Performance Evaluation of MPLS-Enabled Communications Infrastructure for Wide Area Monitoring Systems

M Golshani, G A Taylor, I Pisica, P M Ashton

Brunel Institute of Power Systems, Brunel University, London, UK
mohammad.golshani@brunel.ac.uk, gareth.taylor@brunel.ac.uk, ioana.pisica@brunel.ac.uk, phillip.ashton@brunel.ac.uk

Keywords: MPLS, OPNET Modeler, Phasor Data Concentrator, Phasor Measurement Unit, Wide Area Monitoring System.

Abstract

In order to obtain the transient power system measurement information, Wide Area Monitoring Systems (WAMS) should be able to collect Phasor Measurement Unit (PMU) data in a timely manner. Therefore along with the continual deployment of PMUs in Great Britain (GB) transmission system substations, a high performance communications infrastructure is becoming essential with regard to the establishment of reliable WAMS. This paper focuses mainly on evaluating the performance of the real-time WAMS communication infrastructure when Multi-Protocol Label Switching (MPLS) capability is added to a conventional IP network. Furthermore, PMU communications from geographically distributed substations to a Phasor Data Concentrator (PDC) are investigated over different transport protocols. Using OPNET Modeler, simulations are performed based on the existing WAMS infrastructure as installed on the GB transmission system. The simulation results are analyzed in detail in order to fully determine the different characteristics of communication delays between PMUs and PDC.

1 Introduction

State-of-the-art High Voltage DC (HVDC) transmission system technology can increase power transfer capabilities whilst also improving power system stability. In this regard, WAMS can be employed in order to accurately observe the effect of HVDC technology on stability through the use of remote measurements. Apart from this passive role, PMUs can be actively involved to enhance the control systems by providing direct input signals to the HVDC based controllers. In order to achieve such objectives, underlying ICT infrastructures play an important role in communications of monitoring and control data. The signals measured by PMUs are transmitted to the relevant smart grid applications through the Wide Area Network (WAN), where they may encounter excessive delays. The signals delays can have a disruptive effect on the real-time monitoring and robust control of the power systems. In order to successfully implement WAMS, the performance of WAN communications should be fully investigated [1].

The choice of the proper transmission media, network architecture, and protocols will play important role in fulfilling the idea of wide area monitoring, protection and control. Early communication media, such as power line carrier and microwave, had constraints with regard to channel capacity, data transfer rate, reliability, scalability, robustness and so on. As a consequence of the emergence of optical fibre, these constraints have been improved significantly and it has now become the most suitable candidate for WAMS applications [2]. Furthermore, early communication networks carried continuous bit streams over physical links using a technique called circuit switching. Although this method was well suited for transmitting real-time data, a single physical link failure had dramatic consequences. In fact, this would cause interruption of all communications that were using the failed link. It is important to note that the Internet is a datagram packet switched network that solves this problem by dividing data into small chunks called packets. These packets are individually routed through the network and during a link failure they can be rerouted to avoid the failed link. Compared to circuit switching networks, packet switching networks are more robust, flexible and efficient. However, it is more difficult to guarantee or manage flows of data in a packet switching network than in a circuit switching network since each packet is handled separately [3].

Nowadays the Internet is playing a vital role due to the wide variety of applications and services provided. Meanwhile, the wide range of different Internet applications can cause problems with the communications. Some applications like WAMS need real-time communication and therefore low end-to-end delay. While for other applications like File Transfer Protocol (FTP), delay may not be an important issue. Therefore, a high performance communications network should consider the different applications when routing a packet. Fulfilment of such a requirement on Internet is a challenging task for the conventional IP networks [4]. The Internet architecture has evolved over time to integrate new technologies and meet the new requirements of the users [5]. MPLS as a Traffic Engineering (TE) tool has emerged to provide service requirements and managements for the next generation IP based backbone networks [3]. It should be noticed that MPLS is not a replacement of IP. In fact, MPLS adds a set of rules to IP so that the traffic can be classified and policed [4].

