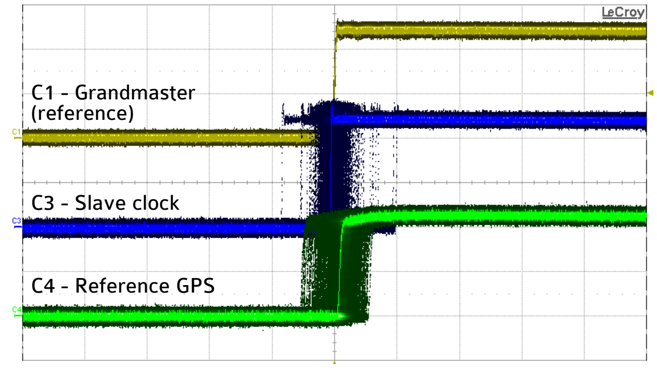

Figure 5. Typical 1PPS waveforms generated by a grandmaster and a slave clock. C3 is the PTP slave clock and C4 is a reference GPS. C1 is used as the reference point for timing. The time scale is 1 μs per division.

The effect of differences in transient response between electromagnetic CTs and NCITs will be modelled using the RTDS, and the effect upon various protection schemes will be assessed.

B. Time Synchronisation

The MUs available for testing and the RTDS GTNET cards do not yet directly support PTPv2, and so PTPv2 slave clocks that generate a 1PPS signal are an interim means of integrating IEEE 1588 with IEC 61850-9-2. MUs use this 1PPS signal as if it were generated from a GPS or IRIG-B receiver, but without the propagation delays inherent in these systems (which can be significant in transmission substations).

Automatic pulse delay measurements were made with a digital oscilloscope sampling at either 500 ps (one or two channels) or 1 ns (three or four channels) between samples. The standard record length was 200 000 samples per channel, giving a pulse delay measuring range of ±100 μs when three or four channels were in use. The oscilloscope was computer controlled, with a standard configuration sent to the oscilloscope at the start of each test. Fig. 5 is a sample of the 1PPS waveforms captured by the oscilloscope, with infinite persistence to show the jitter on screen. Pulse delay measurements in each direction were transferred to the PC after each 1PPS pulse for further statistical analysis.

It is expected that most grandmaster clocks in substations will be synchronised to International Atomic Time (TAI) via the GPS constellation, as GPS is an excellent tool for time transfer [25]. Synchronisation to TAI allows for synchronisation between substations, which is used to achieve common time-stamps in 'sequence of events' records and for some feeder protection schemes. A time clock providing PTPv2 grandmaster functions may also be an IRIG-B or 1PPS source for legacy devices within the substation control room, and an NTP master clock for less demanding IEC 61850 applications.

Two PTPv2 grandmaster clocks are used in this system so the effect of clock failure can be assessed. A monitoring system continually records the delay between 1PPS signals generated by the grandmasters and 1PPS signals generated by the slave clocks.

C. Ethernet Switches

A significant amount of network traffic is created by SV sources, ranging from 4.2 Mb/s–5.8 Mb/s for 9-2LE, and is dependent on the nominal power system frequency and implementation options. Managed switches allow data to be segregated and prioritised based upon VLAN tags or multicast destination addresses [26]. This test system will allow different communication architectures and prioritisation to be investigated.

D. Network Emulation

Network emulation is a technique where a device simulates communication network impairment, but in a controlled and repeatable manner. Common impairments include packet delay variation, packet loss and packet corruption. An Data Link Layer emulator has been selected as SV, GOOSE and PTPv2 use OSI Layer 2 Ethernet frames. The emulator has the ability to selectively filter or modify frames based on source or destination address, payload type and VLAN ID. The selective nature of filtering allows the evaluation system to increase bit error rates for selected protocols and to drop individual devices from the network to test fail-over schemes.

E. Protection IEDs

SV capable protection relays that implement distance and differential protection have been sourced from major manufacturers. All trip and close signals are sent from the IEDs via GOOSE messages rather than using relay contacts. Communication network impairment will be used to determine at what stage protection functions are adversely affected. This will provide information on the suitability of the performance requirements specified in IEC 61850-5 [8]. Other work has shown that GOOSE trip messages transmitted with a high priority (802.1Q priority 7) have trip times that are within 0.1 ms of that achieved with relay contact tripping [27]. As a result this work will use focus on GOOSE tripping for protection IED feedback to the RTDS.

F. Ethernet Capture

An Ethernet capture card with precise time-stamping captures SV and GOOSE traffic at the point of generation and at the point of transmission and at the point where IEDs 'consume' the data. This enables the delays that the network emulator is creating and the delays induced by Ethernet switches with high traffic loads to be measured. Network captures at the source are made with a passive Ethernet tap. Fig. 6 shows this arrangement, and the switch can be replaced by any other device or system under test.

Two capture streams are saved to separate files and post-processing used to extract absolute timing information and a summary of 9-2LE parameters including source and destination addresses, MU name (svID) and sample counter (smpCnt).

