SOFTWARE defined networks for smart substations in an active distribution system

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ABSTRACT

The Smart Substations (SS) which are increasingly being employed in the distribution substation of an Active Distribution System (ADS) encompass the characteristics of smart grid. In order to have effective deployment of a Substation Automation System (SAS), one of the major prerequisites is to have a secure, reliable, resilient, standardized and interoperable communication architecture. The newly evolved technology of Software Defined Network (SDN) is increasingly being used in the domain of Smart Grid. In this paper, concept of SDN is applied in the SAS for prioritizing time critical Generic Object Oriented Substation Event (GOOSE) messages in order to reduce their latency in the network. This approach of prioritizing GOOSE messages for its fast delivery improves the reliability and Quality of Service (QoS) of the SAS. In this paper, the developed prioritization approach is demonstrated in a virtual SDN environment. Finally, performance evaluation of proposed GOOSE prioritization algorithm in SDN based SAS is carried out by developing a Virtual Tenant Network (VTN).

Keywords: Active distribution system; IEC 61850; smart substation; software defined network; substation automation system.

INTRODUCTION

Nowadays, the traditional substations of typical distribution systems are increasingly being transformed as Smart Substation (SS). The high penetration of distributed energy resources (DERs) at the distribution level has led to bi-directional power flows in distribution system and made the conventional distribution system into an Active Distribution System (ADS). A SS refers to a substation of ADS which has a high penetration of distributed energy resources (DERs) connected to its feeders. Increased penetration of DERs into the distribution system has posed challenges in the operation and management of ADS. These challenges can be addressed by effective operation, control and management of SS of ADS through automation system (Ali et al., 2015). For designing an effective automation system for SS requires a secure, reliable, resilient, time critical and deterministic communication infrastructure. This has eventually led to the involvement of Information and Communication Technologies (ICT) in a SS automation system.

Intelligent Electronic Devices (IEDs) employed for carrying out different functions in an automated SS are generally proprietary devices i.e. vendor specific. These IEDs from different vendors cannot be used interchangeably within a substation. For a reliable communication through standardized and interoperable means, a flexible and interoperable communication architecture for a SS is required. This challenge was well addressed by the TC 57 working committee by publishing an IEC 61850 standard (IEC 61850 std.) for substation automation systems. IEC 61850 aims to provide interoperability among different vendor devices to be employed in a Substation Automation Systems (SAS). It is achieved by defining common data classes and specific communication services mapping in a standardized environment. To achieve performance of automation applications, IEC 61850 defines various type messages for implementing different automation functions (Thomas, M.S. & and Ali, I., 2010.). For time-critical events such as protection of electrical equipment and status of breakers, generic object-oriented substation event (GOOSE) messages are exchanged. The GOOSE is a time critical service and needs to be transported within stipulated delay to achieve effective protection and control in a SS (Ali et al., 2015). For periodic messages, sampled value (SV) messages are sent from the conventional CT/PT via merging unit through process bus between devices by means of Ethernet switches (Kumar et al., 2015).

A Software Defined Network (SDN) is a new approach originally employed as a networking middleware to accomplish online services for one or more computers connected to the same network via internet. A SDN separates the control and the data plane into two different entities running in a same network. The control plane contains a controller, typically a SDN controller, to provide dynamic switching of data packet routes to the hardware switching device, i.e. the data plane. It analyses the link disturbance and congestion to provide prioritized solutions. It promises to provide a highly fast and reliable delivery of network packets from source to destination by employing various algorithms and intelligent techniques at the control plane. It also accomplishes network resource utilization in an optimized and efficient manner.

The scope for SDN technology for its implementation in Smart Grid domain has been reviewed by many researchers (Aydeger et al., 2015; Cahn et al., 2013; Dorsch et al., 2014). Zhang (2013) explored various possibilities of SDN as a multi domain and content oriented approach being increasingly deployed for Smart Grid. Rinaldi (2015) evaluated the SDN architecture for Smart Grid applications considering the Round Trip Time (RTT). The results were found comparable with a conventional protocol such as Internet Control Message Protocol (ICMP). SDN along with LTE has been employed for cyber security of communication architecture of Smart Grid (Irfan et al., 2015). Authors in (Leal, E.A. & Botero, J.F., 2016) have showcased the recent efforts available in literature for improving the management and operation of substation automation system communication networks through the appropriation of SDN concepts. Further, authors in (Maziku, H. & Shetty, S., 2017) proposed a security score model which incorporates the criticality of device in SDN and provides the ability to reconfigure the IEC 61850 substation automation network in real time. In another work, authors (O'Raw, J. et al., 2017) proposed a method on how SCL can be used as a basis for network security auto-configuration and highly secure micro-segmentation of IEC61850 networks. Authors in (Pfeiffenberger et al., 2015) aim to achieve fault tolerance in a communication architecture by employing SDN in a substation. The delays for various messages in an IEC 61850 based SAS are evaluated by applying SDN with VLAN and priority tagging.