This paper uses an existing WAMS scenario installed on the GB transmission system to illustrate the benefits of employing MPLS TE to enhance the real-time communication of PMUs. Performance of WAMS communications infrastructure is evaluated and compared with regard to conventional Internet Protocol (IP) and MPLS networks. OPNET Modeler [6] is used to simulate the networks and the comparison is mainly based on the end-to-end delay characteristics. In addition we investigate the impact on PMU communications performance when they use the two different transport layer protocols, Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). The rest of the paper is structured as follows: Section 2 presents an overview of traditional IP communication and associated drawbacks. Section 3 provides a detailed description of MPLS technology. Section 4 describes the WAN model architecture of WAMS installed on the GB transmission system. In Section 5, the WAMS communications network is modelled in OPNET Modeler for three different scenarios. Section 6 presents and discusses the obtained results. Finally, the paper is concluded in Section 7.

2 Internet Protocol (IP)

For transmitting data over network using IP, each node in substations of WAMS is distributed by a unique IP address. The source node sends packets to the destination node through the intermediate routers based on destination IP address. In IP routing each router takes independent routing decision on each incoming packet to identify the next hop, which the packet has to be sent. To make such a decision each router maintains a table called routing table. In conventional IP, building of routing table is performed by routing algorithms like Open Shortest Path First (OSPF), Routing Information Protocol (RIP), Border Gateway Protocol (BGP), Interior Gateway Protocol (IGP) or Intermediate System-to-Intermediate System (IS-IS) [7]. Depending on the destination address in the packet header and routing table, the router forwards the packet to the next planned hop. This process is continued by the following routers until the packet reaches its destination [4].

The conventional IP routing has number of drawbacks. It does not consider the capacity constraints and traffic characteristics when routing decisions are made. Hence some links in a network can become congested while other under-utilized links exist. Furthermore, IP networks are not scalable and TE is difficult to implement. TE is the process of controlling how traffic flows through the network to make the best use of resources and optimize the network performance. Also IP routing takes place in the Network layer which is slower than the switching. Overall, with these limitations, it is very challenging to implement the real-time application like WAMS in the conventional IP network [4]. In order to overcome these limitations, Internet Engineering Task Force (IETF) has introduced MPLS technology [8].

Communication based on IP can be connection-oriented (TCP) or connectionless (UDP). TCP rearranges data packets in the specified order and retransmits lost or corrupted data. Although TCP provides a reliable communication, it is not suitable for real-time communications since the acknowledgment/retransmission feature lead to excessive delays [4]. In the case of UDP there is no built-in ordering and recovery of data, but the transmission speed is higher than TCP. Therefore, time-sensitive applications often use UDP since a small amount of lost data is preferable over delayed data [9,10].

3 Multi-Protocol Label Switching (MPLS)

MPLS is an advanced technology for high performance packet control and forwarding mechanism. In fact, MPLS adds new capabilities to the IP architecture, which enables support of new features and applications. It increases the network performance, improves the scalability of network-layer routing, provides routing flexibility and TE [11]. MPLS domain can be divided into two parts of MPLS core and MPLS edge. The core consists of routers that are only connected to MPLS capable routers. While MPLS edge is the boundary of the MPLS network and consists of routers that are connected to both MPLS capable and incapable routers. The routers which are in the MPLS domain and forward the packets based on label switching are called Label Switch Routers (LSR). Routers that operate at the edge of the MPLS network are specifically called Label Edge Routers (LER). Packets enter into MPLS domain through Ingress LERs and leave the MPLS domain through Egress LERs. The Ingress LER attaches a short fixed-length label to every incoming packet and then forwards it into MPLS core. This label is used, rather than the IP header, by LSRs to forward the packet through the MPLS network. The route that the packet is forwarded through the MPLS domain is assigned when the packet enters the domain. This route that is established between an Ingress and Egress LERs is called Label Switched Path (LSP). On the other edge of the network, Egress router removes the attached label of outgoing packet and sends further to the destination according to the IP routing [4,7].

