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Comprehensive Validation of Packet-Based Communications for Future Energy Systems

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SUMMARY

This paper reports on the use of modern packet-based communications technologies to dependably support system-critical services. Such services include current differential protection, secure time distribution, and coordinated wide-area control applications. The challenges and subtleties encountered in the migration to packet networks will be explained, using evidence from extensive validation tests at three laboratories. Based on this experience, the paper therefore will provide a clear, comprehensive, and practical guide to the application of packet technologies and networks for power system applications. In particular, the paper examines integrating legacy protection devices, the impact of long-range communications using microwave transmission, and future applications involving native packet-based devices such as Phasor Measurement Units (PMUs), through a demonstration of fast-acting frequency control.

KEYWORDS

Communications networks, MPLS, power system protection, teleprotection, time synchronisation.

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1. Introduction

The use of packet-based infrastructure for electrical utility telecommunications has been emerging for several years. There are compelling benefits, such as improved efficiency and flexibility, and other factors driving this adoption, such as the lack of availability of legacy equipment. However, there are also barriers: the initial cost associated with a large-scale network upgrade, the perceived complexity of implementation, and the lack of experience in the required new technologies such as Multiprotocol Label Switching (MPLS).

Furthermore, utilities need to operate critical services, such as current differential protection, with challenging technical requirements. In the context of such critical applications, this paper will clearly define the main challenges and the presently available methods for mitigating these issues. Two case studies relating to multi-hop microwave transmission and packet-based time synchronisation, involving extensive practical testing and demonstration, will be presented. The paper also discusses future opportunities for native packet communications, and how such advanced schemes can provide coordinated, real-time control – and how this can be validated.

2. Challenges in Migration to Packet-Based Networks

There are several challenges relating to connecting legacy, non-packet-based devices, such as protection relays using Time-Division Multiplexing (TDM) interfaces, to modern communications technologies such as MPLS. These challenges involve the following:

- **Provisions for redundancy**, particularly for protection applications [1].
- **There are several parameters to be configured** for transporting TDM data over a packet network, which need to take into account the trade-offs in overall communications latency, data capacity requirements, data channel efficiency, and physical interface types [1], [2]. An example, which highlights the potential complexity involved, is given in Table 1. In particular, there is typically a choice of the number of IEEE C37.94 “slots” used (1-12), the MPLS packetization rate (e.g. 2-12 bytes per packet as shown in Table 1), and the jitter buffer size which results in stable operation. The resulting end-to-end latency (as measured by the protection relays, but which depends on the message length defined by the relay vendor) is given, and the bandwidth use and efficiency are calculated. Further details are given in [3].
- **Latency, asymmetrical latency, and jitter**. There is a clear concern that data channel jitter and asymmetry can disrupt time synchronisation methods [4]. For UK transmission systems, the measured network latency, asymmetrical latency, and relay tripping times satisfy the most restrict requirements specified in ENA 48-6-7 “Communication services for tele-protection system” and National Grid TS 3.24.18 “Unit Feeder Main Protection” (where the network latency should not exceed 6 ms and the asymmetrical latency should not be greater than 0.4 ms). However, there is also a more subtle issue which can occur during the initialisation of protection services over packet networks. In some cases, this can cause protection maloperation. This effect, and an effective solution to eliminate this risk, is analysed in detail in [5].
- **Security of the data transfer**. This can be achieved by using encryption and authentication of the teleprotection service, or by adopting a fully packet-based solution using IEC 61850-90-5 [6].