Although extensive research has been carried out in application of SDN for smart grid scenario, application of SDN for prioritization of GOOSE messages in a SAS has not been discussed in detail. Hence, the prioritization of GOOSE message by appropriation of SDN is proposed in this paper. An algorithm for prioritizing GOOSE messages in a SAS for the SDN controller is presented in this paper. The aim of prioritizing GOOSE messages is to improve the overall performance of different centralized protection schemes, especially at times of flooding in network whenever a fault occurs. The proposed algorithm is evaluated for a typical Substation Communication Network (SCN) simulated virtually in Mininet ("Mininet") environment. The proposed algorithm can completely automate the SAS by providing almost zero transmission delays for time critical GOOSE messages. Also, this paper illustrates establishment of a virtual SDN based network of a SCN by employing a Programmable Flow Controller ("Programmable Flow Controller"), which replicates a SDN controller, running in a Virtual Box environment.

IEC 61850 BASED SUBSTATION AUTOMATION SYSTEM – AN OVERVIEW

Brief history of IEC 61850

IEC 61850 was published as a global standard for "Communication Networks and Systems in Substation" by the International Electrotechnical Committee. It aims to provide communication interoperability among multivendor substation IEDs by following the Object Oriented Data Modeling (OODM) and Substation Configuration Description Language (SCL) approach (IEC 61850 std.). With standardized data models for various functions in substations and the related generic services, the IEC 61850 standard provides standardized communications in substations. In order to make the standard futuristic and fool proof, its object data models and services are mapped to the real time protocols such as Manufacturing Message Specification (MMS), Transmission Control Protocol (TCP) and Switched Ethernet. In an IEC 61850 based substation automation system (SAS), time critical and real time services, such as Sampled Values (SVs) and GOOSE, are mapped directly onto the Ethernet layer of the OSI model and are depicted in Figure 1.
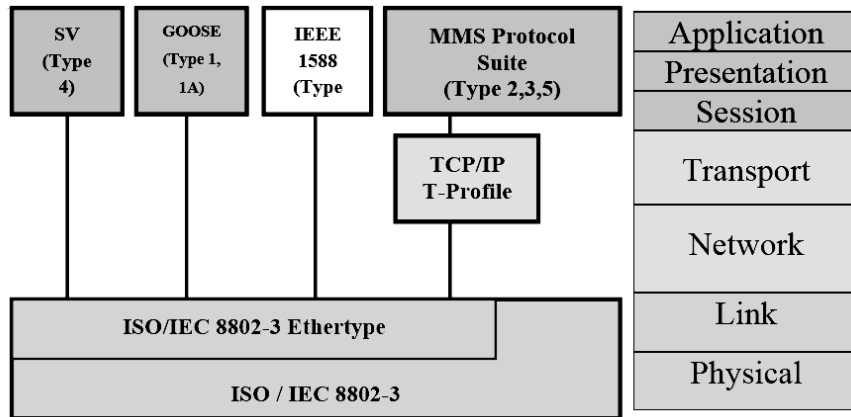
Fig. 1. Mapping of messages as per IEC 61850 standard.

In IEC 61850 based SASs, protective functions involve the messages exchange from Merging Units (MUs) to protection & control (P&C) IEDs and GOOSE messages exchange among substation IEDs. (breaker IED and P&C IED). However, GOOSE and SVs messages, over the substation LAN, are time critical and must be delivered within a stipulated time in order to have effective trip commands in case of contingencies in the system. Thus, performance of SCN is critical for the transmission of GOOSE and SVs in realizing 'all-digital' substation automation applications.

Message format of various IEC 61850 services

IEC 61850 standard's GOOSE and SVs communication are based on 'publisher/subscriber' model and their multicasting nature makes simultaneous delivery of the same message to more than one IED in the peer group. These multicast messages are used for the implementation of high speed peer-to-peer communication in modern IEC 61850 based substations.

IEC 61850-8-1 (IEC 61850-8-1 ed2.0 std.) GOOSE has replaced the conventional hardwired interfaces at the station level with fibre optic based standardized Ethernet link. GOOSE messages are high priority messages which provide a very flexible mean (binary, analog and integer), for exchanging of substation events (analogue value or status change) among IEDs. GOOSE message structure and the service model permit fast transmission of trip/interlocking/blocking commands data for interlocking and protection purposes (Yalla et al., 2002; Simon et al., 1999; Zhang et al., 2008). GOOSE message Ethernet frame structure is shown in Figure 2.