The MPLS header has 32 bits as shown in the Figure 1. The header consists of 20-bit Label value, which represents the LSP assigned to the packet and LSRs use this value to make forwarding decisions. Following the Label field there is the 3-bit Experimental (EXP) field, which is also known as Traffic Class (TC) field and is used for Quality of Service (QoS) related functions and drop precedence. Next field is the 1-bit Stack field and is used to indicate bottom of label stack. Finally, there is the 8-bit Time to Live (TTL) field which has the same function as the TTL field in IP header. The Ingress

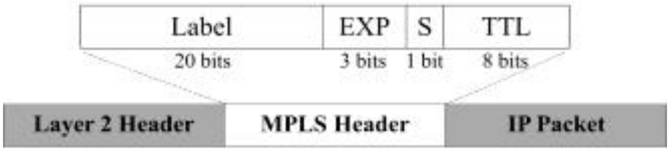

Figure 1: MPLS header [5]

LER sets the TTL, a counter that is decremented by each LSR along the path. If the TTL expires, the LSR discards the packet. MPLS header is placed between the link-layer and network-layer headers. Since MPLS operates between layers 2 and 3, routing process is much faster than conventional IP. In fact, it forms layer 2.5 label switched network on the layer 2 switching functionality without the layer 3 IP routing [11].

The packet is assigned label and mapped on to the LSP in accordance with the Forwarding Equivalence Class (FEC) [12]. FEC is a set of packets that have related characteristics and are forwarded over the same path through a network. FECs can be created from any combination of attributes including source and destination IP address, transport protocol, port number. MPLS uses Label Distribution Protocol (LDP) to exchange label mapping information between LSRs and set up LSPs. LSPs can be manually specified or dynamically computed. Multiple parallel LSPs can be configured between an Ingress-Egress pair. These LSPs can be set up on different physical paths in order to distribute the traffic load and provide more flexibility [13].

4 Wide Area Network Model Architecture

The real WAN model used in this study consists of 9 substations, which are geographically distributed. Except for substations 8 and 9 that have been equipped with two PMUs, all other substations have only one PMU. These PMUs obtain the input signals corresponding to voltages and currents from the instrument transformers and measure power system parameters. PMUs are also connected to a Local Area Network (LAN) and the LAN is in turn connected via a substation router to the WAN. Using this network the measurement data from the PMUs are transmitted to a PDC. Figure 2 presents a simplified schematic of the WAN model infrastructure. Substations 6 and 7 are connected to the WAN through 2 Mbps links and the other substations are connected by 256 Kbps links. In addition, bandwidth of the link between MPLS and PDC is equal to 155 Mbps. Links are shared and used for different communication applications. All PMUs have a sampling rate of 50 samples per second so they generate constant traffic. However, there are other substation based applications that generate variable traffic [14]. The PMU in substation 1 is Arbiter 1133A, which generates packets with the size of 50 bytes [15]. While for the other 8 substations AMETEK TR-2000 multi-function recorder is used as a PMU and generates packets with the size of 42 bytes [16]. The packet size depends on the number of synchrophasor parameters that a PMU measures.