Number of C37.94 slots	*Payload size (bytes)*	Latency (from protection relays)	Total Bandwidth (kbps)	Bandwidth Efficency (%)	*Payload size (bytes)*	Latency (from protection relays)	Total Bandwidth (kbps)	Bandwidth Efficency (%)	*Payload size (bytes)*	Latency (from protection relays)	Total Bandwidth (kbps)	Bandwidth Efficency (%)	*Payload size (bytes)*	Latency (from protection relays)	Total Bandwidth (kbps)	Bandwidth Efficency (%)
12	*24*	1.58 ms	1728 kbps	44	*48*	2.32 ms	1248 kbps	62	*96*	2.83 ms	1008 kbps	76	*144*	3.8 ms	928 kbps	83
11	*22*				*44*				*88*				*132*			
10	*20*				*40*				*80*				*120*			
9	*18*				*36*				*72*				*108*			
8	*16*	1.7 ms	1472 kbps	35	*32*	2.45 ms	992 kbps	52	*64*	2.95 ms	752 kbps	68	*96*	3.94 ms	672 kbps	76
7	*14*				*28*				*56*				*84*			
6	*12*				*24*				*48*				*72*			
5	*10*				*20*				*40*				*60*			
4	*8*	2.0 ms	1216 kbps	21	*16*	2.8 ms	736 kbps	35	*32*	3.28 ms	496 kbps	52	*48*	4.25 ms	416 kbps	62
3	*6*				*12*				*24*				*36*			
2	*4*	2.74 ms	1088 kbps	12	*8*	3.5 ms	608 kbps	21	*16*	4.0 ms	368 kbps	35	*24*	5.0 ms	288 kbps	44
1	*2*	4.22 ms	1024 kbps	6	*4*	4.94 ms	544 kbps	12	*8*	5.45 ms	304 kbps	21	*12*	6.5 ms	224 kbps	29
Frames per payload	2				4				8				12			
Time for each frame	125 us				125 us				125 us				125 us			
Packetisation delay	250 us				500 us				1 ms				1.5 ms			
Jitter buffer required for stable operation	1 ms				2 ms				3 ms				4 ms			

Table 1: Overview of typical teleprotection service settings

3. Testing Overview

The tests described in this paper have been conducted using a Real Time Digital Simulator (RTDS) to simulate various power system scenarios and to generate data outputs (either as analogue signals, or in IEC 61850 format). Real hardware protection relays, from a variety of vendors typically deployed by utilities, have been used in the validation work. In some cases, conventional Plesiochronous Digital Hierarchy (PDH) equipment has also been incorporated to represent certain utility network configurations. Figure 1 and Figure 2 illustrate the typical laboratory testing arrangement.

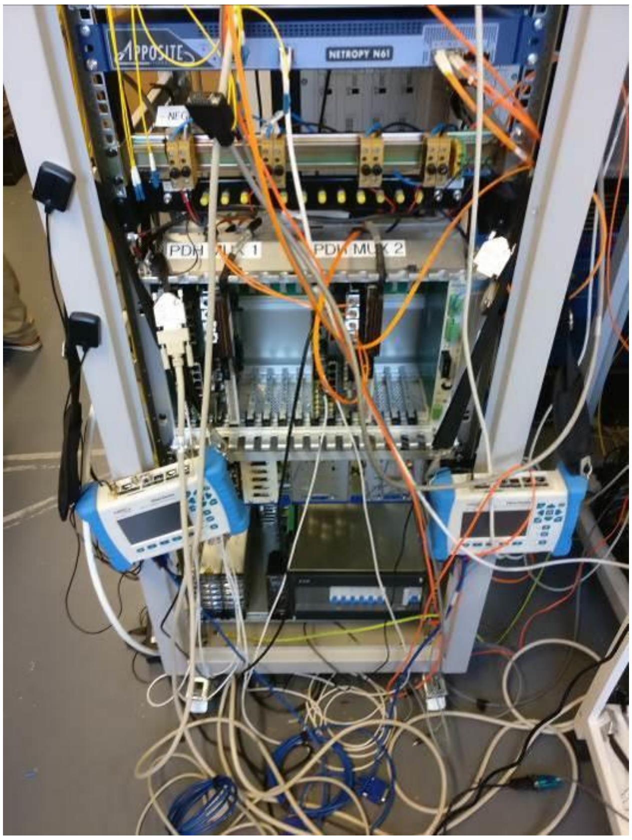

Figure 1: PDH multiplexer equipment, line testers, and network impairment generator

Figure 2: Selection of protection relays, RTDS simulator, and injection equipment

4. Case Study: Packet over Multi-Hop Microwave Links

At present, certain power utilities rely on microwave radio communications to carry operational and control services such as current differential protection. It is mainly used over large geographic distances where it is required to extend the network reach from the core to the end points [7]. Conventional technologies such as Synchronous Digital Hierarchy (SDH) are commonly used in core networks, whilst edge networks in rural areas without resources such as copper or fibre links commonly use microwave radio. Consequently, TDM-based microwave radio has been used where the radio communication is deployed. However, because TDM-based microwave radio technology and equipment are reaching the end-of-life stage, it will become more difficult and costly to maintain such TDM networks. This section therefore summarises an investigation of whether or not it is feasible to replace TDM radio systems with packet-based radio systems, including meeting the stringent requirements for current differential protection.

Figure 3 illustrates the testing environment, including hardware microwave packet radios for two hops and laboratory attenuation equipment to emulate varying distances of microwave transmission. Note that the IRIG-B time synchronisation is required to measure asymmetrical latency, and is not required for typical operation.