IEC 61850-9-2 (IEC 61850-9-2 std.) specifies the Specific Communication Service Mapping (SCSM) for the transmission of the Sampled Values (SVs) according to the abstract specification defined by by IEC 61850-7-2. The standard '9-2 LE' (IEC 61850-9-2 LE std.) specifies the SV packet format, sampling rate, time synchronization needs, and the interfaces for the transmission of SVs of currents and voltages for substation applications.

In order to improve security and performance of protection scheme in a substation LAN, GOOSE/SVs messages are configured to use some of the advanced features of the switched Ethernet frame structure such as priority tagging and VLAN tags. These advanced features paves the way for efficient utilization of available network bandwidth and to minimize overall processing delays of priority messages by employing priority tagging and VLAN tagging.
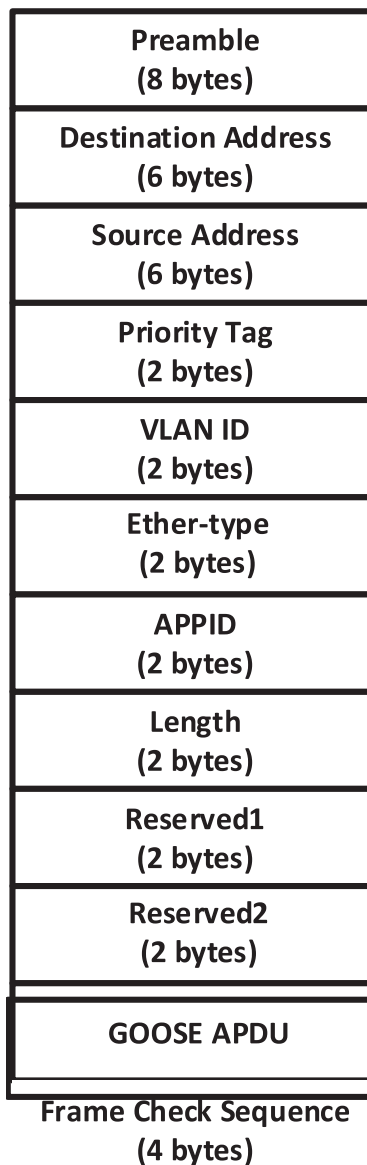
Preamble (8 bytes)
Destination Address (6 bytes)
Source Address (6 bytes)
Priority Tag (2 bytes)
VLAN ID (2 bytes)
Ether-type (2 bytes)
APPID (2 bytes)
Length (2 bytes)
Reserved1 (2 bytes)
Reserved2 (2 bytes)
GOOSE APDU
Frame Check Sequence (4 bytes)

Fig. 2. Ethernet frame for GOOSE message.

SDN BASED IEC 61850 SUBSTATION AUTOMATION SYSTEM

Introduction of mobile devices, virtual servers and cloud services drive the traditional networks to transform their conventional architectures. The conventional network architecture is static in nature and consists of tiers of Ethernet switches arranged in a tree shaped structure for client server communication. However, in case of dynamic architecture the traditional approach is limited and requires a dynamic changing network architecture. This was needed to include paradigm changes in network such as changing traffic patterns, access to multiple databases in single application, etc. This led to the introduction of Software Defined Network (SDN). An SDN separates the control plane and date plane into different entities which runs in a same network as shown in Figure 3. It consists of an SDN controller which decides the dynamic network configuration rules and acts in the control plane.
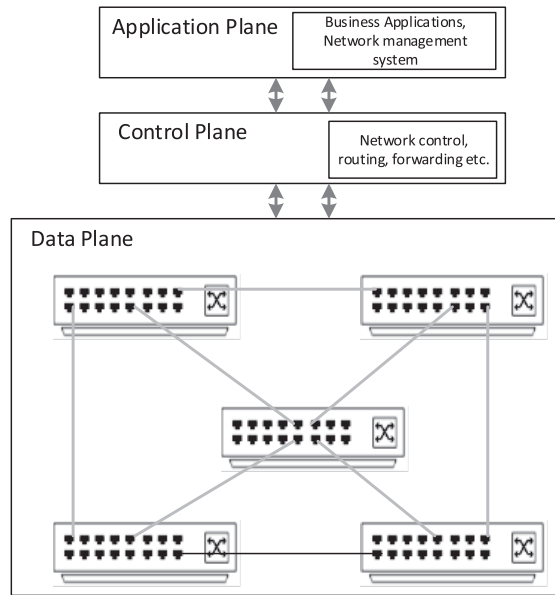
Fig. 3. SDN architecture with decoupled control.