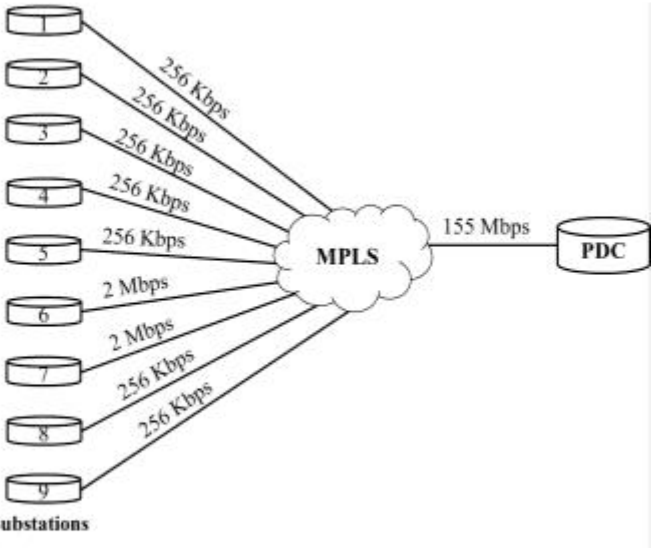

Figure 2: WAN infrastructure schematic of the real system

This section has provided some information about the physical structure and characteristics of the WAN model. Due to a lack of detail regarding some aspects of the model and also for simplicity, some assumptions and simplifications have been made in order to perform the simulations. The simplifications, along with main aspects of the model implementation and configuration, will be fully described in Section 5.

5 Network Simulation

The extent of WAN makes the direct experiment almost impossible. Apart from the economic issues, it can lead to a serious damage and loss of data. Hence there is a need to have simulation models and testbeds which can accurately imitate the network behaviour. By simulating the intended network, it is possible to test the newly proposed mechanisms, protocols, topologies, etc. or modify some network parameters and observe the effect before actual deployment. The simulations in this research are performed on a network simulator, OPNET Modeler [6]. OPNET provides advanced communications network modelling and comprehensive simulation capabilities. OPNET huge library of models and commercially available network technologies, enable the simulation of real-life networks. Its friendly Graphical User Interface (GUI) and flexibility make the model building and implementation phases easier [17].

According to the information provided by National Grid, substations 6 and 7 are connected to the WAN by 2 Mbps links that have more communications network activity in terms of staff presence and data transferred. Whereas substations 8 and 9, which have been equipped with two PMUs, have a lower level of background traffic. Based on this information, some substations were modelled differently from others. All substations have one local server and several workstations. Substations 1 to 5 are assumed to have a similar structure and each of them has five workstations such that one of them is defined to operate as a PMU. Substations 6 and 7 are assumed to have 13 workstations each such that one of the workstations works as a PMU. Finally, substations 8 and 9 have 3 workstations each such that two of them work as a PMU. Figure 3 illustrates the simulation model as implemented using OPNET. The geographical locations of substations and data centre are not their actual locations in the real system.