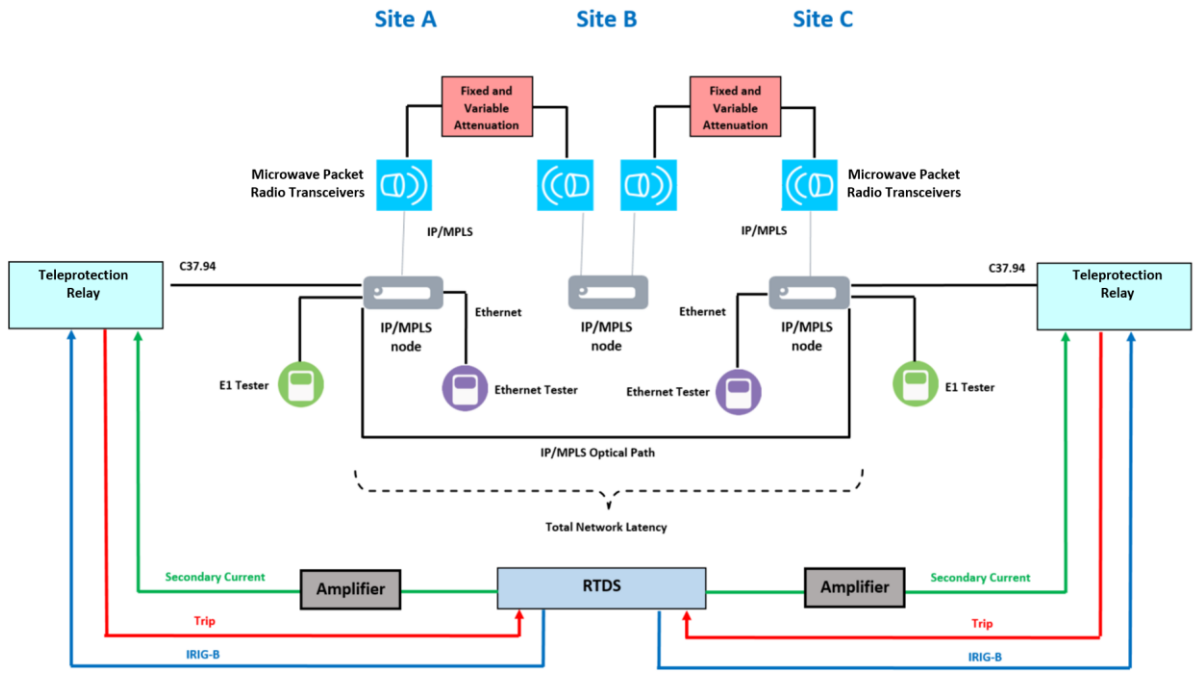

Figure 3: Microwave packet radio test overview

Table 2 briefly summarises the results from the testing. The total network latency (which includes the impact of the two microwave links and the MPLS packetisation process, but not the inherent latency of the relays) is approximately 2.6-3.0 ms, which is very likely to be suitable for teleprotection schemes – especially in distribution systems. The change in network latency was negligible even when the link was significantly attenuated from 1024 QAM to 16 QAM. The data throughput that can be achieved varies from approximately 44-240 Mbps, depending on the configuration and the attenuation (i.e. due to distance or other factors).

Microwave Packet Radio Transceiver bandwidth	Modulation profile (determined by the quality of link which was affected by attenuation)	Network latency measured by relay (ms)	Asymmetry measured by relay (ms)	Typically relay trip time (ms)
14 MHz	16 QAM	2.6-2.8	+/-0.240	24.7
	1024 QAM	2.6-2.8	+/-0.240	24.8
7 MHz	16 QAM	2.8-2.9	+/-0.240	25.4
	1024 QAM	2.8-3.0	+/-0.240	25.5

Table 2: Summary of microwave packet radio tests

Note that injecting additional Ethernet traffic over the same link (but at lower priority than the teleprotection service) had only a very minor impact on the measured path latency due to the Quality of Service (QoS) provisions, and the worst-case results are given in Table 2. Also note that the total latency will depend on the MPLS packetisation rate and the teleprotection message size defined by the specific relay vendor.