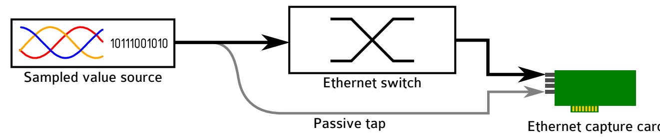

Figure 6. Ethernet timing measurement system.

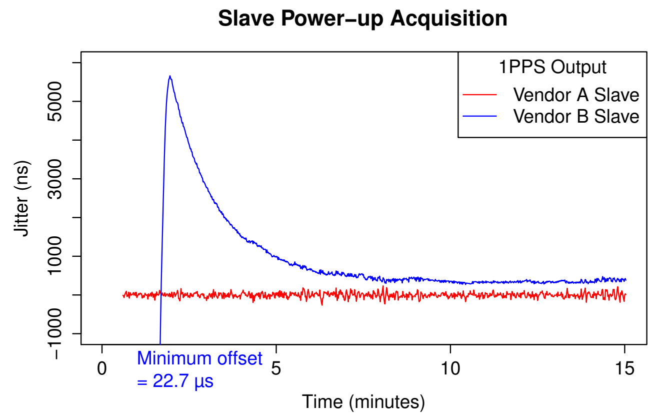

Figure 7. Power up performance for slave clock from two vendors.

A checksum based on CRC32 is used to match frames received on the two ports, and then the difference in arrival time can be calculated.

Other timing tests can be performed by combining the two capture streams and then examining the elapsed time between frames. This is necessary when the message contents do not vary, as the CRC32 matching algorithm requires unique frames.

IV. Results

A. PTPv2 Slave Clock Startup Performance

Slave clocks vary significantly in their ability to synchronise to a grandmaster when first powered on. Slaves from two different manufacturers were connected to the same grandmaster through a transparent clock and were powered up at the same time. Fig. 7 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) immediately. Vendor B's slave clock required 10 min to stabilise, although it was within the ±1 µs specification at 5 min 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 due to increased spill current).

B. Effect of SV on PTPv2

SV data puts some stress on an Ethernet switch, and this results in variation in transit times through the Ethernet

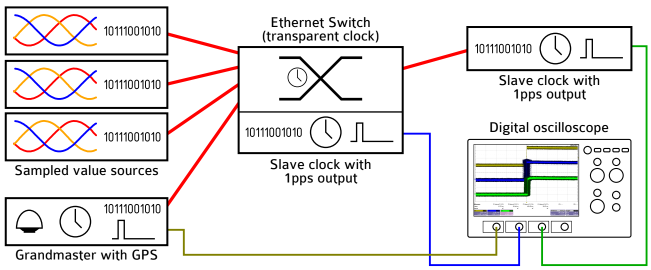

Figure 8. Test arrangement to evaluate effect of SV data on PTP performance.

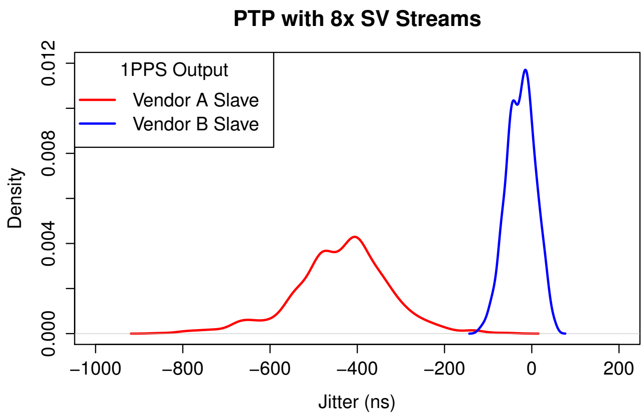

Figure 9. Jitter distribution of two slave clocks with eight SV streams on the shared transparent clock.

switch. The PTPv2 peer-peer transparent clock is designed to compensate for this. A test was performed where eight SV streams were injected into a transparent clock that had two slaves attached, as shown in Fig. 8 (only three SV sources are shown for the sake of clarity).

VLAN filtering was used to prevent SV frames from being sent to the PTP slave clocks, and so the jitter variation is most likely to be due to variations in transit time. The results of Figs. 7 and 9 suggest stability and responsiveness may be mutually exclusive. The design of the servo-loop in the clock recovery function is a compromise between smoothing out variation in frame arrival times (low frequency) and noise (high frequency), and also affects start-up time [28]. The offset in Vendor A's slave clock is due to an offset in ITS 1PPS output system, and the vendor has stated this will be remedied with the firmware release.

C. Frame Delay Measurement

A test of frame delay measurement was performed by injecting test frames into a switch via a passive tap, and from there to three Ethernet switches connected in a chain. 74 m of fibre optic cable inserted into the Ethernet network provided additional delay. Fig. 10 shows that Ethernet frames took between 60 µs and 63 µs to travel from the source to the destination. This confirms that the alignment of frames from separate captures works and can be used to measure switching latencies when the process bus is heavily loaded.