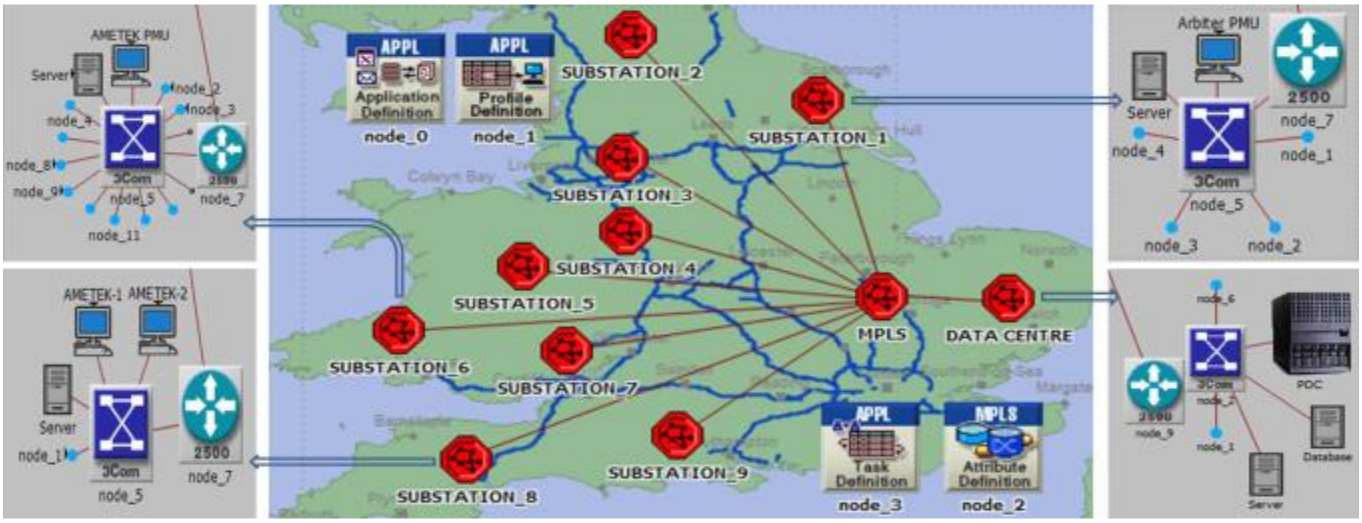

Figure 3: The infrastructure of the simulated network in OPNET

The workstation nodes are *Ethernet_wkstn_adv* model running over TCP/IP as defined in the OPNET model library [6]. There are different methods available in OPNET for introducing communications network traffic. Since the end-to-end delays of PMU packets from the source application layer to destination application layer are required in order to accurately model PMU, traffic custom applications were defined. In OPNET, all custom applications are defined through a series of tasks [18]. Therefore, two tasks were configured by using the *Task Config* utility object in OPNET that represent traffic associated with the two types of PMUs that exist in the model. The main difference between these two tasks is the packet size such that in the case of Arbiter PMU is 50 bytes and for AMETEK PMU is 42 bytes. Both tasks were configured to generate packets every 20 ms, which means they create 50 samples per second. The final destination of all PMUs packets is the PDC server in the data centre node. Apart from PMUs, for other workstations inside the substations standard application models were used to configure traffic. Standard application models provide an adequate level of detail for modelling commonly used applications. For these non-PMU workstations, one profile consisting of, *File Transfer*, *Database Access* and *Email* applications were specified. *File Transfer* application sends data to the substations local server, while *Database Access* and *Email* applications send data to the servers at the data centre.

The PMU generated data will be first transmitted to the substation switch, and then to the substation router. The *100Base-T* link was used for all substation LAN communication. Substations were connected to MPLS using *PPP* point-to-point links and the same type of link used for connecting MPLS to the router in the data centre. The link data rates were selected according to the specified architecture in Section 4. From the router the data will then be transmitted through the LAN to the PDC server. Furthermore, background traffic was defined for the links between substations and data centre in the WAN. The determined background traffic of each link is proportional to the number of workstations in different substations and the traffic they generate. It was not possible to simulate the exact data traffic of the real network due to its stochastic nature. However, reasonably accurate traffic profiles were determined and adopted for implementation. Table 1 shows the applied background traffic for WAN links in terms of percentage of link bandwidth.

The process of configuring MPLS in the network has three main steps of configuring LSPs, creating FECs and configuring LSRs. Due to insufficient information on the exact implementation of the MPLS deployed in National Grid, the architecture shown in Figure 4 was considered for the MPLS subnet in the model. It consists of two LERs, one as Ingress and the other one as Egress router, and several LSRs at the core of the MPLS network. These routers are connected through the *DS1* links. OPNET supports both static and dynamic LSPs. With static LSPs, the exact route used by the LSP can be specified. Therefore, we have used static LSP as allows more routing control and makes the analysis straightforward. Three LSPs were configured as shown in the Figure 4 in green, red and blue colours. MPLS attributes,

From	**To**	**Background traffic** (Percentage of link bandwidth)
Substation 1	MPLS	50 %
Substation 2	MPLS	50 %
Substation 3	MPLS	50 %
Substation 4	MPLS	50 %
Substation 5	MPLS	50 %
Substation 6	MPLS	70 %
Substation 7	MPLS	70 %
Substation 8	MPLS	0 %
Substation 9	MPLS	0 %
MPLS	Data Centre	60 %