5. Case Study: Delivering PTP Time Synchronisation

Many of the issues associated with managing legacy protection relay technologies over MPLS networks can be mitigated by providing accurate time synchronisation directly to the relays. In utility applications, this has conventionally been implemented using Global Positioning System

(GPS) clocks to deliver a signal, such as 1PPS or IRIG-B, directly to each relay. However, some utility experiences have encountered issues with this approach resulting in loss of protection availability or protection maloperation, and practical issues relating to placement of the GPS antenna [5]. An alternative is to use network-based time synchronisation using IEEE 1588 (the Precision Time Protocol (PTP)), using the same MPLS network infrastructure as is used to deliver the protection data. The MPLS wide-area network can therefore deliver time synchronisation to multiple substations, without requiring a separate clock and GPS antenna at each location.

Figure 4 illustrates this approach to time synchronisation, within a laboratory arrangement to test its operation. A single Global Navigation Satellite System (GNSS) clock acts as a PTP grandmaster, which supplies PTP to the wide-area MPLS network. For convenience, a single GTSYNC card (which is part of the RTDS simulator) converts the PTP input to two 1PPS signals for the legacy teleprotection relays; in a real deployment, separate converters in each substation would be required. Note that for best accuracy, hardware timestamping of PTP packets is required in each network element, and therefore extreme levels of network impairment (such as that used in [5]) would not be realistic. Nevertheless, the impact of injected latency, jitter, and asymmetry will be investigated; detailed testing of this arrangement is presently in progress, and will be reported on in the future.

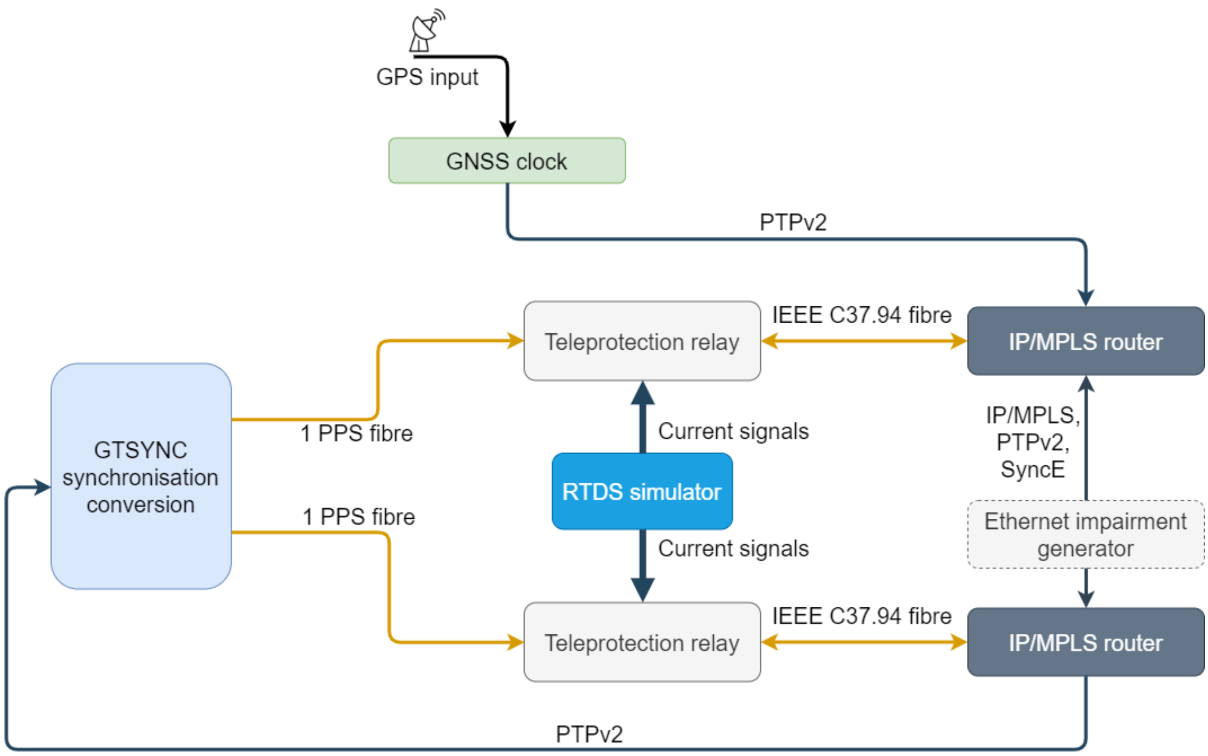

Figure 4: Architecture for teleprotection time synchronisation using PTP

6. Future Applications Using Native Packet Communications

The opportunities for future applications using data which is already packetized, for example using Phasor Measurement Units (PMUs) or IEC 61850 GOOSE protocols, will be highlighted in this section. Figure 4 presents an example of how two laboratories in different countries can collaborate to demonstrate the effectiveness of real-time control methods. The experiment implements the fast-acting control approach given in [8]. The RTDS represents the Great Britain transmission system divided into five control areas, and PMU data streams are produced which represent aggregated measurements from each area in the simulation, and the data are delivered to the controllers.