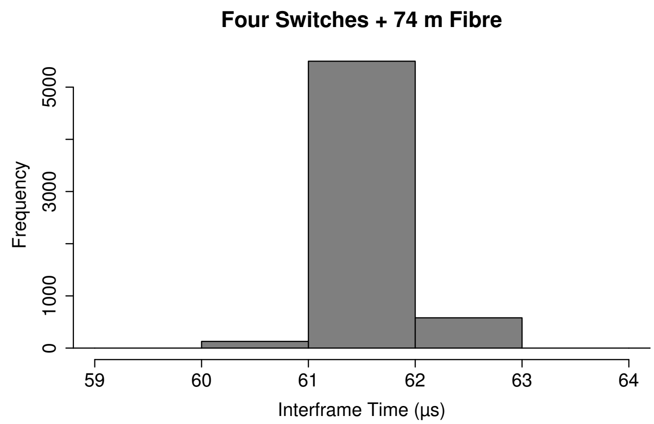

Figure 10. Frame delay variation with four Ethernet switches.

The network emulator selected for this testbed provides a range of impairments that operate at Layer 2, and are therefore suitable for SV and PTP frames. Network timing measurements were used to validate variable delays introduced by the network emulator. Four modes were chosen: wireline (no impairment), uniform delay (1 ms and 2 ms), uniformly distributed delay (1–20 ms) and normally distributed delay ($\overline{x}$=10 ms, σ^2=5 ms). A test stream of SV frames with 100 ms spacing was generated by an Ethernet test set and then injected into the network emulator. Fig. 11 shows the resulting inter-frame times of these four modes. The 'Same Switch' connection bypassed the network emulator and was used to show that the timing variation was not due to the Ethernet switches or the measurement system. The normal distribution is truncated at 0 ms as the network emulator is not capable of transmitting frames before it has received them.

These results show that the network emulator creates precisely controlled network delays and that the frame delay measurement system is accurate.

V. Conclusions

This test and evaluation system enables all aspects of an Ethernet process bus incorporating SV, transduced values and digital inputs/outputs to be controlled, and for end-to-end protection performance to be assessed. A scale-model with 'live' protection IEDs accounts for unknown factors that cannot be explicitly modelled in software. It is expected that this test bed will yield valuable information regarding the optimum communications architecture for various substation topologies, and will enable the capability limits of Ethernet for various protection schemes to be defined. The novel test bed described here can be used to test new protection and communications designs, for fault investigations and the design of new protection schemes.

Results to date show that PTPv2 is a credible option for synchronising IEC 61850-9-2 MUs, but variations in transient and stead-state response between slave clocks will require further investigation. Future work will extend the capability of the test system to include Unified Modeling Language (UML) models of IEC 61850, with the aim of supporting

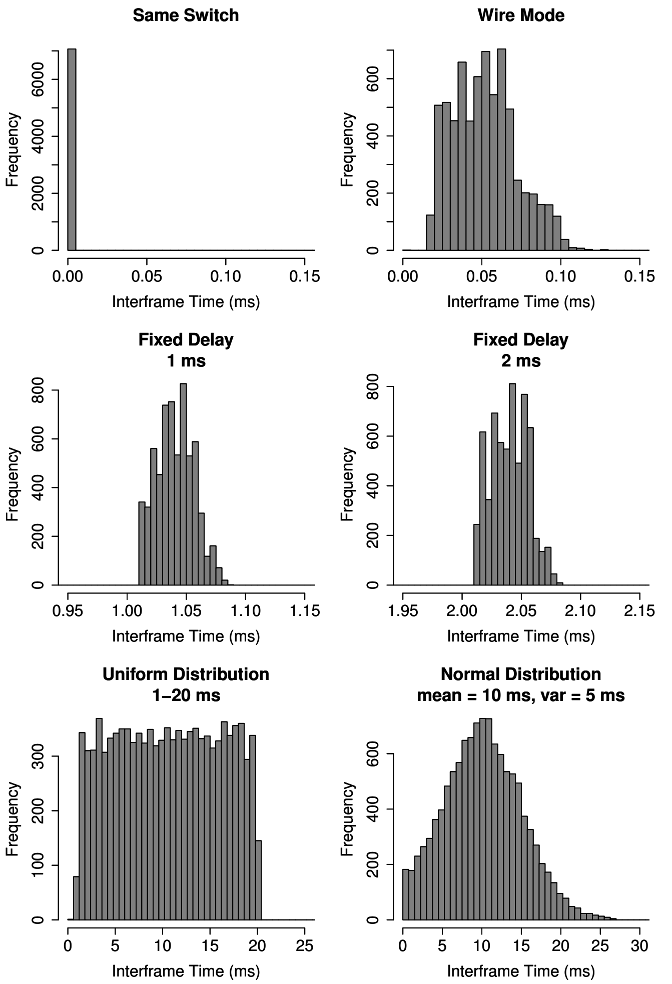

Figure 11. Inter-frame delay under a variety of emulated delay conditions.

fully automated functional testing of substation protection and control.

A digital process bus is a key component of smart substation automation for the smart grid, and enhances safety within substations through the elimination of potentially dangerous currents and voltages in substation control rooms. Knowing the limits of a digital process bus, especially when SV and NCITs are included, will enable utilities to make informed decisions regarding the adoption of this technology.

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