Table 1: WAN links background traffic

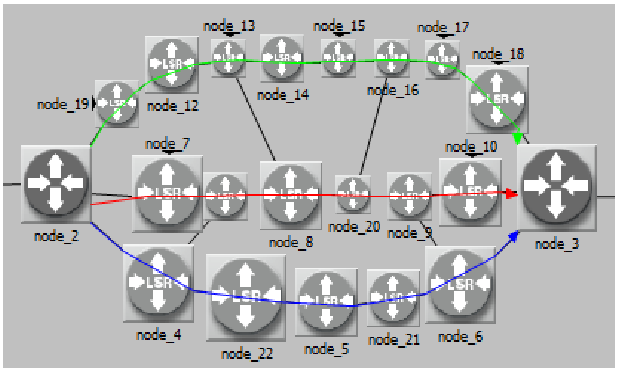

Figure 4: The architecture of MPLS subnet

which are used to configure network-wide MPLS parameters, are grouped in the *MPLS Config* object. *FEC specifications* attribute can be used to specify the FEC parameters employed by MPLS. In our model we have defined three types of FECs for PMU, *Database* Access and *Email* packets. Routers MPLS attributes are grouped in the *MPLS Parameters* attribute on each router. Using this attribute of LERs, TE bindings between FECs and LSPs can be determined. In our simulation the blue LSP, which is the shortest path, has been assigned for PMU packets. In addition, *Database* Access and *Email* packets are transmitted through the green and red LSPs, respectively.

6 Simulation Results

After the completion of network configuration, the statistics to be collected can be specified in OPNET [6]. The main concern of this research is the delay characteristics from the PMUs to PDC, due to their critical role in providing satisfactory performance levels in real-time WAMS applications. Figure 5 illustrates the end-to-end delay results for two PMUs in substation 5 and 9 for three different scenarios. In the first scenario PMUs packets are transmitted over conventional IP network based on TCP protocol. In the second and third scenarios the MPLS feature has been added and PMUs packets are transmitted based on TCP and UDP protocols, respectively. As can be seen from the graphs the MPLS/UDP scenario shows better performance, especially in preventing dramatic increase of delay.