The development of smart grid requires networking between vast number of IEDs deployed in the system. The primary requirement for smart grid applications is to provide reliable, secure and efficient communication infrastructure. Since the smart grid scenario is rapidly changing and thus its ICT requirements can be fulfilled by employing a highly dynamic networking approach. Thus, SDN finds its place in the smart grid. This paper proposes application of SDN for a substation to provide automatic configuration and optimization of the network composed of various IEDs in a substation. The SDN controller could provide configuration rules, as decided by the administrator, which results in low latency and jitter in delivered packets, network security, high performance, and broader network connectivity.

The various types of service in a IEC 61850 based SAS are discussed in detail in previous section. The most time critical IEC 61850 service is a GOOSE message which is initiated when a fault occurs in a substation. In order to provide efficient operation, it is recommended by the standard, that the GOOSE message must reach the destination within a stipulated delay period not exceeding 4ms (IEC 61850-5 std.).

Various approaches have been evaluated in literature to minimize the delay in communicating the GOOSE message (Bing et al., 2014; Kumar et al., 2014; Sidhu et al., 2011). However, application of SDN in an SCN aims to minimize the latency occurrence in the network to its least possible value. The aim of prioritizing the GOOSE messages, allows the improvement of the overall performance of a centralized protection scheme, especially at times of flooding in network, which is expected in case of a fault.

The approach of SDN is applied to a SAS in order to prioritize GOOSE messages which results into reliable, fast and secure delivery of data packets. It can eliminate various delays introduced at switch level while using a definite protocol. Authors in this paper present an algorithm which prioritizes GOOSE messages arriving at the SDN enabled switch in an IEC 61850 based SAS. The proposed algorithm can provide minimum latency in GOOSE packets and achieve high reliability in automation of the substation network. The prioritization algorithm for GOOSE packet is illustrated with a flowchart in Figure 4.

The data packet arriving at the data plane of the SDN controller is filtered to segregate GOOSE messages based on the Application Identifier (APPID) of the GOOSE Protocol Data Unit (PDU). The APPID range for a GOOSE type message is 0x000 to 0x3FFF for GOOSE and 0x8000 to 0xBFFF for GOOSE type (1A) for trip messages. The APPID ranging from 0x4000 to 0x7FFF is for sampled values type messages (IEC 61850-9-2 std.). After identification, the destination of the ether type message is obtained and routes are computed by the controller. Then the sorting of various routes, in precedence order from best to worst, is done, governed by the constraints of minimum number of hops and least queuing of the traversing packet.
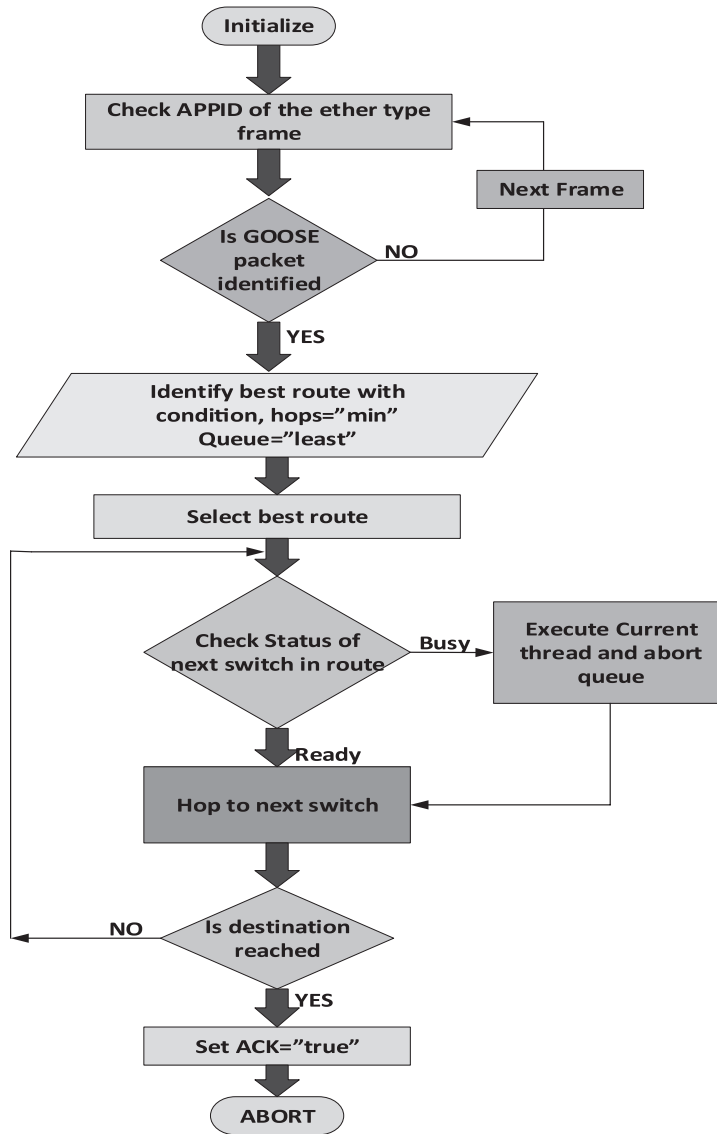
Fig.4. Flowchart for GOOSE prioritization.