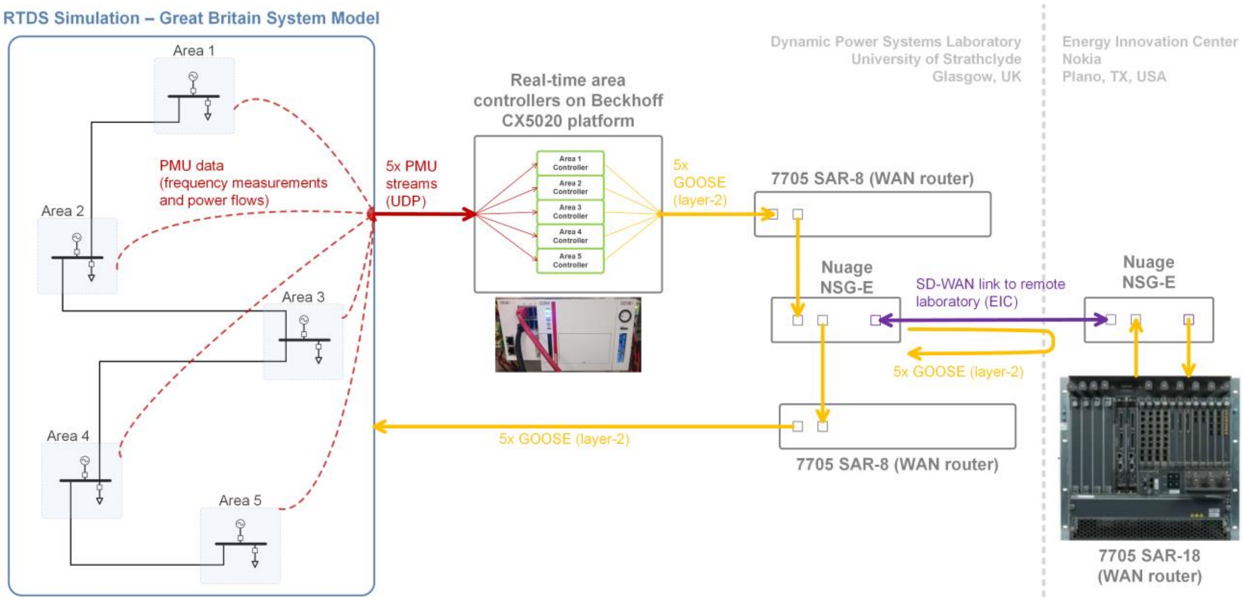

Figure 5: Wide-area protection and control testing using SD-WAN

To emulate the wide-area network communications delay, the GOOSE control commands are transmitted back to the RTDS via the remote laboratory, over the public internet. This is achieved using a Software-Defined Wide-Area Networking (SD-WAN) router in each laboratory. SD-WAN is being used as a convenient method for securely and efficiently (i.e. without significant real-time overhead for the operational data) transferring arbitrary real-time control signals between two or more laboratories. Further details are given in [9].

All packets are timestamped and therefore the RTDS can accurately measure the round-trip time for the control action. For the experiment described in this subsection, the total delay is approximately 120 ms (which reduces to 2-3 ms if the link to the remote laboratory is bypassed with a direct Ethernet connection). For comparison, for the distance of approximately 7,200 km between the laboratories and assuming the speed of light in a fibre of 200,000 km/s, the minimum transport time for the round trip is at least 72 ms.

Therefore, this illustrates how systems involving advanced measurements and fast-acting control can be designed and tested to improve coordinated control in future networks.

7. Conclusions

There are several issues that, understandably, make utilities reluctant to adopt packet technologies – especially for critical services such as protection. This paper has explained the most critical of these issues, and has provided practical guidance for mitigating options. The case studies have highlighted applications using multi-hop microwave applications (particularly for providing communications in rural distribution systems) and PTP time distribution over MPLS.

As utilities increasingly adopt packet-based technologies, there is an opportunity to transfer PTP over WANs to mitigate time synchronisation issues, using time synchronisation converters to avoid the need to also replace legacy relays. In the future, it may also be possible to increasing use native packet-based teleprotection systems, which will avoid the complexities and other issues associated with transporting TDM services over packet-based infrastructure.

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