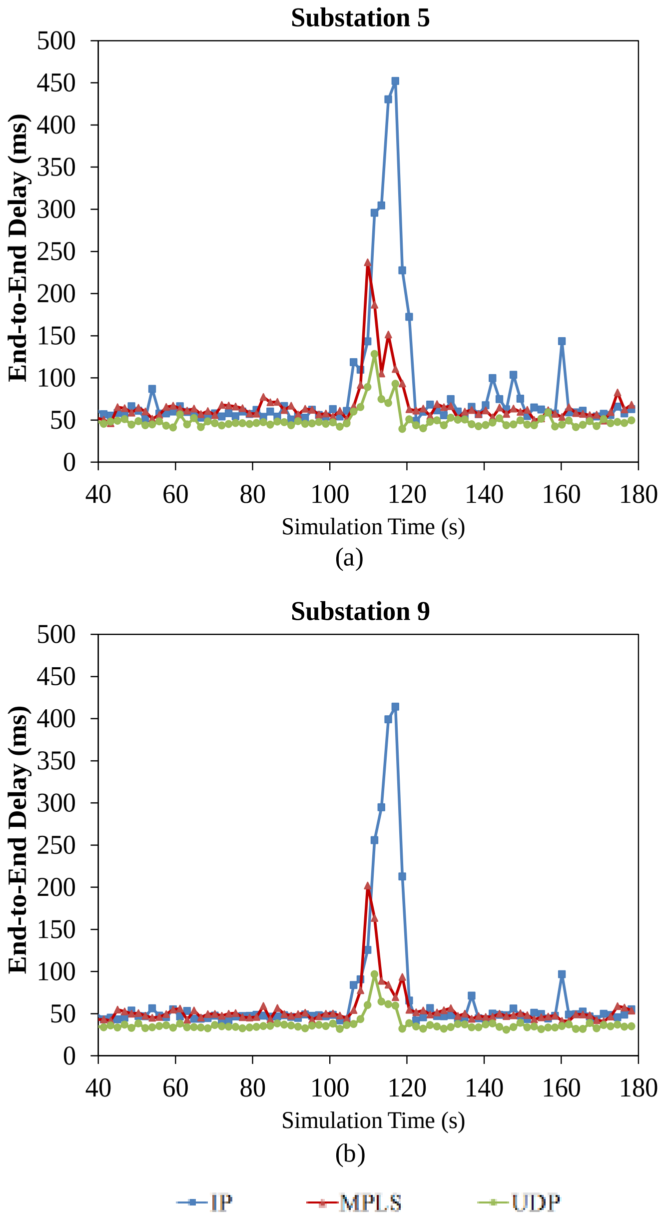

Figure 5: PMU packets end-to-end delay for the three scenarios

(a) Results for substation 5

(b) Results for substation 9

After exporting the end-to-end delay results from OPNET Modeler to Excel, the required delay characteristics of four PMUs have been presented in Table 2 for better comparison. These characteristics are minimum, maximum, average, and standard deviation of the packets delays. It should be noted that the substation 9 has two PMUs and the results for one of them has been presented as they show similar behaviour. For the conventional IP scenario all routers in the MPLS subnet are MPLS disabled and the packets are routed using OSPF protocol without TE. However, simulations are based on the common topology. All the defined applications in IP scenario use the shortest path to forward traffic and this causes congestion on the links form this path. The traffic exceeds the capacity of the shortest path, while there are under-utilized longer paths available. Therefore as can be seen from the IP scenario results, PMUs packets may experience much greater delay than their expected average delay. For example, the PMU in substation 1 has average end-to-end delay of 83.18 ms, however, according to Table 2 and for the considered simulation time period it experienced the maximum delay of 616.84 ms. For the MPLS scenario the MPLS features of the network are enabled, which allows obtaining results for MPLS TE simulation. *Database Access* traffic is routed to the green LSP and *Email* traffic is routed to the red LSP. Hence, these traffics avoid the bottleneck of the shortest path and

End-to-End Delay Characteristics (ms)				
Substation	Min	Max	Average	STDEV
1	47.11	616.84	83.18	85.04
5	40.67	452.05	82.58	73.98
7	40.46	419.60	67.96	68.46
9-PMU1	30.98	414.20	66.91	68.76

(a)

End-to-End Delay Characteristics (ms)				
Substation	Min	Max	Average	STDEV
1	46.42	216.76	68.78	30.84
5	46.09	237.01	67.19	27.90
7	38.28	204.14	55.00	23.13
9-PMU1	34.74	202.05	53.99	23.14

(b)

End-to-End Delay Characteristics (ms)				
Substation	Min	Max	Average	STDEV
1	40.66	158.58	52.36	15.03
5	39.23	128.11	49.59	12.63
7	33.90	99.35	39.82	9.09
9-PMU1	30.90	96.74	37.10	9.14

(c)

Table 2: End-to-end delay characteristics of OPNET results
(a) IP scenario
(b) MPLS scenario
(c) MPLS/UDP scenario

network can offer better service to the WAMS time-critical application. Finally, as can be seen from the results, WAMS communication over UDP through MPLS has shown the lowest end-to-end delay among the three scenarios.

7 Conclusions and Further Work

WAMS capabilities make it an invaluable technology to enhance the reliability of power grids. As one of the vital requirements of WAMS, all PMUs which are installed in geographically distributed substations need to transmit data to a centralized PDC in a timely manner. In this regard, MPLS-enabled communications infrastructure utilizes the network resources efficiently compared to IP network and provides better performance. Furthermore, the study has shown improvement on PMUs data transmission when using UDP transport protocol as compared to when TCP is employed. Further work will be to study the influence of the QoS mechanism on WAMS network delay. QoS policy can be used to ensure the excessive delay does not occur for the time-critical applications packets in a shared network. In addition, the integration of IEC 61850 standard for PMU communications will be investigated. IEC 61850 has some features that make it dominant, especially in time-critical applications.