Since the priority for the GOOSE messages is maximum, the current threads being executed in the switches of the route are completed and subsequent queue is aborted. This is done so as

to transmit the GOOSE message as fast as possible amounting to least latency. As the GOOSE packet is received at destination, the ACK bit is set to true and thread is aborted. The controller then configures the RSTP and routes data packets other than the GOOSE message. It is to be noted that the pattern of arrival of GOOSE packet is random and a poisson distribution is used for their arrival at the switch.
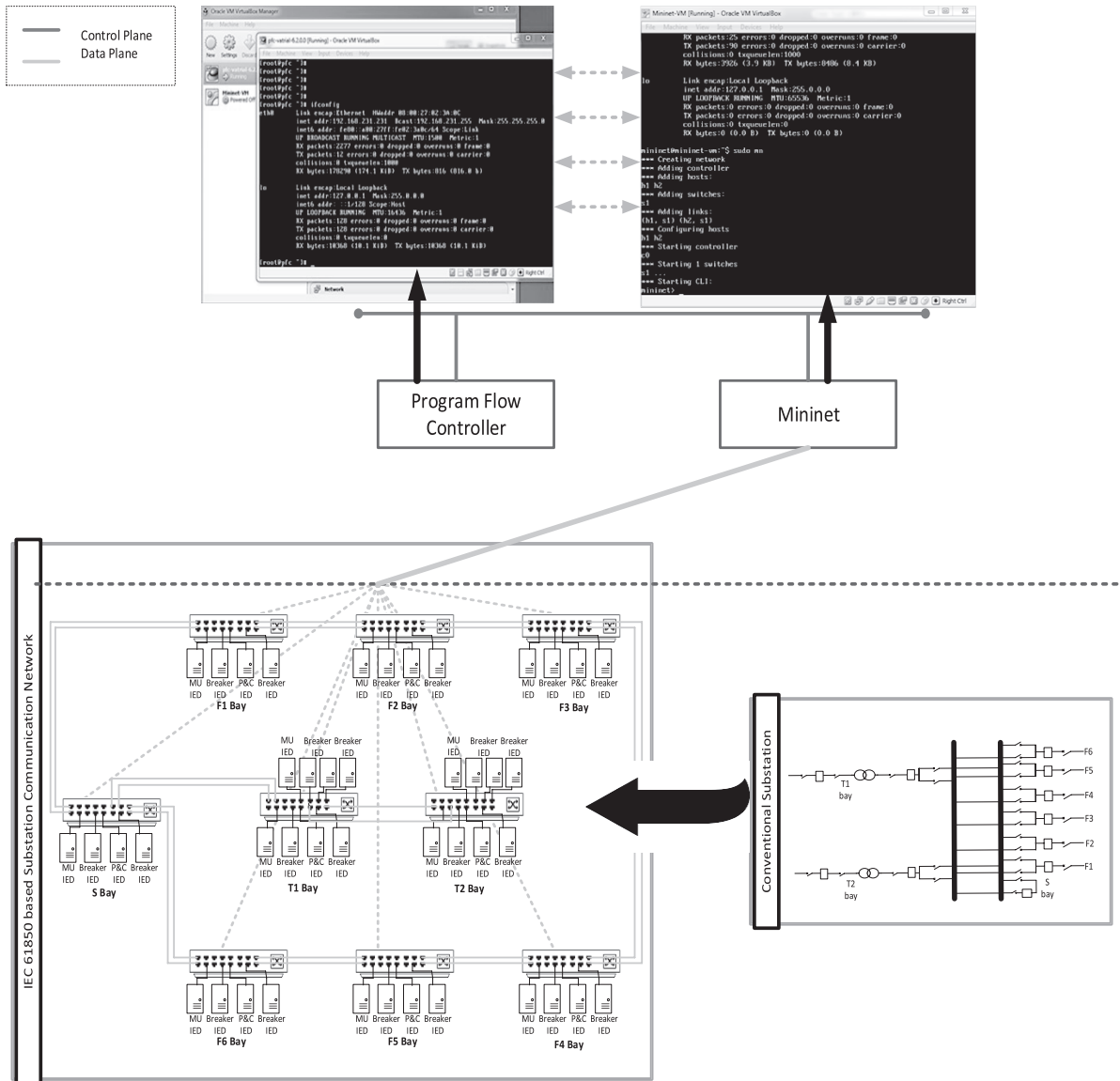
Fig.5. SDN in a Virtual Environment.

EVALUATION OF SDN BASED SUBSTATION AUTOMATION SYSTEM

In order to evaluate the proposed GOOSE prioritization algorithm in a SAS, a Virtual Tenant Network (VTN) has been developed. A VTN is a virtual client-server based networking approach which bifurcates the networking into separate control and data plane to implement a SDN. The virtual environment was established using the Oracle VM VirtualBox software running on a multicore processing workstation. It is to be noted that virtualization feature needs to be enabled in the processor configuration to realize VTN.

The Programmable Flow Controller (PFC), a Linux based platform, was run on the VM VirtualBox. The PFC replicates the features of the SDN controller in virtual environment. In order to configure VTN in the PFC shell, PFC is run in configuration mode and GOOSE priority algorithm is loaded into the memory. The PFC contains the source and destination mac address of the GOOSE packet. The Mininet acts as the network emulator and a connection is established with the PFC in the VM VirtualBox environment. In order to pass traffic in the Mininet network between the

switches, a virtual network consisting of switches and links has been created in Mininet shell. The PFC interacts with the Mininet in the control plane and Mininet acts as a layer to provide interaction among the switches in the data plane. This scenario replicates a layer 2 VTN.

A conventional substation consisting of feeder bays, F1, F2……F6, S and transformer bays, T1 and T2 is transformed into an IEC 61850 based SDN enabled SS. The network is created in Mininet environment and control is governed by the PFC, which acts as SDN controller. The control flows are represented with blue connections, whereas data plane flows are in green color as shown in Figure 5. Once the connection is established between the PFC and the virtual Mininet network, the SS switches act virtually as Open Virtual Switch (OVS) in an Open Virtual Application (OVA).
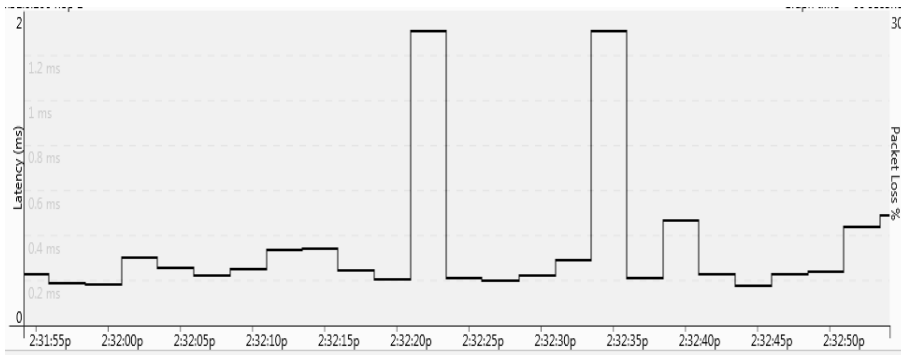

Fig.6. Connection Establishment in virtual network.

The connection was established between the PFC and virtual Mininet network and Quality of Service (QoS) was analyzed by the ping results shown in Figure 6. The sampling interval was considered as 5 sec.