Acknowledgements

The authors would like to thank the electricity transmission system operator of Great Britain, National Grid, for the provision of information on their communications infrastructure and also Psymetrix for their assistance in obtaining the TCP traffic information from the actual WAMS.

References

[1] M. Golshani, G. A. Taylor, I. Pisica, P. Ashton, "Laboratory- Based Deployment and Investigation of PMU and OpenPDC Capabilities" The 10th *International Conference on AC and DC Power Transmission (IET), ACDC 2012*, 4-6 December 2012, Birmingham, UK.

[2] Y. Deng, H. Lin, A. G. Phadke, S. Shukla, J. S. Thorp, L. Mili, "Communication network modeling and simulation for Wide Area Measurement applications", *IEEE PES Innovative Smart Grid Technologies (ISGT)*, pp. 1-6, 16-20 Jan. 2012.

[3] M. K. Porwal, A. Yadav, S. V. Charhate, "Traffic Analysis of MPLS and Non MPLS Network including MPLS Signaling Protocols and Traffic Distribution in OSPF and MPLS", *First International Conference on Emerging Trends in Engineering and Technology*, pp. 187-192, 16-18 July 2008.

[4] K. Jannu, R. Deekonda, "OPNET Simulation of Voice over MPLS with Considering Traffic Engineering", Master Thesis, Electrical Engineering, Blekinge Institute of Technology, Sweden, June 2010.

[5] M. M. Shahsavari, A. A. Al-Tunsi, "MPLS performance modeling using traffic engineering to improve QoS routing on IP networks", *Proceedings IEEE SoutheastCon*, pp. 152-157, 2002.

[6] OPNET Modeler, OPNET Technologies, [www.opnet.com]

[7] A. M. Bongale, N. Nithin, "Analysis of link utilization in MPLS enabled network using OPNET IT Guru", *International Journal of Computer Applications*, vol. 41, no. 14, pp. 35-40, March 2012.

[8] The Internet Engineering Task Force, [Online]. Available: http://www.ietf.org

[9] "A Guide for PMU Installation, Commissioning and Maintenance — Part II PMU Installation Procedures", NASPI, 5 June 2007, [Online]. Available: https://www.naspi.org

[10] M. Golshani, G. A. Taylor, I. Pisica, P. Ashton, "Implementation of Wide Area Monitoring Systems and Laboratory-Based Deployment of PMUs," *48th International Universities Power Engineering Conference (UPEC)*, 2-5 Sept. 2013.

[11] J. Jaffar, H. Hashim, H. Zainol Abidin, M. K. Hamzah, "Video quality of service in Diffserv-aware multiprotocol label switching network", *IEEE Symposium on Industrial Electronics & Applications (ISIEA)*, vol. 2, pp. 963-967, 4-6 Oct. 2009.

[12] J. Xia, M. Li, L. Wan, "Research on MPLS VPN Networking Application Based on OPNET",

International Symposium on Information Science and Engineering (ISISE), vol. 1, pp. 404-408, 20-22 Dec. 2008.

[13] X. Xiao, A. Hannan, B. Bailey, L. M. Ni, “Traffic engineering with MPLS in the Internet”, IEEE Network, vol. 14, no. 2, pp. 28-33, March-April 2000.

[14] S. FengJie, Q. Qi, F. JieQing, “Real-time signal time delay analysis of WAMS based on MPLS VPN technology”, *International Conference on Advanced Power System Automation and Protection (APAP)*, vol. 2, pp. 1089-1093, 16-20 Oct. 2011.

[15] Arbiter Systems, [Online]. Available: http://www.arbiter.com

[16] AMETEK Power Instruments, [Online]. Available: http://www.ametekpower.com

[17] OPNET Modeler Documentation Set, Version 17.1.

[18] A. S. Sethi, V. Y. Hnatyshin, “The Practical OPNET User Guide for Computer Network Simulation”, Boca Raton, USA: CRC Press, 2013.