Initially, the GOOSE message was generated in the network at t=12 sec. The GOOSE message created flooding in the network and the latency value rapidly increased as shown in Figure 7. It is to be noted that the results have been downscaled to highlight latency introduced in the network by GOOSE packet transfer. After emulating the SDN and applying GOOSE prioritization algorithm the results were found to improve and the maximum change in latency value was found to be significantly reduced.
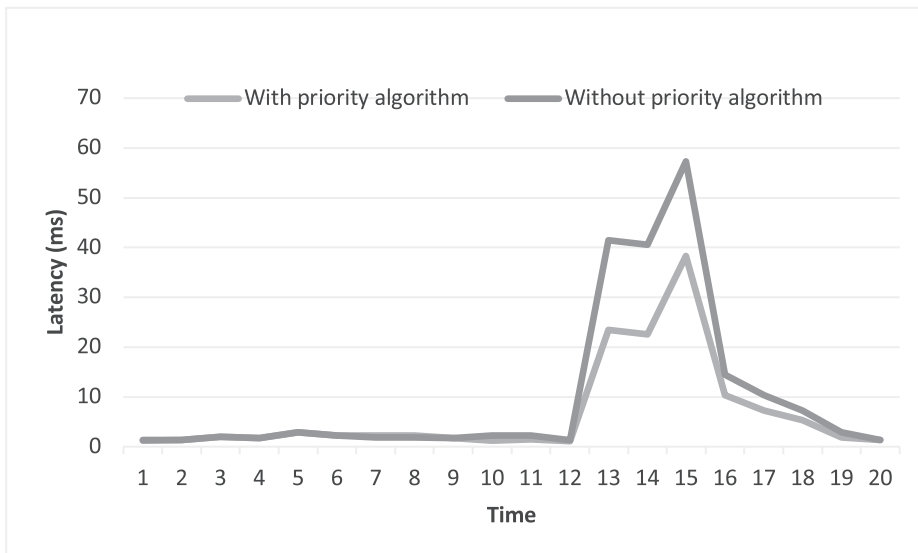

Fig.7. E2E delay comparison in SDN.

CONCLUSION

This paper proposes application of SDN for IEC 61850 based Smart Substations, which is considered as a paradigm technology for a smart grid communication architecture. In order to deliver the GOOSE message to its destination in minimum possible time, a GOOSE prioritization algorithm with SDN appropriation is demonstrated in this paper. In order to fulfil this requisite, concept of SDN is applied to prioritize GOOSE messages in an IEC 61850 based automated substation. Flexibility, ease of control, security and management makes the SDN technology a viable solution for future smart grids. The developed prioritization algorithm for GOOSE messages is applied and tested on a virtual environment.

The performance evaluation results were found satisfactory after applying the prioritization algorithm. Also, suitability and applicability of SDN for Smart Substation have been clearly depicted in the paper. It can be concluded that network latency, which is one of the major hindrance in development of fully automated Smart Substations, can be reduced to very low values by employing the SDN technology.

REFERENCES

Ali, I., Thomas, M.S., Gupta, S. & Hussain. S.M.S. 2015. Information modeling for Distributed Energy Resource integration in IEC 61850 based substations, Annual IEEE India Conference (INDICON), New Delhi.

IEC 61850 2nd ed, 2013. Communication networks and systems for power utility automation.

Thomas, M.S. & and Ali, I. 2010. Reliable, Fast, and Deterministic Substation Communication Network Architecture and its Performance Simulation. IEEE Transactions on Power Delivery **25**(4)2364–2370.

Ali, I. Thomas, M.S. Gupta & S. Hussain. S.M.S., 2015. IEC 61850 Substation Communication Network Architecture for Efficient Energy System Automation. Energy Technology & Policy (2):2381–5639.

Kumar, S., Das, N. & Islam, S. 2015. Performance evaluation of a process bus architecture in a zone substation based on IEC 61850-9-2. IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Brisbane, QLD.

Aydeger, A. Akkaya, K. & Uluagac, A. S., 2015. SDN-based resilience for smart grid communications. IEEE Conference on Network Function Virtualization and Software Defined Network (NFV-SDN), San Francisco, CA.

Cahn, A. Hoyos, J. Hulse, M. & Keller, E., 2013. Software-defined energy communication networks: From substation automation to future smart grids. IEEE International Conference on Smart Grid Communications (SmartGridComm), Vancouver, BC.

Dorsch, N. Kurtz, F. Georg, H. Hägerling, C. & Wietfeld, C., 2014. Software-defined networking for Smart Grid communications: Applications, challenges and advantages. IEEE International Conference on Smart Grid Communications (SmartGridComm), Venice.

Zhang, J. Seet, B.C. Lie, T.T. & Foh, C.H., 2013. Opportunities for Software-Defined Networking in Smart Grid. 9th International Conference on Information, Communications and Signal Processing (ICICS), Tainan.

Rinaldi, S. Ferrari, P. Brandão, D. & Sulis, S.,2015. Software defined networking applied to the heterogeneous infrastructure of Smart Grid. IEEE World Conference on Factory Communication Systems (WFCS), Palma de Mallorca.

Pfeiffenberger, T. Du, J. L. Arruda, P. B & Anzaloni, A., 2015. Reliable and flexible communications for power systems: Fault-tolerant multicast with SDN/OpenFlow. 7th International Conference on New Technologies, Mobility and Security (NTMS), Paris.

Irfan, A. Taj, N. & Mahmud, S. A., 2015. A Novel Secure SDN/LTE Based Architecture for Smart Grid Security. IEEE International Conference on (CIT/IUCC/DASC/PICOM), Liverpool.

Leal, E.A. & Botero, J.F. 2016. Transforming Communication Networks in Power Substations through SDN. IEEE Latin America Transactions **14**(10):4409–4415.

Maziku, H. & Shetty, S. 2017. Software Defined Networking enabled resilience for IEC 61850-based substation communication systems. IEEE International Conference on Computing, Networking and Communications (ICNC), Santa Clara, CA.

O'Raw, J., Laverty, D.M. & Morrow, D.J. 2017. IEC 61850 substation configuration language as a basis for automated security and SDN configuration. IEEE Power & Energy Society General Meeting, Chicago, IL.

"Mininet," http://mininet.github.com/.

"Programmable Flow Controller," http://support.necam.com/SDN/pfv6/download/?id=b5ea21f6-a855-4c50-909d-79de68263e3c

IEC 61850–8–1 ed2.0, 2011. Communication Networks and Systems for Power Utility Automation-Part 8–1: Specific Communication Service Mapping(SCSM) – Mappings to MMS (ISO 9506-1 and ISO 9506–2) and to ISO/IEC 8802–3,

Yalla, M. Adamiak, M. Apostolov, A. Beatty, J. Borlase, S. Bright, J. Burger, J. Dickson, S. Gresco, G. Hartman, W. Hohn, J. Holstein, D. Kazemi, A. Michael, G. Sufana, C. Tengdin, J. Thompsonand, M. & Udren, E.,2002. Application of peer-to-peer communication for protective relaying. IEEE Transactions on Power Delivery (17): 0 885–8977.

Simon, M.S. & Sufana, C.R.,1999. Summary panel discussion: GOOSE [Substation Automation]. Power Engineering Society Summer Meeting, Manhattan, USA.

Zhang, L.X. & Nair, N.K.C., 2008. Testing protective relays in IEC 61850 framework. Australian Universities Power Engineering Conference, Brisbane, Australia.

IEC 61850–9–2 ed2.0, 2011. Communication Networks and Systems for Power Utility Automation - Part 9–2: Specific Communication Service Mapping(SCSM) –Sampled Values Over ISO/IEC 8802–3

IEC 61850–9–2 LE: Implementation guideline for digital interface to instrument transformers using IEC 61850–9–2, UCA International Users Group.

IEC 61850–5, 2012. Communication Networks and Systems for Power Utility Automation - Part 5: Communication requirements for functions and device models.

Bing, H. Xuyang, Z. & Jing, L., 2014. Smart substation precise time research and analysis. IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS), Austin, Texas.

Kumar, S. Das, N. Muigai, J. & Islam, S., 2014. Performance evaluation of data transmission in a single and double bus network within the utility substation based on IEC 61850. IEEE PES General Meeting | Conference & Exposition, National Harbor, Maryland.

Sidhu, T. Kanabar, M. & Parikh, P., 2011. Configuration and performance testing of IEC 61850 GOOSE. International Conference on Advanced Power System Automation and Protection (APAP), Beijing, China.

الشبكات المُعرفة بالبرمجيات لمحطات ذكية في نظام التوزيع النشط

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الخـــلاصـة

تتضمن المحطة الذكية (SS) التي يتم استخدامها بشكل متزايد في محطة نظام التوزيع النشط (ADS) خصائص الشبكة الذكية. من أجل النشر الفعال لنظام أتمتة المحطة (SAS)، فإن أحد المتطلبات الرئيسية هو الحصول على بنية اتصال آمنة وموثوقة ومرنة وموحدة وقابلة للتشغيل البيني. يتم استخدام التكنولوجيا المتطورة حديثاً للشبكة المُعرفة بالبرمجيات (SDN) بشكل متزايد في مجال الشبكة الذكية. في هذا البحث، يتم تطبيق مفهوم SDN في SAS لتحديد أولويات رسائل أحداث المحطات الفرعية الموجهة للأجسام العامة الحيوية (GOOSE) من أجل تقليل زمن الوصول في الشبكة. ويعمل هذا النهج على تحسين موثوقية وجودة الخدمة (QoS) من SAS. في هذا البحث، تم عرض نهج تحديد الأولويات المتقدم في بيئة افتراضية للتوصيل بالبرمجيات. وأخيراً، تم تقييم أداء خوارزمية GOOSE لتحديد الأولويات المقترحة في SAS المرتكزة على SDN عبر تطوير الشبكة الافتراضية (VTN).